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João Carlos Gonçalves dos Reis
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Industrial Engineering and Operations Management

XXIX IJCIEOM, Lisbon, Portugal, June 28–30, 2023

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Preface

Introduction

The 29th International Joint Conference on Industrial Engineering and Operations Management (IJCIEOM) took place between 28 and 30 June 2023 and was organized at Lusófona University in Lisbon, Portugal. The IJCIEOM23 theme was "Developing Resilience in Industrial Engineering and Operations Management" and aimed to analyze the resilience of supply chains in the post-COVID-19 era. The IJCIEOM23 is the result of an agreement between four Industrial Engineering Associations, namely: ABEPRO (Brazilian Association of Production Engineering), ADINGOR (Asociación para el Desarrollo de la Ingeniería de Organización), IISE (Institute of Industrial and Systems Engineers), and ASEM (American Society for Engineering Management). IJCIEOM23 was also supported by several universities, where we highlight the Lusófona University (host), the University of Aveiro, and the University of Minho. During the last few years, both associations and partner universities played a pivotal role in bringing scientists closer to industrial engineering practitioners and academics. Springer Proceedings in Mathematics & Statistics (PROMS) has followed the conference since 2019 (Reis et al. 2019a, b; Thomé et al. 2020, 2021a; López et al. 2022) and played a key role in disseminating scientific knowledge to the entire community of industrial and operations engineers and all readers curious about the subjects addressed. In this regard, the conference partner journals followed the same example as PROMS and published selected scientific articles, highlighting the conference – such as the Special Issue entitled "Industrial Engineering and Operations Management – a view from IJCIEOM 2020–2021" (Thomé et al. 2021b), by *Brazilian Journal of Operations & Production Management*. IJCIEOM has a long tradition of bringing together master's and doctoral students in Industrial Engineering and Operations Management with researchers, professionals, and academics from around the world. In our understanding, networking from an early age is important for the academic growth of young industrial engineers in their search for new and stimulating knowledge. We genuinely hope to continue to support the entire academic-scientific community, increasingly promoting debate and publications.

Book Overview

"Resilience" was the theme chosen for the conference due to its centrality to industrial engineering and operations management in a post-COVID-19 era. In this regard, the articles published in this volume focus on how Digital Transformation (DX) and Artificial Intelligence (AI) have made the manufacturing and service industry more resistant to VUCA elements (i.e., volatile, uncertain, complex, and ambiguous). Regarding DX and AI, the research focused specifically on supply chain management, project management, and industrial 4.0. Additionally, we were very pleased to see that industrial engineers were responsible for incorporating innovative and technological concepts into service and product operations. Despite the growth of publications, the number of articles dealing with sustainable practices in logistics and supply chain management is still small, given that this will be one of the greatest challenges for the next generation of industrial engineers. As in the past year (2022), we continue to believe that demographic factors and ongoing climate change will exert great pressure on resource management and the need to modernize sustainable value production processes. Overall, this year's IJCIEOM/PROMS volume provides a valuable resource for researchers and practitioners alike, as it presents a number of relevant contributions in identifying new challenges and opportunities for industrial engineering and operations management.

Final Remarks

The 29th IJCIEOM brought together scientists from all over the world, having received about 170 submissions. Manuscript submissions came from 4 continents (North and South America, Europe, and Asia) and 18 different countries, namely (by alphabetical order): Argentina, Brazil, Canada, Chile, Colombia, Ecuador, Germany, Greece, India, Italy, Mexico, Morocco, Peru, Portugal, Qatar, Saudi Arabia, Spain, United States of America. Compared to 2022, IJCIEOM23 saw an increase in the participation of six more countries, which reinforces the international nature of the conference. In percentage terms, the conference has also grown by around 50% since last year, which demonstrates greater interest from participants. Of the total number of articles submitted, only about 1/4 of the articles were selected for publication in PROMS. This edition focused on eight relevant areas of industrial engineering and operations management, namely: (1) Production Engineering and Operations Management; (2) Logistics; (3) Operations Research; (4) Transport

System Engineering; (5) Supply Chain risk models and resilience; (6) Last mile delivery optimization; (7) Stochastic Inventory models and optimization; and (8) Human development and digital training for operation management in emergencies.

Acknowledgments

The editors of this book of proceedings are grateful for the support of all participants and the entire Industrial Engineering and Operations Management Community. Moreover, we would like to express a special thanks to (1) the reviewers who worked hard to ensure that each article had at least two high-quality reviews in a timely manner; (2) the organizing and scientific committees, IJCIEOM secretariat, International Associations (ABEPRO, ADINGOR, ASEM, IISE), and partner Universities (U. Aveiro and U. Minho); and (3) our Publishing Editor, Robinson dos Santos, for the permanent support and to the entire Springer team that has been working hard so that all selected papers reach the entire community.

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References

López, S., Freires, F., Reis, J. Dores, J. (Eds.) (2022). *Industrial Engineering and Operations Management*. In IJCIEOM 2022: Springer Proceedings in Mathematics & Statistics, vol. 400. Springer, Cham. https://doi.org/10.1007/978-3-031-14763-0.

Reis, J., Pinelas, S., Melão, N. (Eds.) (2019a). *Industrial Engineering and Operations Management I*. In IJCIEOM 2018: Springer Proceedings in Mathematics & Statistics, vol. 280. Springer, Cham. https://doi.org/10.1007/978-3-030-14969-7.

Reis, J., Pinelas, S., Melão, N. (Eds.) (2019b). *Industrial Engineering and Operations Management II*. In IJCIEOM 2018: Springer Proceedings in Mathematics & Statistics, vol. 280. Springer, Cham. https://doi.org/10.1007/978-3-030-14973-4.

Thomé, A. M. T., Barbastefano, R., dos Reis, J. C. G., Scavarda, L. F., & Freires, F. G. M. (2021a). Industrial Engineering and Operations Management–a view from IJCIEOM 2020–2021. Brazilian Journal of Operations & Production Management, 18(3), 1–6. https://doi.org/10.14488/BJOPM.2021.033.

Thomé, A., Barbastefano, R., Scavarda, L., Reis, J. Amorim, M. (Eds.) (2020). *Industrial Engineering and Operations Management*. In IJCIEOM 2020: Springer Proceedings in Mathematics & Statistics, vol. 337. Springer, Cham. https://doi.org/10.1007/978-3-030-56920-4.

Thomé, A., Barbastefano, R., Scavarda, L., Reis, J. Amorim, M. (Eds.) (2021b). *Industrial Engineering and Operations Management*. In IJCIEOM 2021: Springer Proceedings in Mathematics & Statistics, vol. 367. Springer, Cham. https://doi.org/10.1007/978-3-030-78570-3.

Contents

Blockchain Application for the Supply Chain Optimization

Tiago Rodrigues and P. Carmona Marques

Abstract The last few decades have radically changed the economy, companies have moved from selling directly to online selling, from local suppliers to global suppliers, and as products have become more complex, supply chains have followed suit. These changes have brought challenges to management, such as managing the bullwhip in complex supply chains, while struggling with the need to reduce costs. Considering the previous context, the present work aims to explore the causes of the bullwhip effect, and to evaluate the potential that current machine learning and data storage techniques in blockchain have to mitigate the risk of inventory breakdown. In order to achieve the proposed objectives, a review of the mentioned topics was considered, and based on the identified potential, a supply chain model based on information sharing was suggested. To assess the potential of the proposed model, several strategic analyzes were carried out, and a simulator was developed to study how the change in the flow of information could benefit the supply chain.

Keywords Bullwhip effect · Blockchain · Machine learning · Supply chain · Data science

1 Introduction

The year 2020 proved to be one of the biggest stress tests of the world economy. The pandemic of COVID-19 has shaken, at once, several dimensions of the economy, from means of production to availability of raw materials. Several factories have suspended their production and each country sought to apply containment measures

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that would best protect the population, but in on the other hand, it delayed the processes of goods transactions, which was reflected in the increase delivery times, inventory breaks and, in some cases, total unavailability of products [1].

In May 2021, another test appears, this one of the resilience of the world economy, with the blockade by 6 days of the Suez Canal by the ship Ever Given. The Suez Canal is one of the main waterways communication between Asian low-cost production centers with major markets consumption, the European and American markets. It is estimated that this accidental blockage resulted in in US$54 billion of commercial losses and added strong pressure to the development of methods to prevent and contain future similar occurrences [2].

The growing weight of environmental impact in supply chains must always be considered in strategic decisions and, in recent years, new challenges have arisen that oblige managers to redefine visions and reinvent processes. Some of the latest challenges are, e.g., the ban on the use of heavy vehicles or diesel vehicles in certain city areas, the imposition of the international maritime organization to reduce sulfur in fuel oil, used as fuel for ships, restrictions on the use of single-use plastics or the banning of certain raw materials due to environmental and public health concerns, the ban on animal testing and restrictions on trade with countries or companies that are suspected violations of international human rights law [3].

Along with the previous examples, managers still have to solve problems such as workers' strikes, accidents with carriers, factory accidents with loss of production hours, natural catastrophes, shortage of mineral raw materials, among countless others. These events can easily lead to production gaps that, in like light industry, the impact is negligible, however, when it comes to industries heavy, production stoppage and subsequent start-up can mean several days without production. In addition to the variable costs, the production break has other costs that, as a rule, are more difficult to mitigate, such as unsold products, customers lost to competition and damage to the organization's reputation [4].

To prevent the costs of running out of raw materials, organizations resort to storage of raw material by excess, however, this storage will have costs associated with the occupation of space, conservation and displacement of raw materials, insurance and, for times, to other economic factors, such as the variation in the price of the raw material and the product final market [5].

Finally, it is important to bear in mind that the vast majority of supply chains consist of in companies, as such, there is a concern to guarantee the return, according to the shareholders' expectations. All the questions already posed about organizations are, obviously balanced against the need to guarantee the viability company's economics. To recapitulate, according to [6], despite the wide spectrum of origins of the challenges, if these are analyzed with a certain degree of abstraction, they can be grouped into three major need groups:

1. Delivery, to the customer, in the desired period;
2. Environmental and ethical expectations of the client;
3. Economic viability of the organization.

Considering the importance of collaboration between organizations and the current development of technology that allows global and instantaneous communication, it simplifies the creation of networks universal means of collaboration and open the door to new methods of supply management [7].

With the resources currently offered by the market, it is not only possible, but also potentially viable, reconciling current supply chains, built on decades of experience, with emerging technologies focused on optimization and communication. The last few years have matured Blockchain technology, which already has several cases of success in tracking transactions that, due to inherent characteristics, have high levels of safety and reliability associated with feasibility costs of large-scale applications [8].

Another area that has grown significantly in recent years is the ability of computers to learn, the use of algorithms increasingly sophisticated and associated with more powerful computers, which makes it possible to obtain results for complex problems with a fraction of the resources [9]. The objective of this article is to analyze the potential of new technologies in the optimization of supply chains, at an operational level, and also how the increase in transparency can benefit the organization. To achieve these objectives, the following topics were analyzed:

- Bullwhip Effect – What are your causes and trends in approaching the problem.
- Blockchain and Machine Learning (ML) – What does it consist of and how can it be used to solve problems in organizations

2 Literature Review

Bearing in mind the three guidelines for supply chain challenges, referred before, the three themes will now be deepened in order to answer to each of the challenges, namely:

- About the challenge: “Delivery in the desired period”, the bullwhip effect will be studied and response techniques to it;
- About the challenge: “Environmental and ethical expectations of the client”, will be studied as blockchain can help answer these questions;
- About the challenge: “Economic viability” transformation solutions will be analyzed that help process optimization and decision making, with emphasis in data science and ML techniques

2.1 The Bullwhip Effect in Product Delivery

In the 1940s, the biologist Ludwig von Bertalanffy presented to the community his General Systems Theory (GST), a work whose value goes far beyond of the natural sciences and is cited by Van Assche et al., as one of the most ambitious attempts in the twentieth century to develop scientific interdisciplinarity [10]. TGS is abstract enough to allow its evolution in different areas, thus creating the foundations for the in-depth study of systems.

Years later, in the 1950s and 1960s, Forrester developed the work of Bertalanffy and introduces the concept of systems dynamics, evolving the concepts of interactive systems and feedback loops, basic concepts of current engineering [11]. In his studies, Forrester points to the bullwhip effect as a consequence of the dynamics industry or the time-varying behavior of industrial organizations. In other words, the author indicates that organizational policies can give rise to characteristic and undesirable behaviors.

In 1997, Lee studies the information flows along a supply chain, and states that information transferred in the form of 'orders' tends to be distorted and may misguide the upstream members in their stock management decisions. According to the article, the variance of orders is greater than that of sales and the distortion tends to increase in countercurrent [12]. Lee identifies four main causes for bullwhip, namely:

(a) Demand forecast

Demand information distortions arise when the retailer executes orders based on its updated demand forecast and, as a result, the manufacturer loses sight of true market demand. This information distortion effect is amplified as the number of intermediaries in the channel increases.

(b) Orders in batches

Batch orders are a consequence of two factors. The first is the periodic review process, a technique of stock control in which the quantities of products, in inventory, are analyzed on a regular basis and based on that information, orders for replenishment of inventory will be made. The second factor is the cost of processing a purchase transaction. This element has into consideration aspects such as discounts made by the manufacturer for large quantities, the time spent on bureaucratic aspects is the same regardless of the amount, so it may be advantageous to place one large order instead of several small ones. The transport also has a lot of relevance in batch transactions. As it is not always possible to use 100% of the space destined for the transport of goods (this aspect is valid both in terms of shipping containers, logistics delivery trucks or door-to-door delivery vans), a batch order makes it more viable to maximize the space and these savings can be transferred to the buyer.

(c) Price fluctuation

Price is one of the most complex components of the study area, not only because there are several intrinsic factors that contribute to its fluctuation, but also because the price itself is of the most relevant variables for fluctuations in the supply chain. Among the various sources of price fluctuations are the price/demand ratio, elasticity, cost management, sales objectives and market positioning management.

(d) Rationing and scarcity games

Consider, in this case, a product whose demand potentially exceeds supply due to production capacity limitation or production uncertainty. In a shortage situation, the manufacturer would ration product supply to satisfy retailers' orders. For attempt to secure more units, each retailer will place an order that exceeds that the retailer would request if the supply of the product were unlimited.

In 2016, Wang et al. analyzed how the bullwhip effect evolved over the two decades and the current trends, based on 455 articles reviewed between empirical and experimental studies [13]. Wang et al. suggests that, despite the topic being quite popular in the scientific community, it remains there is marked uncertainty associated with it. For example, empirical studies seem to suggest that the effect is restricted to intermediate links of the supply chain, which contradicts the continued growth of the suggested variance by theoretical models. Supply chains with seasonal demand also tend to observe a smoothing effect of the bullwhip effect. The author also highlights the lack of studies at the business level, warning that they may reveal more information regarding the effects smoothing and enlarging. In addition to the work of Lee et al., Wang suggests five essential elements for a bullwhip study model. The current trend in the study of the bullwhip effect is based on 5 dimensions, namely: demand, forecasting policy, lead time, ordering policy and data sharing information.

2.2 Blockchain in Response to Expectations

Responding to a customer's environmental and ethical expectations implies winning the confidence in the organization, in its processes and in its products or services, however, the resources applied for this purpose do not bring added value to the organization. Blockchain technology is introduced here as an alternative to increase transparency and thus respond to customer expectations, while raising the efficiency level of a supply chain. Blockchain is still an emerging technology, although the concepts that underlie it, such as the use of cryptography for identity validation, go back to the 1990s, from the twentieth century. In this sense, it should be noted that it was only in 2009 that the first implementation of the concept, as it is known today, having been disclosed by an article by an anonymous author under the pseudonym of Satoshi Nakamoto [14, 15]. The case developed by Nakamoto consists of a cryptocurrency, called Bitcoin, which takes Blockchain leverage to store and share cryptocurrency transactions. A cryptocurrency is a virtual asset that can be traded through direct exchange, in a virtual way, similar to physical coins that can be passed from hand to hand. Although it is widely reported in association with Bitcoin, Nakamoto's great achievement consists of in the technology that supports said currency. A Blockchain network consists of a system that allows saving data and, at the same time, makes it possible to share information, securely and in real time, with the added benefit of being more resilient to attacks computers than traditional systems. Literally translated, Blockchain means chain of blocks and, in practice, a Blockchain consists exactly of a set of several blocks fundamental, linked together, umbilically, by the information contained in them [14].

There are 3 types of Blockchains: public, private and hybrid. In the first, all data are public and any user who wishes to participate and meets the technical requirements can make part of the system. Private Blockchain is developed within an organization, the concepts fundamentals remain the same, however, access is only allowed to internal entities. Per in the end, a hybrid Blockchain takes advantage of the two previous worlds, giving the option to keep part of validating and auditing the data to the public, thus maintaining the transparency of the system, leaving, however, some data and operations restricted to a closed organization [16]. For simplicity, throughout the paper, the following concepts will be addressed in the context of a public blockchain.

2.3 Machine Learning Application

To create an ML model, first of all, it is necessary to define the type of problem to be solved, where the algorithms to be used derive from, followed by the type of learning where the architecture to develop. The algorithms used are chosen according to the problem they aim to solve, and these are classified into the following fundamental groups [17]: classification, regression, and clustering. The next step in building the model is to define which type of learning to adopt, the main ones: supervised, unsupervised, and reinforcement learning [9].

Deep Learning (DP) consists of a class of algorithms that, due to their essential, potential and also due to its complexity, deserves special attention. The elementary component of the technique is the artificial neuron, this is based on the biological neuron, where the increased concentration of neurotransmitters in dendritic receptors induces electrical current in a biological neuron, activating it [18].

In the case of the artificial neuron, it receives an input value that is passed by an activation function, calculating the output value. When multiple neurons are added to process an input, it is called a layer, and adding multiple layers creates a neural network. Although an isolated neuron does not bring a relevant gain to the system, the combined power of a neural network creates the closest exists of an artificial brain and gives robots the ability to “learn” by the method of repetition that humans use. The addition of a feedback system to the model allows that it corrects the activation parameters in the neurons, which, with a certain number of iterations, will increase the efficiency of the model [18].

3 Proposed Conceptual Model

The proposed model aims to mitigate the influence of the main variables of the bullwhip effect, creating a network of cooperation, along the entire supply chain, based on the blockchain technology. Its development should be focused on optimizing communication between different actors of the supply chain, while facilitating the entry of new actors. Finally, it should promote transparency and address concerns associated with environmental sustainability. The idealized model is composed of three main entities: (1) the customer, (2) the supplier and (3) the blockchain, who makes the link between the two. The process is started by recognition of a need on the part of the customer, which will lead to the creation of a contract on the blockchain, where it will validate its legitimacy and select the best supplier to the customer who, finally, will send the order, ending the process with the receipt of the same.

To maintain confidence in the system, it is critical to ensure that the promised level of quality matches the one provided. This goal can be achieved through a ranking system of the success of the transaction, and for that, it is essential that the contracts are detailed and composed of measurable parameters. Some of the parameters to be included in the publication of a contract should be: customer details, customer's unique identifier, product details, product code, product description, and product specification (e.g., price range, shipping details, delivery point, valid time period for delivery, acceptable means of transport, minimum level of sustainability). These contracts would be one of the pillars for the success of the model. On the one hand, having a detailed product specification, allows validators to automatically assess the success of the business transaction. If the customer of the contract, upon receiving the goods, prove that the specifications received are in accordance with expectations, this information is automatically registered on the blockchain, and the supplier assessment is automatically enhanced. Otherwise, the supplier's assessment undergoes. Another interesting point to implement is the minimum level of sustainability. This parameter would imply, for e.g., CO_2 emissions during transport. In this way, the customer may favor local suppliers or suppliers that invest in alternative energies, in in order to offset their emissions. The implementation of a system that considers the sustainability of transport is not, certainly a trivial task and, in itself, implies exhaustive study and experimentation. In the medium term, blockchain itself would help in developing the same metric. Using transaction data, both distance and physical characteristics as well as the weight of the material transported and other variables such as frequency, duration of transport, among others, it would be possible to create a metric or algorithm that better reflects the environmental impact of transport.

A class diagram for data storage was proposed. The central point is the blockchain which contains all actors and transactions. The actor is able to play two functions, as a supplier or as a customer, differing the type of contract submitted. The contract of supplier presents the conditions it can offer, and the client presents its needs.

Competitive advantage should be one of the main components of the development strategy of new technologies. No matter how many features a product may have, if there is not something that highlighting the alternatives, will not be viable. In the case of the use case of sharing the information of the supply chain in Blockchain, four dimensions of advantage were identified, namely:

- Improved data management – by placing supply chain data in a decentralized network it allows for a high amount of data consumers in parallel, creating a source of raw material for optimization models.
- Efficiency – the use of smart contracts makes it possible to eliminate a vast set of intermediaries in the processes, resulting in savings in time and resources, which would otherwise end up being consumed, directly or indirectly, by the intermediaries.
- Transparency – unlike traditional systems were relying on intermediaries to validate the legitimacy of business processes, having public information is possible that any interested party can audit the data with minimal resources.
- Security – With current resources, the decentralization of information encrypted on blockchain is the safest method of having data accessible on the internet, but resilient against computer attacks.

4 Case Study

With the purpose of illustrating the features and how blockchain can help, a simulator was developed, which aims to replicate the behavior of actors in the supply chain. The simulator configuration considered the following cases:

- Case 1: Inventory management based only on received orders and security stock, without optimization or information sharing.
- Case 2: The order information is shared with the other actors in the system, and all react when the order is placed on the first actor.

In the development of the simulator, the following assumptions were considered:

- Different supply chain management strategies should be compared;
- The initial state must be identical between different case studies;
- Tests must be replicable;
- Changing the settings must be simple, quick and does not lead to mistakes that jeopardize the execution of the simulator;
- The simulator must be flexible regarding the structure of the supply chain;
- Costs of acquisition, possession, rupture and transport;
- Manufacturing, order preparation and delivery times will be grouped into a single value generated from generated based on the normal distribution, from the configuration of the actor;
- The configuration of the actors must consider that the objective of a chain of supply is to satisfy the needs of the end customer;

- Orders are placed with entire quantities;
- Deliveries are made once a day;
- Each actor will have only one product;
- All actors will have the same lead time statistics.

The platform chosen for development was a program designed from scratch in Python 3, a high-level programming language. The language was chosen not only because it is code open, but also for having a large development community with many frameworks and libraries specialized in data handling and data science. The simulator was developed in an object-oriented architecture, this choice of approach intended to take advantage of the abstraction it allows. By giving identity to an object, its properties are stored in it, as are the methods it uses to perform actions programmed, concept designated with encapsulation. The basis of the simulation is based on a set of classes. The code structure and features of each file exceed four thousand lines of code. In order to keep the project public, it can be consulted at: https://GitHub.com/TiagoSRodrigues/Bullwhip**.**

Case study 1 was used as a control and aimed to replicate the behavior of a simple supply chain, with no optimization and no aids beyond traditional stock management techniques and where information is not shared between actors. In this context, the adjustment of the ideal amount of raw material to order are calculated considering the average demand and the standard deviation of the daily demand, average lead time of delivery of raw material, and its standard deviation. The adjustment of this model to the objectives of the organization is given by the safety factor, value of standard deviations to consider, so that the stock does not run out. In this case study, the safety stock is evaluated every day, and if the quantity in inventory is below the order point, the actor places an order for raw material.

Case study 2 simulated information sharing via blockchain. For academic purposes, with a view to demonstrating the concept, however, does not require significant development resources, since only the analysis factor and the information flow are simulated. The general steps in this case are described below:

1. The customer places an order;
2. The first actor receives the order and places the raw material orders at once necessary to suppress this need, for all actors in the supply;
3. All actors ship their products at the same time.

The premise of this case is that even though there is a minimum stock for a same-day response to the order placed, there is no stock failure.

In order to bring the economic dynamics to the simulation, the exchange US dollar – euro between January 2000 and December 2021 rate value was used, data were obtained from the Bank of Portugal. The use of the exchange value solves two problems. On the one hand it is real economy data, on the other hand it eliminates the need to expose organizational data. This association between an exchange rate and the number of orders simulates a product with unit elasticity, where demand is linearly proportional to the price of the product (e.g., mobile phone and TV).

All actors start the simulation with stock to fulfill orders for the first 30 days without receiving stock, the objective is to avoid the peak of initial orders caused by the absence of stock and allow stock management to gradually correct variations. For each case study, four tests were performed, with the following configurations:

- Test A: Five actors with a factor of safety of 2.33 and an average delivery time of 5 days, with a standard deviation of 1 day.
- Test B: Five actors with a factor of safety of 1.29 and an average delivery time of 5 days, with a standard deviation of 1 day. The purpose of this test is to assess the influence of the factor of security.
- Test C: Nine actors with a safety factor of 1.29 and an average delivery time of 5 days, with a standard deviation of 1 day. The purpose of this test is to assess the impact of supply chain length.
- Test D: Nine actors with a safety factor of 1.29 and a delivery time of 1 day. The purpose of this test is to assess the impact of delivery time. These tests will both be applied to cases 1 and 2, previously mentioned.

Table 1 shows the results of the tests performed. The tests (A, B, C, D) are grouped by the type of case under study (1 – traditional model, 2 – information sharing). In the results presented, the lead time represents the time between the order and the reception material, the order quantity consists of the order size, and the number of deliveries consists of the number of transactions carried out successfully and finally the number of products delivered consists of the final inventory of the zero actor, which represents the final customer.

To facilitate the analysis of the results, Table 2 presents the coefficients of lead time variation. The coefficient of variation represents the dispersion of the population. The higher the coefficient the greater the dispersion. In a supply chain, the coefficients of variation should be lower, which indicates that for a low standard deviation, the process is stable and predictable.

A common factor in all tests of case 1 is its high variation, arising from the bullwhip effect propagated through the supply chain. In case 2 the variation is significantly more reduced, showing evidence of successful information sharing. In Table 3 is possible to observe the comparison between the test cases, more

Table 1 Outputs of the tests

Test	Lead time		Order quantity		Number of deliveries	Products supplied
	Mean	St. Dev.	Mean	St. Dev.		
A-1	23.12	10.41	12,052	1602	248	2,992,149
A-2	7.45	1.10	16,870	3306	28,662	69,093,658
B-1	22.77	10.28	12,052	1602	252	3,038,141
B-2	7.48	1.11	16,869	3306	28,663	69,104,975
C-1	23.07	10.68	12,052	1602	249	2998,634
C-2	7.65	0.87	17,405	2999	51,590	69,093,658
D-1	22.79	10.31	12,052	1602	252	3,035,475
D-2	1.94	0.23	17,404	2998	51,642	69,138,921

Table 2 Test variation coefficients

Test	Lead time (%)
A-1	45
A-2	15
B-1	45
B-2	15
C-1	46
C-2	11
D-1	45
D-2	12

Table 3 Comparison of variation between models

Test	Lead time (%)	Delivered products (%)
A	27	2209
B	36	2175
C	32	2204
D	64	2178

specifically the gain on each test of case 2 relative to case 1. The results suggest that information sharing by supply chain actors is very favorable for the reduction of the lead time as this improvement is verified in all the tests. It particularly stands out in test D, where the lengthening of the supply chain, case in which the sharing of information is especially revealed. Considering the previous results, it appears that the hypothesis of sharing of information favoring the efficiency of the supply chain is verified, under the conditions studied.

5 Conclusions

This work aimed to analyze the bullwhip effect in the context of industry 4.0, and identify how new technologies can, and are, giving companies new tools so that the goals are able to respond to market variations in a timely manner, without additional costs, whether due to excess inventory or lack of it.

In order to better understand how ML techniques can help the management to develop more efficient and resilient progress, the entire path to be taken in consideration was analyzed, to add data techniques in an organization.

The current market is one of the most fast and competitive in history, which is reflected in the pressure placed on managers to put into production new projects that generate long-term value, normally associated with data processing automation, however, unlike other raw materials, an information related accident is usually not reversible, such as a leak of sensitive data.

In the blockchain component, attention was also paid to the importance of understanding its components in order to better visualize the technology's potential for the industry future.

The adoption of a conceptual model had the vision of making use of industrial management tools not only for the idealization of the model, but also for its strategic analysis and viability. This strategic analysis identified a strong expansion potential of the technology, not only to respond to the bullwhip effect, but also the potential to respond to transparency in supply needs was also identified.

The construction of the supply chain simulator was successfully completed, and the cases were carried out as planned and the results obtained reveal a potential significant improvement in supply chain efficiency.

It was concluded that sharing information along a supply chain has potential to increase supply chain efficiency while provides new data on the same that can serve as raw material not only for future optimizations of the order forecasting models, but also, for the development of markets that are able to gain knowledge of the new data generated.

The development of the present work had some limitations from the initial phase to its implementation. Therefore, the following limitations are mentioned:

- Due to the scope and complexity of the topics covered, it was not possible to detail strategic analysis techniques, mainly Unified Theory of Acceptance and Use of Technology (UTAUT), which would be an interesting tool, probing the market in order to assess in a quantitatively its opening to the blockchain.
- The optimization of the parameterization of the inventory management of the actors proved to be especially difficult, even though steady-state results have emerged interesting, the application of real data generates great instability that ends up in disturbing the system. As a future improvement, it would be necessary to optimize the methods of inventory management in order to bring them closer to realities.
- A topic that could be better explored is the integration of ML techniques in the supply chain simulator. In the present work it was not possible to develop the theme further by the additional layer of complexity and the additional computational resources brought by said integration, however, its value is recognized, and the architecture of the simulator was designed to allow the integration with future systems.

References

1. Soltas, E., Helper, S.: Why the Pandemic Has Disrupted Supply Chains. The White House, https://www.whitehouse.gov/cea/written-materials/2021/06/17/why-the-pandemic-hasdisrupted-supply-chains, last accessed 2021/12/15.
2. Lee, H. L., So, K. C., Tang, C. S.: The Value of Information Sharing in a Two-Level Supply Chain. Management Science 46(5), 626–643 (2000).
3. International Maritime Organization Homepage, https://www.imo.org/en/MediaCentre/PressBriefings/Pages/02-IMO-2020.aspx, last accessed 2021/12/15.
4. Sarkar, B., Guchhait, R., Sarkar, M., Pareek, S., Kim, N: Impact of safety factors and setup time reduction in a two-echelon supply chain management. Robotics and Computer-Integrated Manufacturing 55, 250–258 (2019).

5. Muller, M. Essentials of Inventory Management. AMACOM, New York (2011).
6. Gasowska, M. K.: Logistics challenges in enterprise management in contemporary conditions. Scientific Papers of Silesian University of Technology. Organization and Management Series (149), 189–204 (2020).
7. Chatfield, D. C., Kim, J. G., Harrison, T. P., Hayya, J. C.: The Bullwhip Effect-Impact of Stochastic Lead Time, Information Quality, and Information Sharing: A Simulation Study. Production and Operations Management 13(4), 340–353 (2009).
8. Adenso-Díaz, B., Moreno, P., Gutiérrez, E., Lozano, S.: An analysis of the main factors affecting bullwhip in reverse supply chains. International Journal of Production Economics 135(2), 917–928 (2012).
9. Boehm, M., Kumar, A., Yang, J.: Data Management in Machine Learning Systems. Synthesis Lectures on Data Management 14(1), 1–173 (2019).
10. Van Assche, K., Valentinov, V., Versc, G.: Ludwig von Bertalanffy and his enduring relevance: Celebrating 50 years General System Theory. Systems Research and Behavioral Science 36(3), 251–254 (2019).
11. Forrester, J.: Industrial Dynamics-After the First Decade. Management Science 14(7), 398–415 (1968).
12. Lee, H. L., Whang, S., Padmanabhan, V.: The Bullwhip Effect in Supply Chains. Sloan Management Review Spring, 93–102 (1997).
13. Wang, X., Disney, M. S.: The bullwhip effect: Progress, trends and directions. European Journal of Operational Research 250(3), 691–701 (2016).
14. Haber, S., Stornetta, W. S.: How to time-stamp a digital document. Journal of Cryptology 3(2), 99–111 (1991).
15. Nakamoto, S.: Bitcoin: A Peer-to-Peer Electronic Cash System. http://www.bitcoin.org/bitcoin.pdf (2009).
16. Drakopoulos, G., Kafeza, E., al Katheeri, H.: Proof Systems In Blockchains: A Survey. 4th South-East Europe Design Automation, Computer Engineering, Computer Networks and Social Media Conference (SEEDA-CECNSM), pp. 1–6 (2019).
17. Gambella, C., Ghaddar, B., Naoum-Sawaya, J.: Optimization problems for machine learning: A survey. European Journal of Operational Research 290(3), 807–828 (2021).
18. Mehrer, J., Spoerer, C. J., Kriegeskorte, N., Kietzmann, T. C.: Individual differences among deep neural network models. Nature Communications 11, 5725 (2020).

A Proposal of Web Application for the Study and Resolution of the Job Shop Problem with Makespan Minimization Via Mixed Integer Linear Programming

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Abstract This study proposes software that allows the user to solve the Job Shop Scheduling Problem (JSSP) with makespan minimization to support the teaching and learning of the JSSP, one of the main scheduling problems in the Operations Research literature. The application allows the user to enter instance data, solve it using four different mixed integer linear programming (MILP) models and evaluate the results in graphical form through an interactive Gantt chart and tabular form. The computational tool was developed in Python, using Streamlit, Pyomo, and GLPK as main libraries, and it can be accessed free via the internet. In addition, its source code is available for anyone to reproduce, redistribute and modify under the terms of the GPL v3.0. This work demonstrates the resolution of a 5 × 3 size problem through the four models available in the application, which observed four different optimal solutions. However, the performance of the disjunctive models is superior to the others in the execution time. Furthermore, it was found that the time-indexed model may not be useful in larger problems.

Keywords Scheduling · Job shop · Integer programming · Python · Streamlit

1 Introduction

Arenales et al. [2] define Operations Research (OR) as applying scientific methods to complex problems with a focus on supporting decision-making. OR, although essentially an interdisciplinary area of study, is firmly used for problems involving

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production system management. Scheduling, in OR literature, is a class of problems involving allocating limited resources over time to perform a set of activities, which can be divided into single-machine problems and multiple-machine problems.

Among the multiple machine problems is the job shop scheduling problem (JSSP). The classic JSSP considers a production environment with m machines and n jobs, where each job is processed once on each machine in a non-simultaneous way. Each job has its known processing time for each machine and a pre-established route. Each machine can process a single job at a time, and the processing of a job cannot stop once a job is started. One of the possible goals of JSSP is to minimize the makespan, which is the end time of processing the last job on the last machine.

In a recent survey, Xiong et al. [13] mention that the JSSP is among the best-known combinatorial optimization problems in the OR literature and has been studied extensively in several academic areas. Modeling and solving combinatorial optimization problems like JSSP requires computational support. However, programming these methods can be quite challenging, given the interdisciplinarity of OR, and this challenge can make learning difficult or even demotivate the student.

Given the above, the purpose of this article is to present software for solving the JSSP with makespan minimization through four different mixed integer linear programming (MILP) models. These MILP models were chosen based on the work of Ku and Beck [7] and Aguiar Júnior [1]. The proposed software allows the user to enter data, solve different JSSP instances through the four models mentioned above, view the results in tabular form and through an interactive Gantt chart, and download these results. The purpose of this computational tool is to support the teaching and learning of JSSP.

The paper is organized as follows. First, Sect. 2 discusses the theoretical foundation of the JSSP modeling by MILP. Then, Sect. 3 presents the proposed software. Then, in Sect. 4, a numerical application is carried out through the proposed software, and finally, Sect. 5 presents the final considerations.

2 Theoretical Foundation

According to Xiong et al. [13], the first work on the JSSP was published in the 1950s. After a search for articles containing the keyword “job shop” and its variations in the Scopus database, we observed a strong growth in the number of works published since the 2000s (see Fig. 1), which indicates that the subject has increasingly attracted more researchers.

The approaches used in solving scheduling problems and many other combinatorial optimization problems can be divided into exact and approximate methods. Aguiar Júnior [1] defines exact methods as methods that guarantee the optimal solution, provided there is enough time and computational capacity. On the other hand, approximate methods generally find satisfactory feasible solutions in considerably less time than exact methods, even though they do not guarantee optimality.

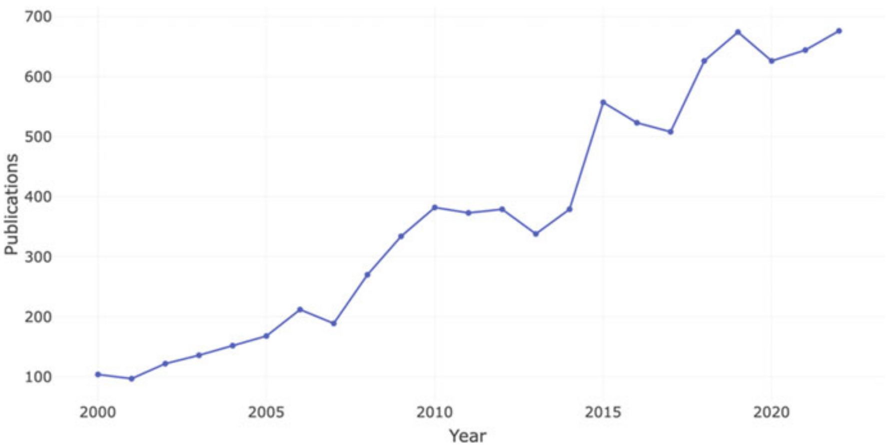


Fig. 1 Publications about JSSP in the Scopus Database

Ku and Beck [7] mention that 14 of the 40 papers on scheduling published in 2014 in the Journal of Scheduling used MILP as the primary resolution method. After a search in the Scopus database, we observed that 10 of the 32 works on JSSP published in the same journal since 2020 used the same approach, which reaffirms the relevance of this technique as a form of modeling and solution. Ku and Beck [7] highlight three main MILP formulations to solve the JSSP: disjunctive, time-indexed, and rank-based.

2.1 *The Formal Definition of JSSP*

Ku and Beck [7] define the JSSP with makespan minimization (JSSPMM) as a set of jobs $J = \{1, 2, \ldots, n\}$ and a set of machines $M = \{ 1, 2, \ldots, m\}$, where for each job $j \in J$ there is a vector $(\sigma_{j1}, \sigma_{j2}, \ldots, \sigma_{jm})$ representing the processing route of j by the m machines. Furthermore, for each job j and each machine i, there is a p_{ji} representing the processing time from j to i. Each machine can process only one job at a time, and preemption is not allowed once a job starts processing. The objective is to find the sequence of all jobs across all machines that minimizes the processing time of the last job on the last machine (makespan). The authors point out that JSSPMM is NP-hard for $n \geq 3$ and $m \geq 2$.

2.2 Manne's Disjunctive Model

Given the following sets and parameters,

$$J : \text{set of jobs}, \quad J = \{1, 2, \ldots, n\},$$

$$M : \text{set of machines}, M = \{1, 2, \ldots, m\},$$

$$p_{ji} : \text{processing time of job } j \in J \text{ on machine } i \in M,$$

$$\sigma_{ji} : \text{processing route of job } j \in J \text{ on machine } i \in M,$$

$$V : \text{big} - \text{M}.$$

and the following decision variables,

$$C_{\max} : \text{makespan}$$

$$x_{ji} : \text{start time of job } j \in J \text{ on machine } i \in M,$$

$$z_{ijk} : \begin{cases} 1, & \text{if the job } j \in J \text{ precedes the job } k \in J \text{ on machine } i \in M \\ 0, & \text{otherwise.} \end{cases}$$

the formulation based on the work of Manne [9] is defined as

$$\min \ C_{\max} \tag{1}$$

$$x_{j,\sigma_{ji}} \geq x_{j,\sigma_{ji-1}} + p_{j,\sigma_{ji-1}}, \forall i \in M; j \in J; i \geq 2, \tag{2}$$

$$x_{ji} \geq x_{ki} + p_{ki} - V \cdot z_{ijk}, \forall i \in M\, j; k \in J; \ \ j < k, \tag{3}$$

$$x_{ki} \geq x_{ji} + p_{ji} - V\left(1 - z_{ijk}\right), \forall i \in M; j; k \in J; j < k, \tag{4}$$

$$C_{\max} \geq x_{j,\sigma_{jm}} + p_{j,\sigma_{jm}}, \forall j \in J, \tag{5}$$

$$x_{ji} \geq 0, \forall i \in M; j \in J, \tag{6}$$

$$z_{jik} \in \{0, 1\}, \forall i \in M; j \in J. \tag{7}$$

The objective function is indicated in (1). Constraint set (2) ensures that the precedence of each job is respected. The disjunctive constraint sets (3) and (4) ensure that two jobs are not processed on the same machine at the same time. Constraint set (5) ensures that the makespan is at least the longest completion time among all jobs. The sets of constraints (6) and (7) ensure the variables domain.

2.3 Liao and You Disjunctive Model

The difference between Liao and You [8] model and Manne's is the inclusion of the surplus variable q_{ijk} and the replacement of constraint sets (3) and (4) by (8) and (9). This adaptation improves Manne's model performance by reducing the number of constraints.

$$V \cdot z_{ijk} + \left(x_{ji} - x_{ki}\right) - p_{ki} = q_{ijk}, \forall i \in M; j, k \in J; j < k, \tag{8}$$

$$q_{ijk} \leq V - p_{ji} - p_{ki}, \forall i \in M; j, k \in J; j < k. \tag{9}$$

2.4 Time-Indexed Model

In this formulation based on Kondili et al. [6] work, in addition to the sets and parameters used so far, we added the set $H = \{0, 1, 2, \ldots, S\}$, which represents the discretized time, where S is the total sum of the processing times. Because it is a didactic approach, we discretized the time in intervals with a size equal to a unit of time in this work. In addition, we use the following decision variable:

$$y_{ijt} : \begin{cases} 1, & \text{if the job } j \in J \text{ starts processing at time } t \in H \text{ on machine } i \in M \\ 0, & \text{otherwise.} \end{cases}$$

Thus, we have the following formulation:

$$\min \ C_{\max} \tag{10}$$

$$\sum_{t \in H} y_{ijt} = 1, \forall i \in M; j \in J, \tag{11}$$

$$\sum_{t \in H} \left(t + p_{ji}\right) y_{ijt} \leq C_{\max}, \forall i \in M; j \in J, \tag{12}$$

$$\sum_{j \in J} \sum_{t' \in T_{ijt}} y_{jit'} \leq 1, \forall i \in M; j \in J; t \in H; T_{ijt} = \left\{t - p_{ji} + 1, \ldots, t\right\}, \tag{13}$$

$$\sum_{t \in H} \left(t + p_{j,\sigma_{ji-1}}\right) y_{\sigma_{ji-1},jt} \leq \sum_{t \in H} t \cdot y_{\sigma_{ji},jt}, \forall i \in M; j \in J; i \geq 2, \tag{14}$$

$$y_{jit} \in \{0, 1\}, \forall i \in M; j \in J. \tag{15}$$

Constraint set (11) ensures that each job starts only once on each machine. The constraint set (12) ensures that the makespan is at least the longest completion time among all jobs. Constraint set (13) ensures that no more than one job runs simultaneously on the same machine. The set of constraints (14) guarantees that the precedence of each work is respected, and (15) ensures the domain of the variable.

2.5 Rank-Based Model

In this formulation based on Wagner's work [12], we consider the following dichotomous parameter:

$$r_{jil} : \begin{cases} 1, & \text{if the operation } l \in M \text{ of job } j \in J \text{ requires machine } i \in M \\ 0, & \text{otherwise.} \end{cases}$$

In addition, we added the following decision variables:

$$h_{ik} : \text{start time of job } \ k \in J \text{ on machine } i \in M,$$

$$w_{jki} : \begin{cases} 1, & \text{if the job } j \in J \text{ is sequenced in order } k \in J \text{ on machine } i \in M \\ 0, & \text{otherwise.} \end{cases}$$

$$h_{ik} : \text{start time of job } \ k \in J \textit{ on machine } i \in M,$$

$$w_{jki} : \begin{cases} 1, & \text{if the job } j \in J \text{ is sequenced in order } k \in J \text{ on machine } i \in M \\ 0, & \text{otherwise.} \end{cases}$$

We define the rank-based model formulation as:

$$\min \ C_{\max} \tag{16}$$

$$\sum_{j \in J} w_{jki} = 1, \forall i \in M; k \in J, \tag{17}$$

$$\sum_{k \in J} w_{jki} = 1, \forall i \in M; j \in J, \tag{18}$$

$$h_{ik} + \sum_{j \in J} p_{ji} w_{jki} \leq h_{ik+1}, \forall i \in M; k \in J; k < n, \tag{19}$$

$$\sum_{i \in M} r_{jil} h_{ik} + \sum_{i \in M} r_{jil} p_{ji} \leq A + \sum_{i \in M} r_{jil+1} h_{ik'}, \forall j, k, k' \in J; l \in M, \tag{20}$$

$$h_{in} + \sum_{j \in J} p_{ji} w_{jni} \leq C_{\max}, \forall i \in M, \tag{21}$$

$$h_{ik} \geq 0, \forall i \in M; k \in J, \tag{22}$$

$$w_{jki} \in \{0, 1\}, \forall i \in M; j, k \in J, \tag{23}$$

where

$$A = V\left(1 - \sum_{i\in M} r_{jil} w_{jki}\right) + V\left(1 - \sum_{i\in M} r_{jil+1} w_{jk'i}\right).$$

The constraint set (17) ensures that each position on each machine is assigned to a single job. The constraint set (18) ensures that each job gets a position on each machine. Constraint set (19) ensures that the start time of a job on a machine is greater than the job completion time assigned to the previous position. The constraint set (20) ensures that the precedence of each job is respected. Constraint set (21) ensures that the makespan is, at least, the longest completion time among all jobs. The sets of constraints (22) and (23) ensure the domain of the variables.

3 Software Proposal

The proposed software, Job Shop Web, was developed in Python [10], using Streamlit [11], Pyomo [3], and GLPK [5] as main libraries (see Fig. 2).

Streamlit is an open-source framework for building web applications in Python. Through Streamlit, it is possible to quickly develop the front end of an application without directly using HTML, CSS, or JavaScript. However, it is possible to enhance a Streamlit application with these resources. We developed the entire Job Shop Web user interface with Streamlit.

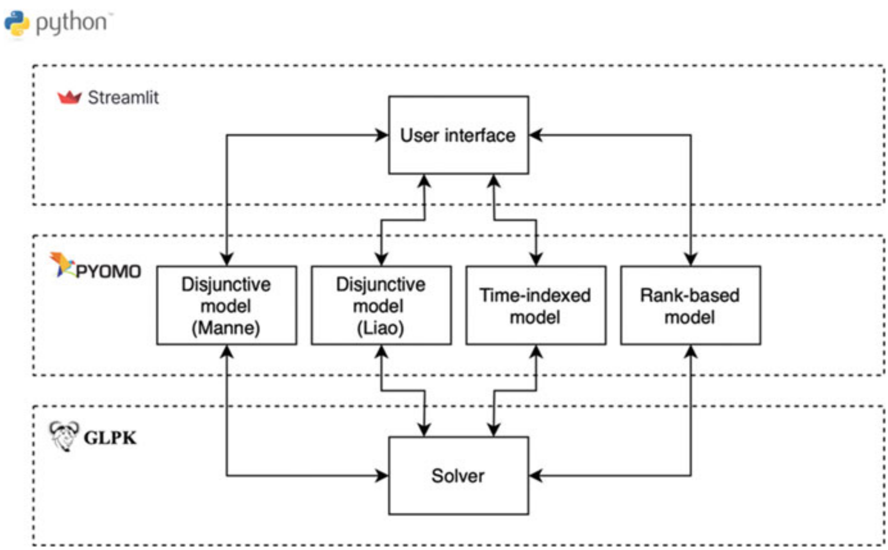


Fig. 2 Simplified architecture of the Job Shop Web

Pyomo is an open-source Python-based language for modeling optimization problems. We modeled computationally the four MILP models mentioned in Sect. 2 with Pyomo. However, it is possible to solve them only through mathematical optimization software (solver). The project's purpose was to make Job Shop Web available free of charge via the internet, so we chose the popular free solver GLPK. However, Pyomo is compatible with many other solvers, including market leaders like Gurobi and CPLEX.

We use Streamlit Cloud, a free service of Streamlit to publish the Job Shop Web and make it available via the internet at https://jobshopweb.streamlit.app/. We also used the Poetry library [4] to manage the dependencies to guarantee the project's reproducibility. Thus, once accessing the source code available at https://github.com/juniorssz/jobshop-web, anyone can reproduce it. It is even allowed to redistribute and modify the source code under the terms of the GNU General Public License version 3.0 (GPL v3.0).

3.1 Job Shop Web User Manual

When accessing the web address mentioned in Sect. 3, the user will initially see the general information page about the program (see Fig. 3). Then, through the links available on this page, the user can view the mathematical formulations of each model, the primary references used, and the source code of Job Shop Web.

In the menu on the left side, the user can choose between the four MILP model options mentioned in Sect. 2 of this work. When accessing the page of any of the models (see Fig. 4), the user must inform the dimensions of the problem. In addition, for the final report, the user must notify the start date and time and the input data's time unit.

Once the initial information has been entered, the next step is to enter data on processing and routes times (see Fig. 5). The user can also upload the data through files in CSV format. To enable this possibility, the user must select the "Import

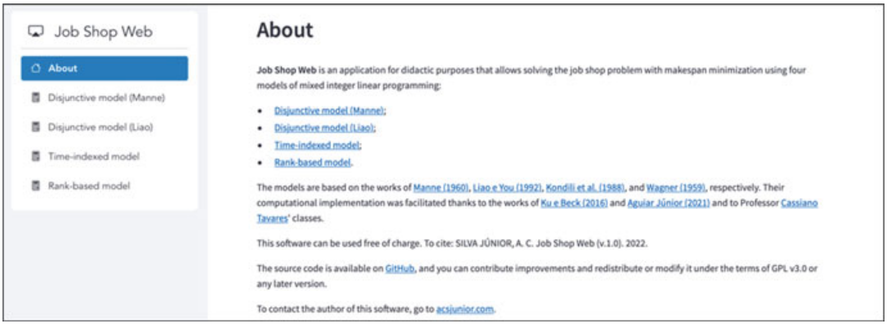


Fig. 3 Job Shop Web general information page

Fig. 4 Initial definitions page of Manne's disjunctive model

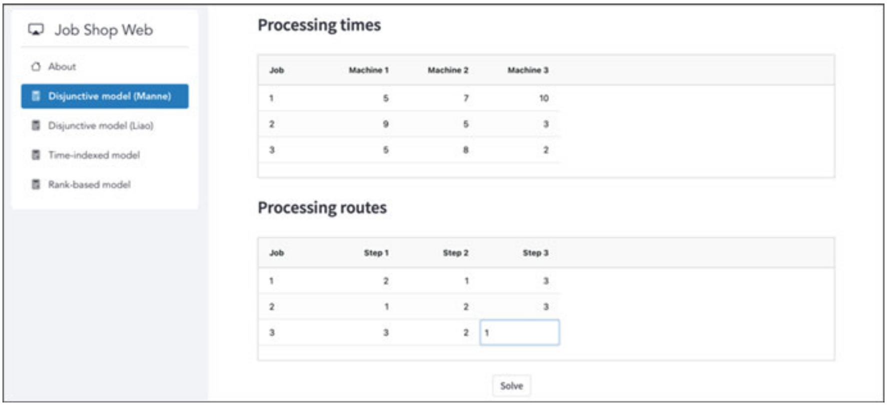


Fig. 5 Interface for inserting input data

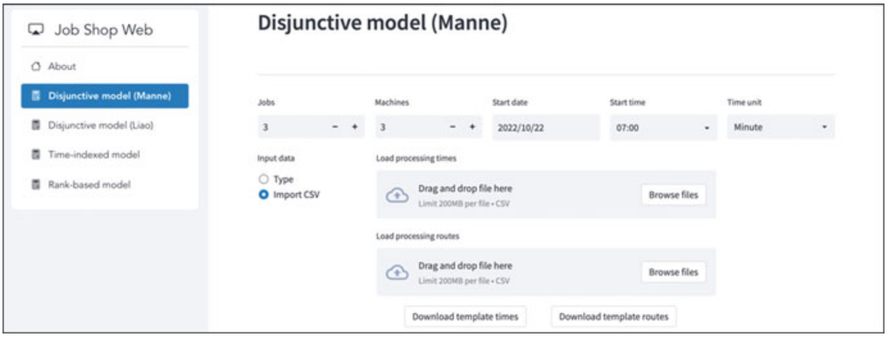


Fig. 6 Upload input data via CSV files

CSV" option (see Fig. 6). The file must respect a certain standard. Therefore, we recommend that the user use the templates that can be downloaded using the "Download template times" and "Download template routes" buttons.

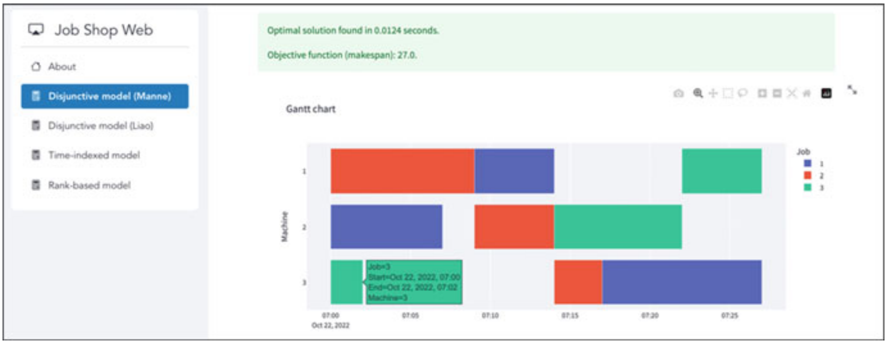
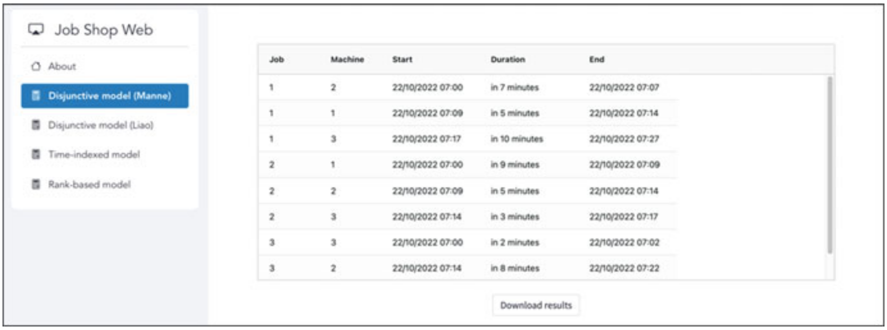


Fig. 7 Solution in graphical form



Job	Machine	Start	Duration	End
1	2	22/10/2022 07:00	in 7 minutes	22/10/2022 07:07
1	1	22/10/2022 07:09	in 5 minutes	22/10/2022 07:14
1	3	22/10/2022 07:17	in 10 minutes	22/10/2022 07:27
2	1	22/10/2022 07:00	in 9 minutes	22/10/2022 07:09
2	2	22/10/2022 07:09	in 5 minutes	22/10/2022 07:14
2	3	22/10/2022 07:14	in 3 minutes	22/10/2022 07:17
3	3	22/10/2022 07:00	in 2 minutes	22/10/2022 07:02
3	2	22/10/2022 07:14	in 8 minutes	22/10/2022 07:22

Fig. 8 Solution in tabular form

Once the input data has been imported or typed, the user must press the "Solve" button for the program to start solving the problem and, in the sequence, provide the results obtained. If the model finds an optimal solution, Job Shop Web will display a message with the time it took to find the solution, the value of the objective function, and an interactive Gantt chart (see Fig. 7). The system will also display the solution in tabular form (see Fig. 8), followed by a button to download the results. If the model does not solve the problem, the system will display an alert for the user.

4 Numerical Application

This section aims to demonstrate the solution of the problem 5 × 3 proposed by Arenales et al. [2], using the four MILP models available on Job Shop Web, and to compare the results. Table 1 displays the processing times for each job on each machine. For example, job 1 will be processed in 5 time units (TU) on machine

Table 1 Processing times

Job	Machine 1	Machine 2	Machine 3
1	5	7	10
2	9	5	3
3	5	8	2
4	2	7	4
5	8	8	8

Table 2 Processing routes

Job	Step 1	Step 2	Step 3
1	2	1	3
2	1	2	3
3	3	2	1
4	2	1	3
5	3	1	2

Fig. 9 Initial definitions of the solution

1, 7 TU on machine 2, and 10 TU on machine 3, totaling 22 TU. Table 2 displays the processing routes of each job through the machines. For example, job 1 will be processed first on machine 2, then on machine 1, and finally on machine 3.

To solve the problem, we used the parameters shown in Fig. 9.

Evaluating Fig. 10, we observe that the four approaches found different optimal solutions. Regarding the time needed to find the solution, we observed that the two disjunctive models performed better than the others and that the time-indexed model had the worst performance.

5 Conclusion

This work aimed to present the Job Shop Web, a software for didactic purposes with free access via the internet, for solving the JSSPMM through four different MILP models. The application was developed in Python, using Streamlit, Pyomo, and GLPK as the main libraries.

Job Shop Web allows the user to enter instance data by typing directly into the graphical interface or importing a file in CSV format. Furthermore, once the optimal solution is found, it displays the output data through an interactive Gantt chart and tabular form, allowing the user to analyze the results and compare the solutions obtained through the four MILP models.

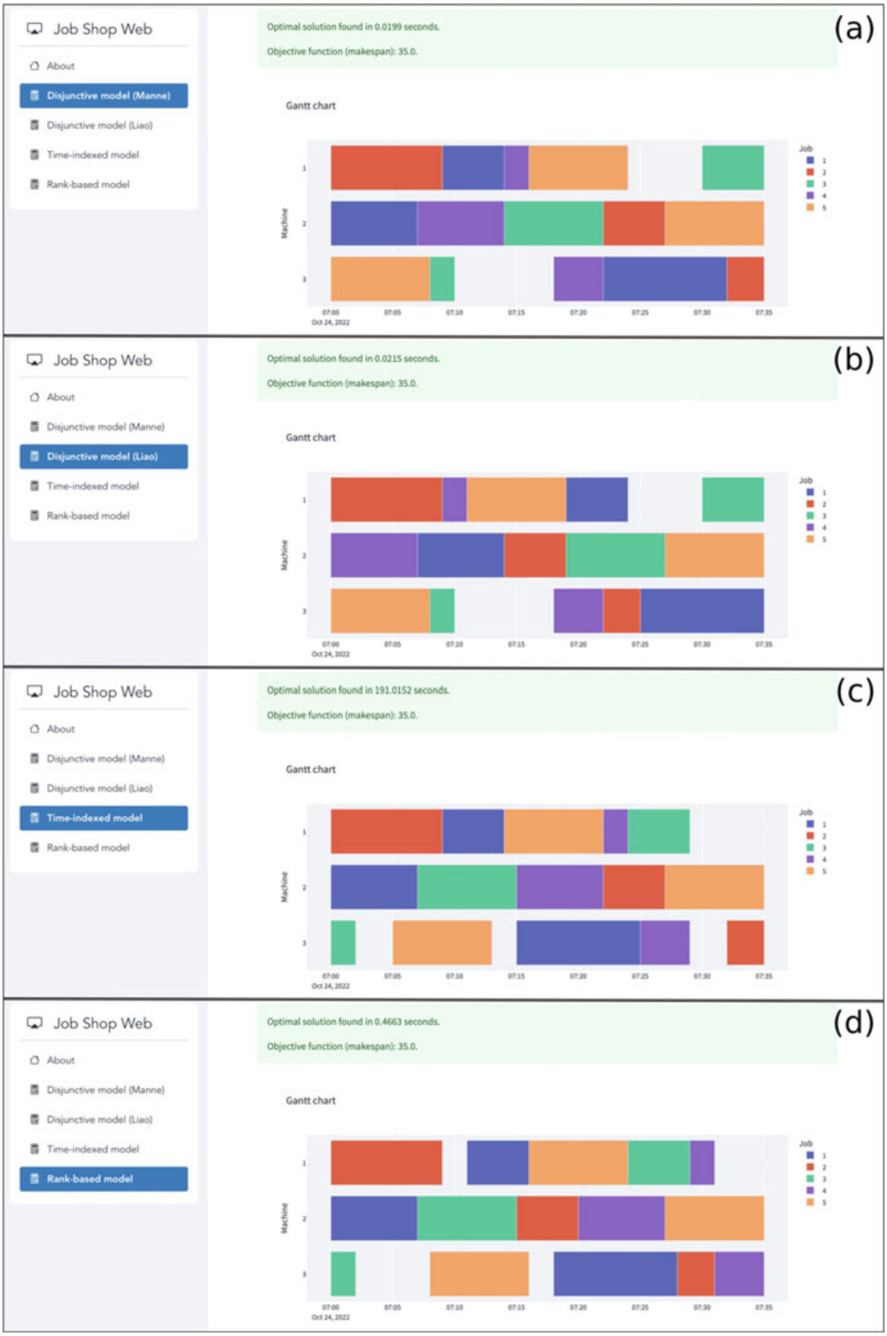


Fig. 10 Graphic solutions of the proposed problem

After solving the proposed 5 × 3 problem, we observed four different optimal solutions and found that the disjunctive models performed better than the others in terms of execution time. In addition, we found that the time-indexed model may be infeasible in slightly larger problems.

Finally, we conclude that Job Shop Web can be a helpful tool to support teaching and learning in the context of scheduling problems. As a future perspective, we intend to replace GLPK with another free solver, but with parallel execution capacity, to try to improve the efficiency of the models, especially the time-indexed model.

References

1. Aguiar Júnior, J. C.: Modelo de arranjo linear e desigualdades válidas para o problema do job shop com minimização do makespan. Dissertação (mestrado) – Programa de Pós Graduação em Modelagem de Métodos Quantitativos. Universidade Federal do Ceará, Fortaleza (2021).
2. Arenales, M. et al: Pesquisa Operacional. Elsevier, Rio de Janeiro (2007).
3. Bynum, M. L. et al: Pyomo – Optimization modeling in Python. Springer International Publishing, Cham (2021).
4. Eustace, S.: Poetry, https://pypi.org/project/poetry, last accessed 2022/10/11.
5. Finley, T.: GLPK, https://pypi.org/project/glpk, last accessed 2022/10/11.
6. Kondili, E., Pantelides, C. C., Sargent R. W. H.: A general algorithm for scheduling batch operations. In: PSE'88: Third International Symposium on Process System Engineering: In Affiliation with CHEMECA 88, a Bicentennial Event. Institution of Engineers, Sidney (1988).
7. Ku, W. Y., Beck, J. C.: Mixed integer programming models for job shop scheduling: A computational analysis. Computers & Operations Research, Elsevier BV, v.73, 165–173 (2016).
8. Liao, C. J., You, C. T.: An improved formulation for the job-shop scheduling problem. Journal of the Operational Research Society, Informa UK Limited, v.43, n.11, 1047–1054 (1992).
9. Manne, A. S.: On the job-shop scheduling problem. Operations Research, Institute for Operations Research and the Management Sciences (INFORMS), v.8, n.2, 219–223 (1960).
10. Python: A dynamic open-source programming language, https://www.python.org/, last accessed 2022/10/11.
11. Streamlit, https://streamlit.io/, last accessed 2022/10/11.
12. Wagner, H. M.: An integer linear programming model for machine scheduling. Naval Research Logistics Quarterly, Wiley, v.6, n.2, 131–140 (1959).
13. Xiong, H. et al: A survey of job shop scheduling problem: The types and models. Computers & Operations Research, Elsevier BV, v.142, 105731 (2022).

An Approach to the Design of Resilient Biomass Supply Chain Using Discrete Event Simulation

Helena Paulo, Miguel Vieira, Bruno S. Gonçalves, Tânia Pinto-Varela, and Ana P. Barbosa-Póvoa

Abstract The biomass supply chains are subject to several potential uncertain factors and disruption risks. The assessment of these conditions is of critical importance to be considered while designing biomass-based supply chains to achieve resilient supply chains. This work explores the decisional impact of biomass availability due to seasonality as an uncertain factor and the disruption risk of biomass supply caused by extreme climate conditions. The proposed methodological approach combines optimization with discrete-event simulation to evaluate the long-term economic viability of a supply chain design solution, analyzing the strategic variables defined by the optimization model in the simulation model subject to a plausible disruption scenario. The performance and capability of the supply chain to be prepared, respond, and recover from unexpected events is analyzed. The results show the advantage of the simulation-optimization approach to simulate scenarios allowing the improvement of supply chain design decisions accounting for not only the impact of uncertainty but also disruption events occurrence.

Keywords Biomass supply chains · Resilience · Discrete event simulation

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1 Introduction

1.1 Research Context

The worldwide dependence on fossil resources represents a fundamental challenge to society. Beyond its recognized negative climate effect, recent events imposing the price instability of fossil resources may stimulate decision-makers to accelerate the transition to the use of cleaner sources for energy and materials production. As noted by Dermibas et al. [1], biomass resources have already proved to be a sustainable alternative. Nonetheless, the viability and feasibility of such a transition are strongly dependent on the biomass supply chains efficiency and effectiveness. The development of these supply chains to produce bioenergy and biomaterials are seen to represent an important role in reducing environmental impact of energy usage and increasing energy supply security [2].

Biomass based supply chains are, to some extent, a promising market business and field of research, but strongly subject to the influence of uncertainty and disruptions [3]. At a strategic level, the supply chain requires the appropriate design variables to be defined, such as the number, location, technologies, capacities of the production facilities, biomass sources allocation, or customers to satisfy, among others. The overall objective is to attain a reliable network able to satisfy customers and be economically profitable, pursuing a long-term perspective [4]. However, supply chains are exposed to diverse risks as the ones caused by uncertain factors of low impact with a high probability of occurrence, but also the ones associated with disruptive events of low probability of occurrence but with a high impact on supply chain performance [5]. In such a changing environment where supply chains operate, ignoring the occurrence and the consequences of such events compromises attaining the supply chain goals. For this reason, the development and implementation of tools to improve decision-making on investment viability are required in the assessment of resilient biomass supply chains [6].

As reported by Pires Ribeiro and Barbosa-Póvoa [7], a resilient supply chain should be able to prepare, respond and recover from disturbances, and afterward maintain a positive steady state operation in an acceptable cost and time. Therefore, within the design of biomass supply chains able to face the multiple challenges, it becomes of strategic relevance to establish decisions that cope with (1) uncertain factors such as biomass availability and properties, processing technologies, transportation problems, or demand; and (2) disruption risks like natural disasters, financial crisis, or other dynamic human causes.

1.2 Literature Review

The impact of uncertainty and the risk of disruptions in the performance of supply chains has been raising the attention of researchers committed to identify the suitable approaches to improve overall efficiency at the design project phase. The supply chain risk of disruption can happen due to various causes that need to be properly identified according to the scope. The main phases of an approach comprises the (i) risks identification, (ii) potential impacts assessment, (iii) critical evaluation, (iv) risk response strategies definition and implementation, and (v) monitoring/control, which allows taking the most appropriate actions to foresee supply chain resilience [6]. Regarding the supply chain resilience topic, researchers have provided a wide set of studies concerning disruptive risk factors. The risk can result from natural disasters (e.g., floods or drought, earthquakes, and hurricanes) or man-made threats (e.g., terrorist attacks and employee strikes). Regarding the recovery policies to cope with diverse disruptive events, Kamalahmadi and Parast [8] and Suryawanshi and Dutta [5] reviewed supply chain resilience strategies, for example, multiple source assignment, contracting with backup facilities, suppliers collaboration, holding additional or pre-positioning emergency inventory, adding extra supply/production capacities, managing flow and node complexity, and the use of big data analytics and digitalization.

The development of appropriate decision-making tools is of great importance to the design of resilient biomass supply chains. Most of the literature is supported by quantitative optimization studies, such as a multiobjective stochastic mixed-integer programming model developed by Huang and Pang [9] to establish a biofuel infrastructure system that is effective and resilient while hedging natural hazards. A case study is used to evaluate the infrastructure requirements for cellulosic ethanol production from biomass wastes in California, which is prone to seismic hazards. Maheshwari et al. [10] develop a model to optimize a biomass to biofuel supply chain that balances cost efficiency and resilience. The optimization model considers regional biomass pre-processing depots and incorporates resilience in the objective function, quantified in the form of expected disruption cost. Some disruptions in the form of droughts or floods are modeled, and the changes in supply chain design are highlighted. A robust and resilient framework for designing and planning an integrated biomass supply chains and a number of petroleum refineries exposed to disruption risks is presented by Yazdanparast et al. [11]. The developed optimization model integrates long-term decisions on infrastructural investments and biomass supply contracts with operational decisions on production and distribution. Furthermore, the authors investigate a comprehensive set of resilience-enhancement strategies related to sourcing and procurement, process and operation design, and inventory control policies. Noteworthy, the application to these problems of alternative methods to overcome the limitations of optimization approaches, such as hybrid approaches, is limited. Tordecilla el al. [12] reviewed hybrid simulation-optimization methods for designing and assessing resilient supply chain networks and recognized the advantage to deal with both operational and disruption risks subject to uncertainty in real-world size problems. Considering multiple uncertain parameters, disruption events and objectives may become computationally intractable for exact optimization methods. It is highlighted that this combined advantage with discrete event simulation (DES), already used in multiple application scopes and able to generate a digital representation with useful data information and performance indicators, allowing to replicate how the system reacts in different scenarios as a sequence of events in time. Despite the application to several problem scopes, to our knowledge, the use of simulation-optimization methods to the design of resilient supply chains using discrete-event simulation dedicated to specific problems of design and planning of biomass supply chains remains fairly unexplored.

1.3 Main Contributions

The paper explores an approach to the design of a resilient biomass supply chain using a simulation-optimization methodology. Through the analysis of the impact of uncertainty and a disruption in the supply chain, the results provide directions to support the decision-makers to design resilient biomass supply chains. The model computes the supply chain Net Present Value (NPV), accounting for the scenario effect of uncertain biomass availability related to the seasonality of this resource and disruption caused by extreme weather conditions that strongly affect biomass availability during a long period. A case study of Portuguese biomass to energy network is used to apply the proposed methodology. The paper is organized as follows: this section defines the context of the research and identifies the main contributions in the research area. In Sect. 2 the methodology is presented. Section 3 describes and analyzes the results of the case study. Section 4 presents the main conclusions and future work.

2 Methodology

Given the stochastic nature of biomass supply chains, the development of hybrid techniques to overcome the computational burden has proven its relevance to deal with large dimensional solution spaces. Vieira et al. [13] have identified that simulation with optimization approaches combines the advantages of the system detail representation with the ability to optimize solutions, leaving the hard-to-model constraints to the former. The authors defined that this hierarchical combination can be one-way or iterative, whereas our focus is on optimization-based simulation. Therefore, in order to compute some variables as part of the solution generation, the optimization model generates a solution under ideal conditions, while the simulation model considers the inherent variability and provides the expected realistic outcomes.

An optimization model based on Paulo et al. [14] was implemented in GAMS, defining a deterministic Mixed Integer Linear Programming model to determine the design and planning variables of a biomass supply chain. As input is given all possible locations of biomass sources (with the corresponding availability per type), biorefineries (set of available technologies and capacities), demand centers, and transportation modes with the distances between all points as parameters of the model. The model includes a set of equations to define the constraints for the biomass availability, the total inflow/outflows of the biorefineries and the corresponding mass balances, demand constraints, and a set of constraints to define the biorefineries to install, when to install, and not allowing their dismantling. The model includes continuous non-negative and binary variables to define the design and planning variables. The determined variables are the number, location, technology, and capacity of biorefineries to install, with the corresponding amounts produced and demand centers to serve, as well as the amount of biomass type collected at each source and transportation flows. The model objective is to minimize supply chain total cost given by Eq. 1.

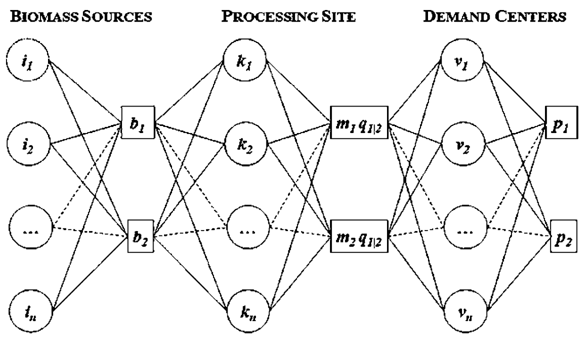
$$\begin{aligned} \min \mathit{Total\ Cost} \\ = \sum (\mathit{Biomass\ Cost} + \mathit{Fixed/Variable\ Operating\ Cost\ at\ Biorefineries} \\ + \mathit{Transportantion\ Costs} + \mathit{Annualized\ Investment\ Cost}) \end{aligned} \tag{1}$$

The DES model aims to represent the supply chain spatial case, considering the optimized solution under the proposed uncertain and disruption conditions. The model is implemented in SIMIO and is programmed to compute multiple output scenario statistics involving the occurrence of events, considering probability distributions of parameters. The main library of objects available in the SIMIO software is used, which, in its main concept, considers model entities (e.g., products) processed at servers (e.g., biorefinery), which then depart from the represented system. Suitable to the level of detail of the supply chain design solution, the simulated environment is set on the viability assessment and related impact of seasonal biomass uncertainty and disruption availability, being simulated 1000 replications to guarantee statistical significance and the average values are shown. The interaction of the two models aims to discuss the supply chain network performance under the proposed scenario, while computing the net present value (NPV) of cashflow operations (Eq. 2), for n time periods and CF_k as the annualized value of cashflows at time period k with i discount rate.

$$\mathrm{NPV} = \sum_{k=0}^{n} \frac{CF_k}{(1+i)^k} \tag{2}$$

3 Case Study

The proposed methodology is applied to the case study of the biomass supply chain to bioproducts production in Portugal, integrating the process of biomass collection, processing facilities, demand centers, and all the logistic activities for biomass/bioproducts transportation. Supply chain superstructure and data considered in this



278 candidate locations biomass supply (i)	28 candidate locations for biorefineries installation (k)		18 demand centers (v)
Biomass type (b)	**Technol. (m)**	**Capacity (q) | Conversion factor**	**Bioproducts (p)**
b1	m1	75 (q1)/250 (q2) kton/year | 0,3446	p1
b2	m2	50 (q1)/200 (q2) kton/year | 0,3316	p2
Biomass acquisition cost	**Investment cost**		**Selling price**
b1: 185,33€/ton	m1q1: 36415 k€ m1q2: 74991k€		p1: 904,09€/ton
b2: 411,85€/ton	m2q1: 12164 k€ m2q2: 27945k€		p2: 947,72€/ton
	Fixed annual costs	**Variable operating costs**	
	m1q1: 2798k€ m1q2: 9328k€	p1: 318,32 €/ton	
	m2q1: 1190k€ m2q2: 4763k€	p2: 198,79 €/ton	

Fig. 1 Case study data

study are summarized in Fig. 1, considering two technologies, m1, and m2 to produce bioproduct p1 and bioproduct p2, using biomass type b1 and b2, respectively.

The optimization model determines the design and planning variables of the supply chain structure under deterministic conditions. This primary solution is modelled in SIMIO to assess alternative scenario solutions to support the decision-makers in the development of a resilient supply chain. In this study, a scenario is proposed that accounts for the effects on the network, exploring the biomass/bioproducts seasonality uncertain parameter and the biomass disruption caused by extreme weather conditions. The DES model computes the supply chain performance measurement as the NPV, run for a period of 10 years considering a discount factor of 10%. These effects assume variations in availability and demand during the years, as well as stochastic distribution of parameters following case analysis, detailed as follows:

- effect of variability: the increase in biomass availability and bioproducts demand follows a uniform distribution between 2% and 4%, and the increase in price forecast of the bioproducts follows a uniform distribution between 2.8% and 4%.

Table 1 Seasonality discretization of biomass availability and bioproducts demand

Seasons/months		Annual biomass availability (%)	p1 (%)	p2 (%)
Winter	Dec–Feb	10	25	21
Spring	Mar–May	40	23	20
Summer	June–Aug	30	26	31
Fall	Sept–Nov	20	26	28

Table 2 Annual biomass availability at the disruption level

Seasons/year	*No disruption*	Lisboa/p1 (%)	Santarém/p2 (%)	Pombal/p1 (%)	Vila real/p1 (%)
Spring/year 5	*40*	20	25	30	40
Summer/year 5	*30*	10	15	20	30
Fall/year 5	*20*	10	15	20	20
Winter/year 6	*10*	10	10	10	10
Spring/year 6	*40*	30	35	40	40
Summer/year 6	*30*	20	30	30	30

- effect of seasonality: the annual biomass availability and bioproducts demand are distributed unevenly to represent the four seasons of a calendar year, presented in Table 1.
- effect of disruption level: a shortage of a biomass due extreme weather events occurs at the Spring of year 5 with ripple effects to last until the following year, affecting dissimilarly the corresponding availability at the biorefineries, presented in Table 2.

All models run in an Intel(R) Xenon(R) CPU ES-2660v3@2.60 GHz with 64 GB RAM, with GAMS (42.1.0 ver.), using CPLEX (22.1.0.0 ver.) solver, and SIMIO (15.240 ver.).

3.1 Results and Discussion

The primary deterministic solution is provided by the optimization model that generates the supply chain superstructure with the determined design capacities, location, and technology. In Fig. 2., the shaded areas surrounding the biorefineries exemplify the biomass supply locations determined by the solution: on the left, the three biorefineries installed of bioproduct p1 using the production technology m1, and on the right, the biorefinery installed of bioproduct p2 using technology m2. The installed capacities are of q2 at the Lisbon and Pombal biorefineries and the remaining Vila Real and Santarém are of q1 capacity.

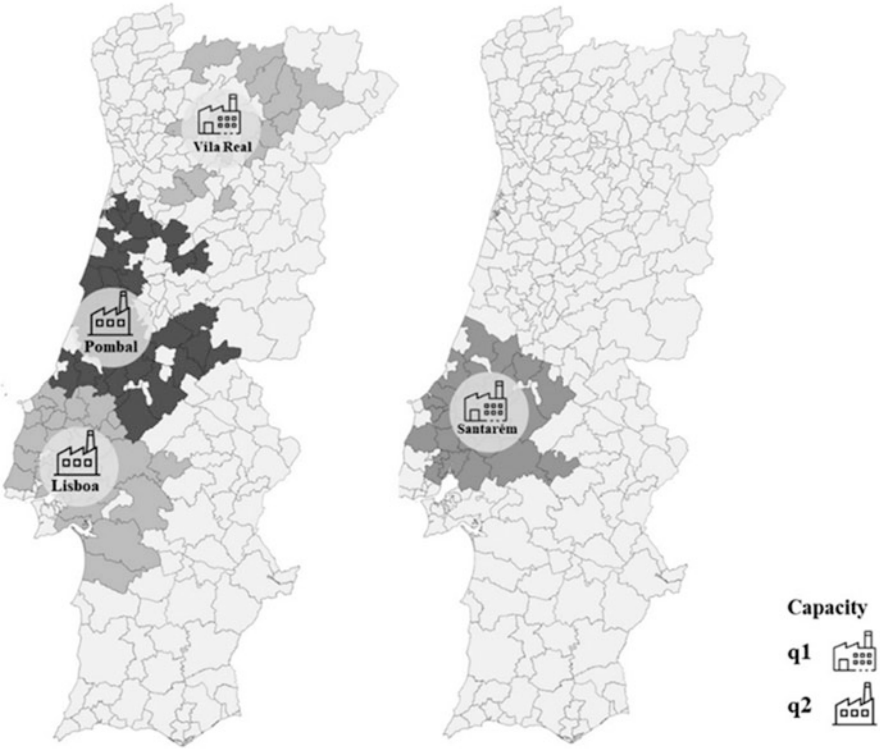


Fig. 2 Supply chain initial solution

At the simulation model, each of the four biorefineries account with the corresponding cluster amounts of biomass sources and demand centers (see [15]). As expected, the network feasibility is highly impacted by the variability of biomass availability per season and the disruption occurrence, penalizing the profits and leading to an average NPV of the investment project of $-4{,}8.10^6$€. In the results shown in Fig. 3, the simulations allow to assess the operational viability of the network given the proposed annual demand. Beyond the seasonal mismatch between the available biomass and the bioproducts demand, it is possible to overlook that the installed capacity can be insufficient to address demand in peak seasons, which cumulates unfulfilled demand by each year. This implies that the design decisions, assuming a fixed installed capacity, should consider a planning strategy to balance production across other seasons, with expected impact in bioproduct storage costs not addressed in this preliminary study. Also evident is that the primary solution is unable to follow the proposed demand increase, which suggest that processing technology improvements are essential to be put in place to potentiate production conversion effciency.

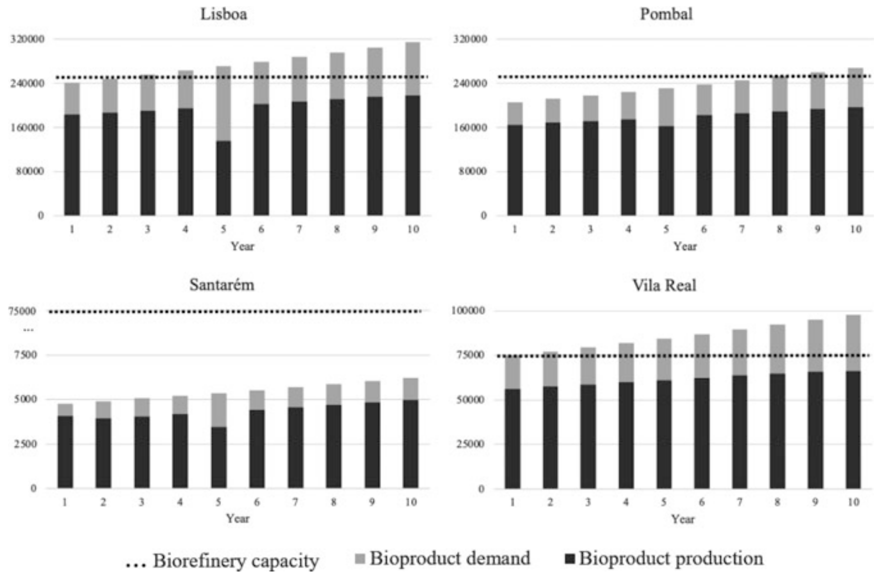


Fig. 3 Bioproducts demand and productions per biorefinery (tons)

The analysis of results statistics shows the diverse effect on production at the disruption of year 5, proportional to the corresponding availability restrictions of biomass. Therefore, in this study, we propose the incorporation in the network of a dry-storage warehouse for biomass buffer at each biorefinery. This change in the supply chain design is now simulated and the improved output production results are shown in Fig. 4. It is possible to note that with the biomass stored the process is able to accommodate the seasonality variability by increasing the production closer to capacity (except in the first years since there was no prior storage). Likewise, this buffer is also critical to deal with a much smoother production disruption, whereas this margin was also given by the limiting capacity to fulfill demand. In Fig. 5 is possible to control the simulated amounts of biomass stored per biorefinery throughout the years, enabling an adequate inventory management to suit production. For this case, it is noted the accentuated amounts decrease in the years of disruption, and, since no restriction in storage was considered, it is possible to verify the maximum required capacity. Considering these values for each biomass storage capacity, an estimation of additional 6% investment costs of installation were computed in the NPV to generate a solution under these scenario conditions of $5{,}8.10^7$€.

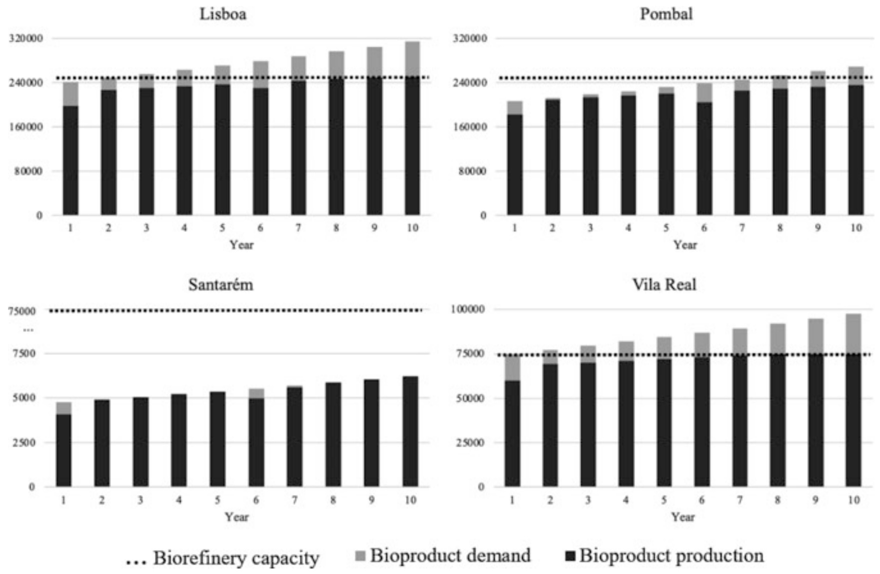


Fig. 4 Bioproducts demand and productions per biorefinery (tons) considering a storage facility

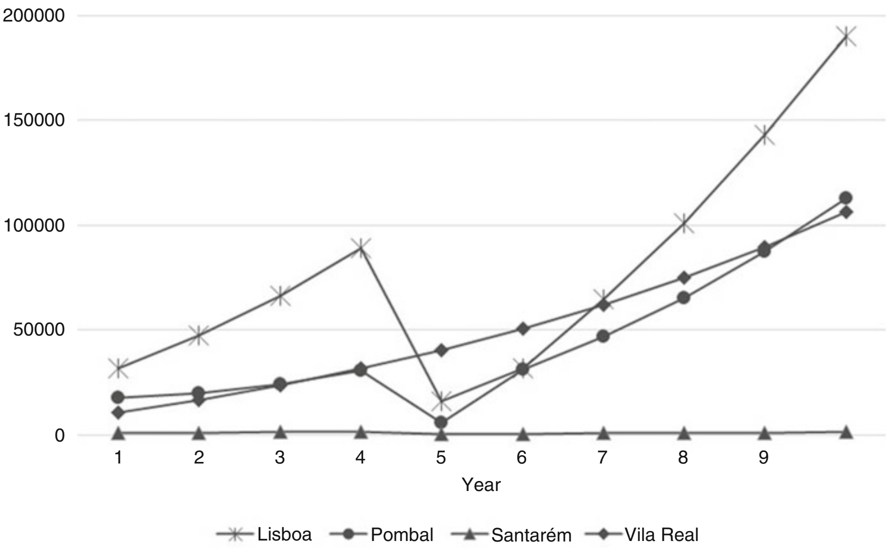


Fig. 5 Storage capacity per biorefinery (tons)

4 Conclusions

This work explored an approach to the design of resilient biomass supply chain using discrete event simulation. Bioproducts production is recognized by government institutions around the world as one driver to increase sustainability in the energy sector. However, biomass-based businesses are, due to its perishable nature, subject to uncertainty and disruptions that must be carefully taken into consideration in the design and management of the network, able to accommodate adverse conditions. The present work proposes a hybrid methodology that combines optimization with simulation to assess a biomass supply chain solution through its NPV investment viability when subject to scenarios of seasonality and disruption. The DES simulation model enables to mimic real-world environment conditions, potentiating the study of alternative scenarios with investment in additional capacity or storage, increasing the resilience of the supply chain under dynamic interdependencies and parameters variability. The results highlight the advantage to understand and mitigate the impact of many other critical issues in the design project phases to be pursued in future work.

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References

1. Demirbas, M. F., Balat, M., & Balat, H.; Potential contribution of biomass to the sustainable energy development. Energy Conversion and Management, 50(7), 1746–1760. (2009).
2. Mottaghi, M., Bairamzadeh, S., & Pishvaee, M. S.; A taxonomic review and analysis on biomass supply chain design and planning: New trends, methodologies and applications. Industrial Crops and Products, 180, 114747. (2022).
3. Salehi, S., Zare Mehrjerdi, Y., Sadegheih, A., & Hosseini-Nasab, H.; Designing a resilient and sustainable biomass supply chain network through the optimization approach under uncertainty and the disruption. Journal of Cleaner Production, 359, 131741 (2022).
4. di Paola, N., Cosimato, S., & Vona, R.; Be resilient today to be sustainable tomorrow: Different perspectives in global supply chains. Journal of Cleaner Production, 386, 135674 (2023).
5. Suryawanshi, P., & Dutta, P.; Optimization models for supply chains under risk, uncertainty, and resilience: A state-of-the-art review and future research directions. Transportation Research Part E: Logistics and Transportation Review, 157, 102553 (2022).
6. Oliveira, J. B., Jin, M., Lima, R. S., Kobza, J. E., & Montevechi, J. A. B.; The role of simulation and optimization methods in supply chain risk management: Performance and review standpoints. Simulation Modelling Practice and Theory, 92, 17–44 (2019).
7. Pires Ribeiro, J., & Barbosa-Povoa, A.; Supply Chain Resilience: Definitions and quantitative modelling approaches – A literature review. Computers & Industrial Engineering, 115, 109–122 (2018).
8. Kamalahmadi, M., & Parast, M. M.; A review of the literature on the principles of enterprise and supply chain resilience: Major findings and directions for future research. International Journal of Production Economics, 171, 116–133 (2016).

9. Huang, Y. X., & Pang, W. C.; Optimization of Resilient Biofuel Infrastructure Systems under Natural Hazards. Journal Of Energy Engineering, 140(2) (2014).
10. Maheshwari, P., Singla, S., & Shastri, Y.; Resiliency optimization of biomass to biofuel supply chain incorporating regional biomass pre-processing depots. Biomass & Bioenergy, 97, 116–131. (2017).
11. Yazdanparast, R., Jolai, F., Pishvaee, M. S., & Keramati, A.; A resilient drop-in biofuel supply chain integrated with existing petroleum infrastructure: Toward more sustainable transport fuel solutions. Renewable Energy, 184, 799–819 (2022).
12. Tordecilla, R. D., Juan, A. A., Montoya-Torres, J. R., Quintero-Araujo, C. L., & Panadero, J.; Simulation-optimization methods for designing and assessing resilient supply chain networks under uncertainty scenarios: A review. Simulation Modelling Practice and Theory, 106, 102166 (2021).
13. Vieira, M., Moniz, S., Gonçalves, B. S., Pinto-Varela, T., Barbosa-Póvoa, A. P., & Neto, P.; A two-level optimisation-simulation method for production planning and scheduling: the industrial case of a human–robot collaborative assembly line. International Journal of Production Research, 60(9), 2942–2962 (2022).
14. Paulo, H., Azcue, X., Barbosa-Póvoa, A. P., & Relvas, S.; Supply chain optimization of residual forestry biomass for bioenergy production: The case study of Portugal. Biomass and Bioenergy, 83. (2015)
15. Paulo, H., Vieira, M., Gonçalves, B. S., Pinto-Varela, T., & Barbosa-Póvoa, A. P.; Assessment of biomass supply chain design and planning using discrete-event simulation modeling. In L. Montastruc & S. Negny (Eds.), Computer Aided Chemical Engineering (Vol. 51, pp. 967–972). Elsevier (2022).

Industrial Production and Economic Growth Since the 1950s: Analysing the Portuguese Case Using Kaldorian and Causality Approaches

Ricardo Ferraz

Abstract The Portuguese economy recorded its highest rates of growth between the early 1950s and early 1970s of the twentieth century, with the industrial production/GDP ratio remaining at a historically high level during the same period. When this phase came to an end, Portugal's economic growth slowed down and the industrial production/GDP ratio presented a pronounced downward trend. This paper analyses the relationship between industrial production and economic growth for the specific case of Portugal over the last half century, using two models: one inspired by the Kaldor First Law and the other using a causality econometric approach. The results obtained enable one to conclude that in Portugal a positive causality relationship exists between these two variables in the long run, specifically in the period 1955–2020. This conclusion reinforces the argument that the industrial sector is crucial for boosting the economic growth of a country.

Keywords Industrial production · Economic growth · Portugal · Econometric causality

1 Introduction

In the period known as the Golden Age (1950–1973), the Portuguese economy grew at the highest rate ever, standing out in the international context (see the data of Refs. [15, 16], and the Ref. [17]). The literature has converged in the sense that it justifies the Portuguese performance during this period as coinciding with the beginning of European integration, the relative liberalisation of Portugal's economy, and the developmental orientation of its economic policy [20]. It was precisely during this

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period that Portugal experienced a strong process of industrialisation [12, 13, 19] and that it converged, economically, with the European average and with the group of the most industrialised economies [4, 6–8].

Recently-published empirical evidence shows precisely that international trade and investment have been key variables in determining Portuguese economic growth since those times [6]. With the aim to study Portuguese economic growth in more depth, this paper sets out to test the relationship between industrial production and economic growth in Portugal during the period from the 1950s up to the present day. For this purpose, we use the new data that was recently made available by the official institutions in Portugal and apply econometric technics, including a causality approach.

The paper is divided as follows: after this introduction, Sect. 2 presents a brief framework of the evolution of economic growth and industrial production during the period in question. Next, the empirical methodology for estimating the relationship between the variables of interest is presented in Sect. 3. The estimated results are discussed in Sect. 4, and the main conclusions are documented in Sect. 5.

2 Economic Growth and Industrial Production in Portugal Since the 1950s: A Brief Illustrative Analysis

We begin our analysis by presenting Fig. 1, which was produced using the new long time series from *Banco de Portugal* and the *Instituto Nacional de Estatística* [22].

In this figure it is possible to verify that the period comprising the 1950s up to the beginning of the 1970s corresponded to higher rates of economic growth. It is worth mentioning that on average between 1955 and 1973, the Portuguese economy grew, on average, by 5.1% per year, whereas later on, more specifically between 1974 and 2020, the average annual GDP growth rate was a mere 1.8%.

It was during the Golden Age that the Portuguese economy experienced a strong industrialization process (see Fig. 2). On average, between 1955 and 1973 industrial production represented 27% of GDP,[1] while the average was less than 22% from 1974 to 2020.

It thus seems clear that the period of greatest economic growth for Portugal also corresponded to the phase when industrial production recorded the greatest weight in GDP. In this sense, the following question arises: What has been the relationship between industrial production and economic growth in Portugal over the last decades?

[1] In this regard, it should be noted that several important economic policy initiatives were adopted, an example being the case of the Development Plans (1953–1974), which included several investments in the industrial sector [5, 9].

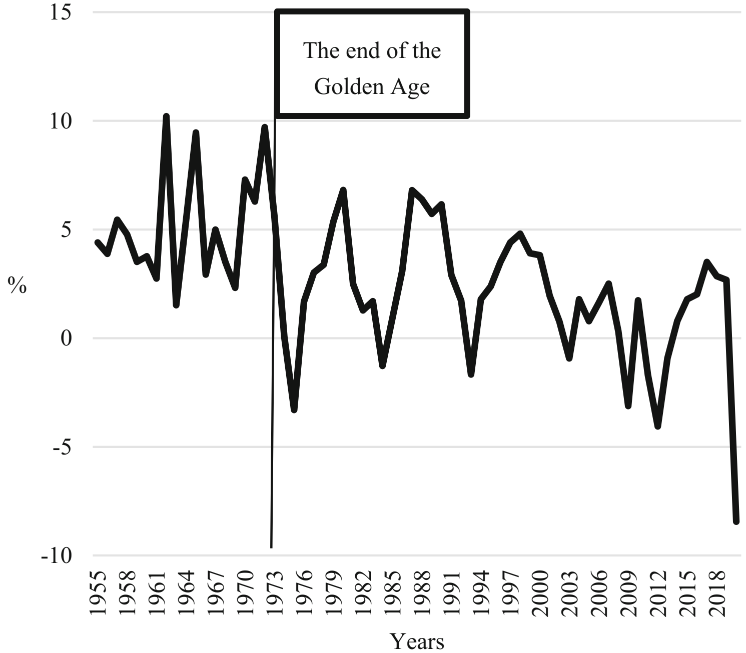

Fig. 1 Portuguese real GDP growth rate, 1955–2020. (**Sources**. Own calculations, using data from SLEP [22]. **Note**. The growth rates were calculated from amounts expressed at 2012 prices)

3 Empirical Methodology

The literature converges in the sense that it considers industrial activities to be determinant for the growth and development of an economy (see, for example, [2, 14, 21, 23]). As can easily be understood, some of the effects of industrial production can occur in a more immediate perspective, while others can only be felt in the economy later on in time. Accordingly, we propose to estimate two different econometric models in order to capture these above-mentioned effects.

3.1 Models

We start by presenting the first linear regression model, where Y corresponds to GDP, and P to industrial production, being both expressed in real terms:

$$Y_t = \mu + \beta\, P_t + u_t \tag{1}$$

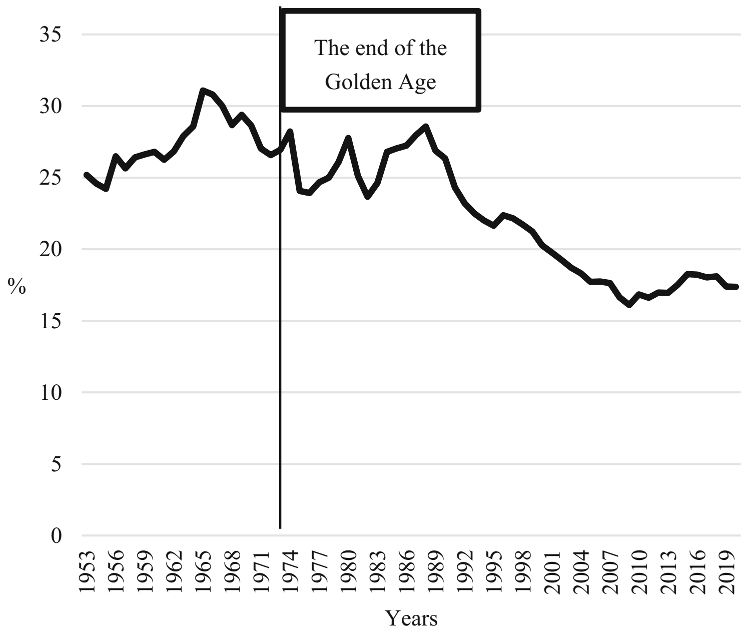

Fig. 2 Industrial production of the Portuguese economy as a percentage of GDP, 1953–2020. (**Sources**. Own calculations, using data from SLEP [22]. **Note**. The production of the industrial sector includes the specifical activities of extractive and manufacturing industries, namely: (1) food, beverage and tobacco industries; (2) textile, clothing, leather and leather products industry; (3) wood, pulp, paper and cardboard industry and their printing articles; (4) manufacture of coke and refined petroleum products; (5) manufacture of chemical products and synthetic and artificial fibers; (6) manufacture of basic pharmaceutical products and pharmaceutical preparations; (7) manufacture of rubber, plastic and other non-metallic items; (8) basic metallurgical industries and manufacture of metallic products; (9) manufacture of computer, communication, electronic and optical equipment; (10) manufacture of electrical equipment; (11) manufacture of machinery, equipment, among others; (12) manufacture of transport material; (13) other activities)

The objective of Eq. (1) is to test the correlation between P and Y in a certain period t. The construction of this model was inspired by the Nicholas Kaldor "first growth law" that was presented in the 1960s [11] and which assumes that manufacturing is the true engine of economic growth.

In order to obtain better results in terms of stationarity – which is an important property in time series – it makes sense to estimate the model with variables in the form of growth rates, as shown in Eq. (2):[2]

$$y_t = \phi + \alpha\, p_t + u_t \tag{2}$$

[2]For more details on this important property see, for example, Marques [18].

In this case, y and p respectively represent the real GDP growth rate and the real industrial production growth rate. If these variables are truly stationary, which allow us to estimate the model, then the coefficient of p needs to present statistical significance in the regression, with $0 < \widehat{\alpha} < 1$, in order for us to conclude the existence of a positive correlation between the two variables.

Should there be a positive correlation, it makes sense to go further and try and assess whether the growth rate of real industrial production was indeed responsible for causing a positive effect on economic growth. It is important to state that by using the term "causing", we mean that the past values of an explanatory variable can produce effects on the present values of the dependent variable. Therefore, we also propose to estimate the following growth model:

$$y_t = \theta_0 + \sum_{i=2}^{a} \theta_i p_{t-i} + u_t \tag{3}$$

In this model, the existence of a causality relationship will be confirmed if the estimated coefficients of the lagged variable p presents statistical significance in the regression.

3.2 Data and Time Horizon

Annual data for GDP, industrial production, and prices can all be extracted directly from SLEP [22]. These data report to the period of 1955–2020, however when we calculate growth rates we are oblige to discard the first observation, and therefore our sample has a total of 65 observations.

4 Estimated Results and Discussion

We start our analysis by testing the stationarity of the two variables, using the tests commonly used for this purpose. The results are documented in Table 1.

As can be seen in Table 1, the real growth rates of GDP and industrial production are both integrated of order 0, I(0), which means that we are dealing with stationary variables. Therefore, y and p can be used to estimate the model presented in Eq. (2) in order to assess whether a correlation exists between these variables, and if so, to ascertain whether this correlation was positive or negative.

Thus, Table 2 presents the estimated results using the well-known Ordinary Least Squares (OLS) method, with robust standard errors. A series of tests were also carried out to detect any potential problems in the model.

Table 1 ADF and ADF-GLS tests

Variable	Lags	Test statistic	Conclusion
ADF tests with constant and without trend			
y_t	0	−3.82***	**I (0)**
p_t	0	−5.90***	
ADF-GLS tests with constant and without trend			
y_t	0	−3.78***	**I (0)**
p_t	0	−5.95***	

Note 1: ADF [1] and ADF-GLS [3] were performed using Gretl [10]

Note 2: *, ** and *** denote the rejection of the null hypothesis (h_0) of a unit root at the 10%, 5% and 1% levels

Table 2 Estimation of Eq. (2) by the OLS method (with robust standard errors)

Explanatory variables	Coefficients
Const	**1.90 (0.43)*****
$\boldsymbol{p_t}$	**0.39 (0.06)*****
Adjusted R-squared	*0.51*
P-value (F)	*0.00*
P-value of LM test	*0.37*
P-value of White test	*0.28*

Note 1: The estimation and the tests were performed using Gretl [10]

Note 2: '*', '**', and '***' represent the statistical significance of the regressor at the 10%, 5%, and 1% levels, respectively. Figures in brackets are standard errors

According to the results of the different tests (presented in italics), it can be verified that the basic assumptions of the model are not violated, and that all regressors are jointly significant. It is also confirmed that the explanatory power is not very low.

Furthermore, it is possible to observe that the estimated parameters present statistical significance and that $0 < \widehat{\alpha} < 1$. That is to say, an increase of 1 percentage point (pp) in p in a certain year t was associated, with increases in y of 0.39 pp. in that same year, on average. This means that during the period of 1956–2020 there was a positive correlation between the two variables.

Taking this into account, it also makes sense to test the possible existence of a causality relationship by estimating Eq. (3). The results of this second estimate are presented below in Table 3.

We can firstly conclude from this second estimate case that the basic assumptions of the model are not violated, and that all the regressors are jointly significant. However, the power of the model is now low, which is not surprising, since in this regression we only admit that apart from the constant, the present values of y are only explained by the past values of p.

Table 3 Estimation of Eq. (3) by the OLS method (with robust standard errors)

Explanatory variables	Coefficients
Const	**1.99 (0.51)*** **
p_{t-1}	**0.17 (0.06)*** **
p_{t-2}	**0.11 (0.05)***
Adjusted R-squared	*0.14*
P-value (F)	*0.00*
P-value of LM test	*0.74*
P-value of White test	*0.93*
Variation inflation factor (VIF)	*Less than 1.1*

Note 1: The estimation and the tests were performed using Gretl [10]

Note 2: '*', '**', and '***' represent the statistical significance of the regressor at the 10%, 5%, and 1% levels, respectively. Figures in brackets are standard errors

Note 3: The appropriate lag order of p was chosen, using the Akaike Information Criterion (AIC)

More importantly, we continue to observe that all explanatory variables are statistically significant in the regression, which means that we can confirm that a positive causal relationship exists between these variables. That is to say, increases of 1 percentage point (pp) in p in a certain years $t-1$ and $t-2$ caused, on average, respectively increases of 0.17 pp. and 0.11 pp. in y in a following given year t.

5 Conclusion

The Portuguese economy grew at its highest rate ever during the 'Golden Age' (1950–1973), standing out internationally, and the industrial production/GDP ratio remained at an extraordinarily high level. After this phase Portuguese economic growth the deaccelerated, and the industrial production/GDP ratio presented a pronounced downward trend.

The aim of this paper was to test the relationship between industrial production and economic growth in Portugal from the 1950s to the present day. For this purpose, the new long time series from *Banco de Portugal* and the *Instituto Nacional de Estatística* [22] were used to estimate two different models.

The first model was constructed inspired by the so-called 'Kaldor growth first law', which assumes that manufacturing is the true engine of economic growth. The estimated results of this model show that for each increase of 1 percentage point (pp) in the real industrial production growth rate (p) in a certain year t, there was an average increase in the real GDP growth rate (y) of 0.39 pp. in that same year. This proves the existence of a positive correlation in the long-run between the two variables, more specifically during the period of 1956–2020.

In order to study this relationship in more depth, we also estimate a second growth model, this time using a causality approach, with the objective to assess whether the past values of industrial production causes a positive effect on economic growth. In this case, the estimated results show that an increase of 1 percentage point (pp) in the real industrial production growth rate in a certain years $t-1$ and $t-2$ caused, on average, an increase in the real GDP growth of 0.17 pp. and 0.11 pp., respectively, during a following given year t. This proves that a positive causality relationship existed during that same period.

These results are in line with the international literature, as they reinforce the argument that the industrial sector is crucial for stimulating the economic activity of a country.

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References

1. Dickey, D. and Fuller, W. (1979). "Distribution of the Estimators for Time Series Regressions with a Unit Root". *Journal of the American Statistical Association,* 74 (366), pp. 427–431.
2. Elfaki, K; Handayo, R. and Ibrahim, K. (2021). "The Impact of Industrialization, Trade Openness, Financial Development, and Energy Consumption on Economic Growth in Indonesia". *Economies*, 9, pp. 1–13.
3. Elliot, G; Rothenberg, T. and Stock, J. (1996). "Efficient tests for an autoregressive unit root". *Econometrica* 64, pp. 813–836.
4. Ferraz, R. (2020a). *Grande Guerra e Guerra Colonial: Custos para os Cofres Portugueses*. Edições Sílabo: Lisboa.
5. Ferraz, R. (2020b). "The Portuguese Development Plans in the Postwar Period: How Much Was Spent and Where?". *Investigaciones de Historia Económica – Economic History Research* 16(1), pp. 45–55.
6. Ferraz, R. (2022a). "The golden age of the world economy and Portuguese economic growth: applied study, 1950–2018". *Cogent Economics & Finance*, 10 (1), pp. 1–17.
7. Ferraz, R. (2022b). "The Portuguese Military Expenditure from a Historical Perspective". *Defence and Peace Economics*, 33 (3), pp. 347–365.
8. Ferraz, R. (2022c). "The Financial Costs of the Portuguese Colonial War, 1961–1974: Analysis and Applied Study". *Revista de Historia Economica – Journal of Iberian and Latin American Economic History*, 40 (2), pp. 243–272.
9. Ferraz, R. (2022d). *Os Planos de Fomento do Estado Novo: Quantificação e Análise*. Edições Sílabo: Lisboa.
10. Gretl. (2021). "Gnu Regression, Econometrics and Time-Series Library – Version 1.9.4": http://gretl.sourceforge.net/.
11. Kaldor, N. (1967). *Strategic Factors in Economic Development*. Cornel University Press: NY.
12. Lains, P. (1994). "O Estado e a Industrialização em Portugal, 1945–1990". *Análise Social*, 29 (128), pp. 923–958.
13. Lains, P. (2003). *Os Progressos do Atraso – Uma Nova História Económica de Portugal*. ICS: Lisboa.
14. Lucchese, M; Nascia, L. and Pianta, M. (2016). "Industrial policy and technology in Italy". *Econ Polit Ind* 43, pp. 233–260.
15. Maddison, A. (2001). *The World Economy – A Millennial Perspective*. OECD: Paris.

16. Maddison, A. (2003). *The World Economy – Historical Statistics*. OECD: Paris.
17. Maddison Project. (2020). “Maddison Project Database, version 2020 – Bolt J, Van Zanden J”. Accessed 30 September, 2022:https://www.rug.nl/ggdc/historicaldevelopment/maddison/releases/maddison-project-database-2020
18. Marques, C. (1998). *Modelos Dinâmicos, Raízes Unitárias e Cointegração*. Edinova: Lisboa.
19. Mata, E. and Valério, N. (2003). *História Económica de Portugal – Uma Perspectiva Global*. Editorial Presença: Lisboa.
20. Mateus, A. (2013). *Economia Portuguesa: Evolução no Contexto Internacional (1910–2013).* Principia: Cascais.
21. Ndiaya, C. and Lv, K. (2018). “Role of Industrialization on Economic Growth: The experience of Senegal (1960–2017)”. *American Journal of Industrial and Business Management,* 8 (10), pp. 2072–2085.
22. SLEP. (2021). “Séries Longas para a Economia Portuguesa 2020”. Lisboa: Instituto Nacional de Estatística (INE) e Banco de Portugal.
23. Yong, L. (2021). “Why industrial development matters now more than ever”. *Industrial Analytics Platform*. Accessed 22 December, 2022: https://iap.unido.org/articles/why-industrial-development-matters-now-more-ever

Green Logistics, Reverse Logistics, Sustainable Logistics, and Eco-efficiency in the Construction Industry

Bruna Simões da Silva, Jorge Luiz Gayotto de Borba, Danieli Braun Vargas, and Carlos Manuel Taboada Rodriguez

Abstract Sustainable logistics, green logistics, reverse logistics, and eco-efficiency logistics have become emerging issues when dealing with environmental problems, especially in the building construction industry, consuming a considerable demand of natural resources throughout the entire logistics process in the works. Therefore, this research aims to represent the importance of sustainable logistics, green logistics, reverse logistics, and eco-efficiency logistics and bring up their importance on civil construction. The research also focuses on the Brazilian market. The paper uses the literature review to introduce the relevance of the subject, in addition to dealing with logistical performance indicators for organizations. The research also defined gaps in the literature and opportunities for future work, including research related to the assessment of logistical performance, which is suggested based on the results found during the research. Finally, the study presents research gaps and trends within the green, reverse, and sustainable logistics that could be linked to the context of civil construction.

Keywords Sustainability · Performance evaluation · Eco-efficiency

1 Introduction

The civil construction sector is responsible for many natural resources and solid waste generation, so the logistics stage must recognize the importance of sustainability in its logistics processes. In this perspective, Green, Reverse, and Sustainable Logistics form a set of tactics aimed at improving the efficiency in the logistics system aligned with the analysis of impacts on the environment, society, and the economy of organizations [1, 2].

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In addition, the environmental issue is increasingly central to business, given the importance of preserving resources and adapting companies to meet more ecologically aware demands [1, 3].

In this way, logistics is a fundamental part of making the supply chain sustainable since it represents strategic procedures for purchasing, moving, and storing goods that directly influence the competitiveness, quality, and costs of organizations [4].

Thus, studies and practices about the so-called Green, Reverse, and Sustainable Logistics emerged to understand how to reduce negative impacts and enhance the benefits of logistical activities about nature, society, and the economy [5]. Regarding civil construction, planning processes, and material use aligned with sustainability become essential in daily life at the construction site [2].

Moreover, the eco-efficiency concept might be applied on the logistics analysis, in other words it means focus on improving performance, considering use of energy and resources, product life cycle and so on. With this in intention, the cost-effectiveness of the process is evaluated to avoid significant negative impacts on the environment and enhance the value delivered [6].

Faced with the crisis on the civil construction sector and also focus on keeping the quality in the sector, management tools are essential to companies which would like to reduce costs and increase their own productivity in order to satisfy the customer needs [7]. Therefore, the objective of this research seeks to present the importance of Green, Reverse, and Sustainable Logistics in the field of civil construction for better efficiency in the works through a literature review.

2 Literature Review

The civil construction sector is responsible for significant consumption of raw materials and generates large amounts of waste, which requires a properly management and dispose of waste, on the contrary can cause damages for the environment [8].

In this step, the concepts of Green, Reverse, Sustainable Logistics, and Logistic eco-efficiency found according to the literature will be presented.

2.1 Green Logistics, Reverse Logistics, and Sustainable Logistics

The environmental consequences of logistics activities are increasingly present in the strategic decision-making of companies worldwide, as they represent a significant competitive advantage on the market [1].

Green logistics includes practices such as route optimization, efficient use of fuels, and monitoring of carbon emissions in order to reduce waste generation, pollution, and other negative effects of transporting and storing goods [9]. These activities, therefore, are the connection of efficiency with cooperation to identify weaknesses and improve methods that affect the edges of logistics [10].

In regard to indicators, five dimensions are frequently applied for supporting managers on green logistics issues, according to [11]:

- Green design: product features, materials, operations manual, and energy use;
- Green purchasing: recyclable, reusable, or recycled materials;
- Green transformation: greener manufacturing steps;
- Green logistics: minimization of routes, less polluting vehicles.
- Reverse logistics: stages after a product has been used;

In general, reverse logistics seeks to reduce costs, increase revenues, enhancing customer satisfaction, and improve the company's environmental performance through the analysis and improvement of the reverse flow, which means, the flow from the customer to the manufacturing industry [12]. Practices related to this topic are waste management, recovery of materials (recycling), and components and/or remanufacturing of products [13].

In the civil construction industry, the environmental impacts are particularly high during the building construction processes at the construction site, where inefficient management of raw materials can result in significant losses on the final product. On the other hand, supply chain management, which includes business logistics and reverse logistics, can contribute to efficiency in the civil construction production chain if there is a joint and integrated action among all the agents involved [14]. This underscores the importance of collaboration and coordination among stakeholders to minimize waste and promote sustainability throughout the entire supply chain.

Sustainable Logistics is based on reducing waste and losses in operations considering environmental, social, and economic areas, in the light of organizational strategy [15, 16]. Social, environmental, and economic dimensions refer to many aspects such as raw material consumption and disposal of waste, in addition to adherence to programs such as ISO (International Organization for Standardization) 14,000 for environmental management and also the Construction Waste Management Plan [14].

2.2 Logistic Eco-efficiency

Eco-efficiency is defined by the World Business Council for Sustainable Development as the "delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth's estimated carrying capacity" [17].

Thus, it is a business strategy for products and services that provides greater efficiency in resources utilization considering the effect on the environment and market demand [17]. In the industrial context, the interest in this tool is related to increasing sustainable initiatives and, therefore, impacting the environmental, social, and economic dimensions of the company [18].

Eco-efficiency logistics can be essential to achieving sustainable logistics and improving process performance. Therefore, the seven competencies necessary for sustainable actions in companies to be successful can be described: systematic thinking, interdisciplinarity, diversity, predictive thinking, knowledge of norms, interpersonal competence, and strategic management [19].

In this perspective, logistics, as an area that encompasses transportation, handling, and storage of products, has a significant role to play in sustainable operations since moving good from one location to another can be a huge polluter and resource consumer [20]. Thus, measures to enhance eco-efficiency logistics can significantly benefit the sustainable performance of companies. To this end, the development of relevant indicators and objectives is crucial for maintaining process performance and identifying potential obstacles in activities that have environmental and social impacts [20, 21].

3 Methodology

The Bibliometric analysis consist of researching scientific papers, citations, and patents to allow the researcher a broad and systematic view of the scientific production on a subject [22]. This is applied research with a qualitative approach, which can be considered exploratory, through a bibliographic survey [23].

The literature analysis was conducted in two stages to broaden the search. In the first stage (1), the search was focused on the keywords of sustainable logistics, green logistics, reverse logistics, and logistics performance. In the second stage (2), a search was conducted using the keywords 'eco-efficiency'and 'logistics performance' to further expand the scope of the search. The keywords used in the search strategies are presented in Table 1.

Table 1 Keywords applied in the two stages in literature search on the database

Performance evaluation (1, 2)	Sustainable logistics (1)	Reverse logistics (1)	Green logistics (1)	Eco-efficiency (2)
Indicator*	Sustain* logistic*	Reverse logistic*	Green logistic*	Eco-efficienc*
Performance evaluation				Logistic* eco-efficienc*
Performance				

Two databases were selected for the research due to their representativeness in the academic issue, Scopus and Web of Science. Besides, documents focus on civil construction industry approach were added from Google academic. The searches were conducted from November 2020 to December 2021.

The search used in the literature review did not initially include keywords related to civil construction due to a limited number of relevant articles found. However, an additional search was conducted through Google Academic to complement the search, and academic sources such as conference proceedings, journals, and dissertations were considered in the study which focus on Brazilian scenario.

Instead, 383 articles on the logistics performance evaluation of Sustainable Logistics, Reverse Logistics, and Green Logistics were found in the Scopus database, while 451 documents were identified in the Web of Science. Following the initial search, the following filters were applied: exclusion of duplicates, leaving 386 articles; aligned titles and abstracts: reaching 128 articles of interest; aligned full text: resulting in 49 articles selected, 20 on sustainable logistics, 12 on green logistics, and 17 on reverse logistics.

Henceforth, 383 documents on the logistics performance evaluation of sustainable logistics, reverse logistics, and green logistics were found in the Scopus database, while 451 documents were identified in the Web of Science (stage 1). Following the initial search, the following filters were applied: exclusion of duplicates, leaving 386 documents; titles and abstracts matched to the keywords: reaching 128 articles of interest; full text reading: resulting in 48 documents, which 20 on sustainable logistics, 11 on green logistics, and 17 on reverse logistics.

Regarding the review of eco-efficiency logistics and performance evaluation, a total of 264 articles were identified in Scopus database, while 207 articles were found in the Web of Science (stage 2). Using the search strategy and filters outlined in Table 1, the initial number of documents was reduced to 253 after removing duplicates. Subsequently, further refinement was done by matching titles and abstracts, which yielded 125 documents. Finally, after conducting a full-text analysis, 30 of them were selected for inclusion in this study.

Moreover, a temporal analysis of the publications revealed a significant increase in the number of documents related to the topics surveyed from 2015 onwards, indicating a growing interest among researchers in understanding the concepts and practices related to the search areas. The distribution of publications is presented in Figs. 1 and 2.

Regarding the academic journals with the highest number of publications in the research topic, Journal of Cleaner Production and Sustainability stands out, which appears among the top four for green logistics, reverse logistics, sustainable logistics, and logistics eco-efficiency. Figures 3 and 4 show journals with more than one work selected for inclusion.

With the overview presented from the literature search, it is possible to deepen the concepts and relate performance evaluation methods for each selected topic.

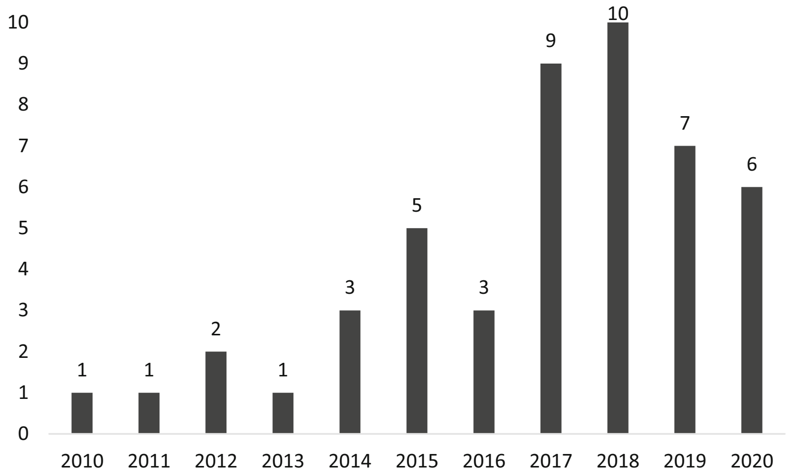

Fig. 1 Time distribution of green logistics, reverse logistics, and sustainable logistics documents (stage 1)

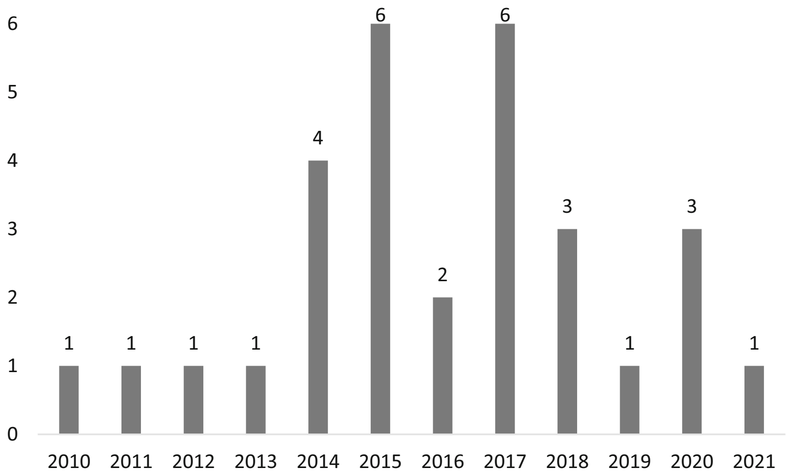

Fig. 2 Time distribution of eco-efficiency logistics and performance evaluation documents (stage 2)

4 Gaps and Research Trends

The research gaps have been identified through literature support, as the proposals for future studies are supported by the literature review on green logistics, reverse logistics, sustainable logistics and eco-efficiency logistics.

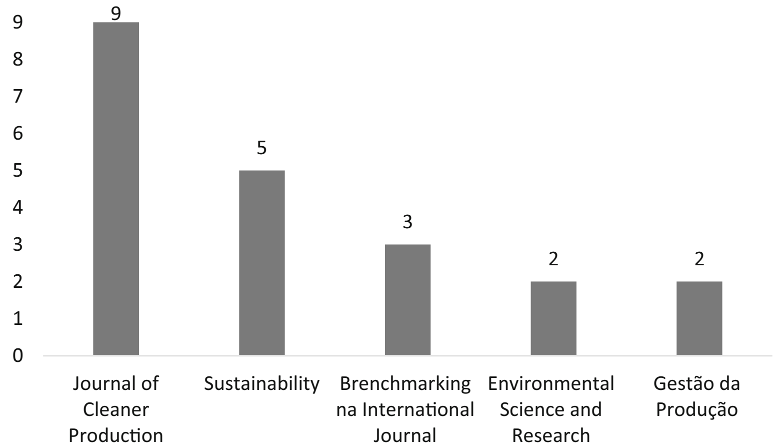

Fig. 3 Journals with the most expressive number of papers on green, reverse, and sustainable logistics

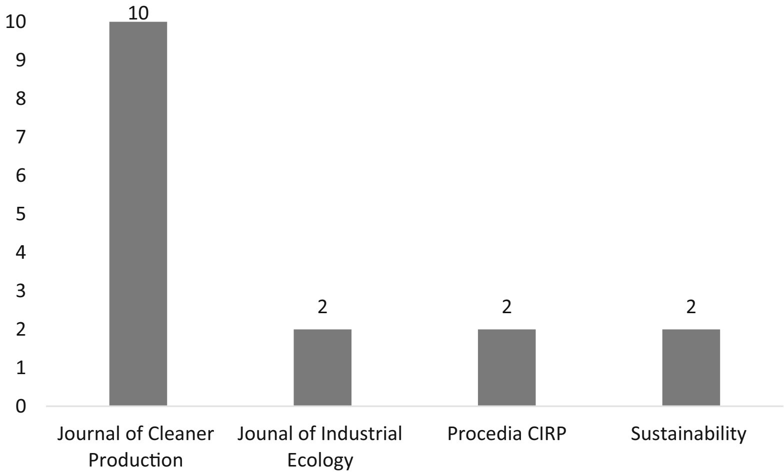

Fig. 4 Journals with the most expressive number of papers on eco-efficiency logistics

The first relevant aspect is the number of publications on these topics, which, excluding duplicates, amounted to 78 scientific articles considering all issues. After filtering and reading the articles, some aspects became relevant to this study.

Regarding sustainable logistics, on Brazilian scenario, the main focus is in the economic dimension, leaving a gap in environmental and, even more significantly, in social aspects. It is also important to emphasize that most indicators of the environmental and social dimension are associated with financial aspects [24].

In relation to green logistics, a gap that should be highlighted not only in the international but also in the Brazilian scenarios is the lack of connection between research and sustainability reports. It is also important to highlight that the surveys are generally empirical and specific to the company (case study), hindering the generalization of the analyzes [11, 25].

There is also a lack of literature in the field of reverse logistics, and the studies that were found present isolated assessments of logistics performance without following a standardized method of measurement. While the published research shares a common line of reasoning, there is no theoretical contribution to measure reverse logistics in the building construction processes [26, 27].

When dealing with the issue of eco-efficiency in logistics, gaps similar to described above can be highlighted. Again, there is a lack of literature on the subject, and it is usually presented focuses on sustainability issues [28]. Additionally, the lack of stakeholder engagement, and inefficient control of public agencies have been identified as problems for improving eco-efficiency [29].

5 Conclusions

This study aimed at analyzing sustainable logistics, reverse logistics, green logistics, and eco-efficiency in logistics on civil construction sector in Brazil, by a literature review.

The environmental dimension has been an emerging issue in the global landscape, not only in academia but also in companies. Our research showed that logistics plays an essential role in sustainable supply chains, especially on green logistics, reverse logistics, and sustainable logistics. Similarly, eco-efficiency in logistics can support Brazilian civil construction market, since it aims to improve process performance by adopting a conscious approach towards the use of resources and energy, in order to achieve sustainable processes.

Through the literature review of green logistics, reverse logistics, sustainable logistics, and eco-efficiency logistics, this study sought to connect the logistics field with the construction sector on Brazilian scenario. Furthermore, this research highlighted the importance of sustainable management in order to achieve improvements in process efficiency on construction sites. Increasing efficiency in operations can bring greater competitiveness to the sector by making their processes more sustainable, considering the three dimensions of sustainability - social, environmental, and economic.

Managing logistics activities on the construction sites has been highlighted as a way to measure and evaluate their impact, specially to improve the processes and increase competitiveness on that kind of industry. For this purpose, to develop eco-efficiency indicators can be considered a helpful tool for developing process improvements, and also for evaluating the organizations impacts.

Through the literature review, we could provide insights regarding to the lack of eco-efficiency indicators in logistics on the civil construction sector, mainly on deficit in public incentives, as well as on companies' investment by their selves.

It is important to highlight that analyzing studies in the field of eco-efficiency, we realized that they are often being presented combined to the context of green logistics, reverse logistics, and sustainable logistics, showing connection among all the areas addressed in the study.

The keywords search in the databases seemed to be a study's limitation since we found insufficient documents on civil construction industry, although research has been extensive. Therefore, the searches were complemented by Google Scholar database in order to comprehend Portuguese literature as well.

Besides, it is important to note that the literature on green logistics, reverse logistics, sustainable logistics, and eco-efficiency in logistics on a wide-ranging of sectors might support future research on logistics topics focus on civil construction issues.

Finally, as opportunities for future research, we suggest developing further studies for assessing eco-efficiency in logistics performance and conducting research that integrates the eco-efficiency in logistics focus on civil construction, especially in order to increase competitiveness in Brazilian industry in this field.

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References

1. Abdul, S.; Khan, R.; Zhang, Y.: Development of Green Logistics and Circular Economy Theory. Advances in Social Science, Education, and Humanities Research 516, 121–127 (2021).
2. Marchi, C.; Bohana, M.; Fernandez, J.: Environmental management in solid waste: sustainable construction and eco-efficiency. Sistemas & Gestão 13 (1) 118–129 (2018).
3. Kazancoglu, Y.; Kazancoglu, I.; Sagnak, M.: A new holistic conceptual framework for green supply chain management performance assessment based on circular economy. Journal of Cleaner Production 195, 1282–1299 (2018).
4. Tan, B. Q.; Wang, F.; Liu, J., Kang, K.; Costa, F.. A blockchain-based framework for green logistics in supply chains. Sustainability (Switzerland). 12 (11), 43–56 (2020).
5. Martínez, V. R.; Rodríguez, S. A.; Campdesuñer, P. R.; Vida, G. G.I.. Contribution to the logistic evaluation system in the transportation process in santo domingo, Ecuador. Journal of Industrial Engineering and Management 11 (1), 72–86 (2018).
6. Carvalhaes, B. B.; Rosa, R. A.; D'Agosto, M. A.; Ribeiro, G. M. A method to measure the eco-efficiency of diesel locomotive. Transportation Research Part D-Transport And Environment 51, 29–42 (2017).
7. Silva, B. S.; May, P. R.; Taboada, C. M. R.; Souza, N. L. S.; Alves, M. D. T.: Aplicação das ferramentas da qualidade em Construtoras Na Grande Florianópolis, SIMPEP, on-line (2020).
8. Silva, W. A.; Seleme, R.; Zattar, I. C.; Marques, M. A. M.; Drozda, F. O.; Kleina, M. Barreiras à sustentabilidade ambiental na logística da construção civil habitacional em Curitiba/PR. Revista de Gestão Ambiental e Sustentabilidade 101, 126–148 (2021).
9. Mutie, M. D.; Odock, S.; Litondo, K. Effect of green logistics practices on performance of logistics firms in Kenya. DBA Africa Management Review 10(4), 20–35 (2020).

10. Richnák, P.; Gubová, K. Green and reverse logistics in conditions of sustainable development in enterprises in Slovakia. Sustainability (Switzerland), v. 13, n. 2, p. 1–23, (2021).
11. Uygun, Ö. Dede, A.: Performance evaluation of green supply chain management using integrated fuzzy multi-criteria decision making techniques. Computers and Industrial Engineering 102, 502–511 (2016).
12. Hammes, G.; Souza, E.D.; Rodriguez, C.M.T.; Rojas, R.H.; Mojica, J.C.: Evaluation of the reverse logistics performance in civil construction. Journal of Cleaner Production 248 (2020).
13. Bouzon, M.; Miguel, P. A. C.; Rodriguez, C. M. T.: Managing end of life products: A review of the literature on reverse logistics in Brazil. Management of Environmental Quality: An International Journal 25(5), 564–584 (2014).
14. Fonsêca, R. De O.; Uchôa, F. P.: A importância da logística reversa para construção civil. V Simpósio Internacional de Gestão de Projetos, Inovação e Sustentabilidade, (2016).
15. Baah, C.; Amponsah, K. T.; Issau, K.; Ofori, D.; Acquah, I. S. K.; Agyeman, D. O. Examining the Interconnections Between Sustainable Logistics Practices, Environmental Reputation and Financial Performance: A Mediation Approach. Vision, (2021).
16. Campos, J. T. G. A. A.; Vivas, R. C.; Ferreira, A. M. S.; Freires, F. G. M. Operational decisions and sustainability: A Brazilian case of a drugs distribution center. Sustainability (Switzerland) 12(21) 1–17 (2020).
17. Olaru, O.; Galbeaza, M. A.; Banacu, C. S.: Assessing the sustainability of the wine industry in terms of investment. Emerging Markets Queries In Finance And Business (EMQ 2013), (2014).
18. Shah, I. H.; Dong, L.; Park, H. S.: Tracking urban sustainability transition: An eco-efficiency analysis on eco-industrial development in Ulsan, Korea. Journal of Cleaner Production 262, 121–286 (2020).
19. Fernando, L.; Evans, S.: Competencies to move beyond eco-efficiency. 13th Global Conference On Sustainable Manufacturing – Decoupling Growthfrom Resource Use. (2016).
20. Trochu, J.; Chaabane, A.; Ouhimmou, M.: A carbon-constrained stochastic model for eco-efficient reverse logistics network design under environmental regulations in the CRD industry. Journal Of Cleaner Production 245 (2020).
21. Yang, L.; Zhang, X.: Assessing regional eco-efficiency from the perspective of resource, environmental and economic performance in China: A bootstrapping approach in global data envelopment analysis. Journal Of Cleaner Production 173, 100–111 (2018).
22. Soares, P. B.; Carneiro, T. C. J.; Calmon, J. L.; Oliveira Castro, L. O. da C. Análise bibliométrica da produção científica brasileira sobre Tecnologia de Construção e Edificações na base de dados Web of Science. Ambiente Construído, 16(1) 175–185 (2016).
23. Martins, V.W.B.; Anholon, R.; Rodrigues, S. V.; Filho, L.W.; Quelhas, O.L.G. Brazilian logistics practitioners' perceptions on sustainability: an exploratory study. International Journal of Logistics Management, (2020).
24. Uyar, A.; Karaman, A. S.; Kilic, M.:. Is corporate social responsibility reporting a tool of signaling or greenwashing? Evidence from the worldwide logistics sector. Journal of Cleaner Production 253, (2020).
25. Fernandes, S. M.; Rodriguez, C. M. T.; Bornia, A. C.; Trierweiller, A. C.; Silva, S. M.; Freire, P. de S..: Systematic literature review on the ways of measuring the of reverse logistics performance. Gestão e Producão 25(1), 175–190 (2018).
26. Rauen, F.: Roteiros de iniciação científica. 2nd, Unisul, Tubarão (2018).
27. Voigt, D.; Casarotto Filho, N.; Macedo, M. A.; Braga, T. G.; Rocha, R. U. G. Performance evaluation of reverse logistics: Opportunities for future research Sustainability (Switzerland) MDPI AG, (2019).
28. Koskela, M.; Vehmas, J.: Defining Eco-efficiency: A Case Study on the Finnish Forest Industry. Business Strategy and the Environment 21(8), 546–566 (2012).
29. Fernandez-Vine, M. B.; Gomez-Navarro, T.; Capuz-Rizo, S. F.: Assessment of the public administration tools for the improvement of the eco-efficiency of Small and Medium Sized Enterprises. Journal of Cleaner Production. 47, 265–273 (2013).

Suicide Prediction in Workers Using Neural Networks and Stress-Related Factors

Daniel Alejandro Barajas Aranda, Aurora Torres Soto, and María Dolores Torres Soto

Abstract The article aimed to use a combination of typical testors and a neural network classifier to predict access to healthcare and identify relevant variables influencing suicide in the workplace. Stress-associated factors and the sociocultural environment experienced by suicidal individuals were deemed significant. The study presented data about high suicide rates in Aguascalientes, Mexico, and their negative consequences on the economy and society.

The article introduced the concept of pattern recognition, which involves categorizing objects into different classes, and its applications in various fields such as medicine and astronomy. It also explained how typical testers were used as a feature reduction mechanism and a neural network classifier to predict access to healthcare and identify the most influential factors in suicidal behavior at work, such as job loss, retirement, pregnancy, and the death of a close friend.

The study recommended the use of data mining and machine learning techniques to analyze data from suicide attempts, identify behavior patterns, and prevent suicide. The article highlighted the importance of dimensionality reduction techniques in achieving better classification accuracy. In conclusion, the article provided insights into factors that contributed to suicidal behavior and suggested strategies to address and prevent suicide.

Keywords Suicide · Typical testors · Prediction

1 Introduction

In Aguascalientes the suicide rate is very high. Since 2012, more than 100 suicides per year have been recorded, and this situation is increasing over the years [1]. In 2021, a historical value of 184 suicides was obtained. On the other hand, for every completed suicide there are at least 10 suicide attempts [2].

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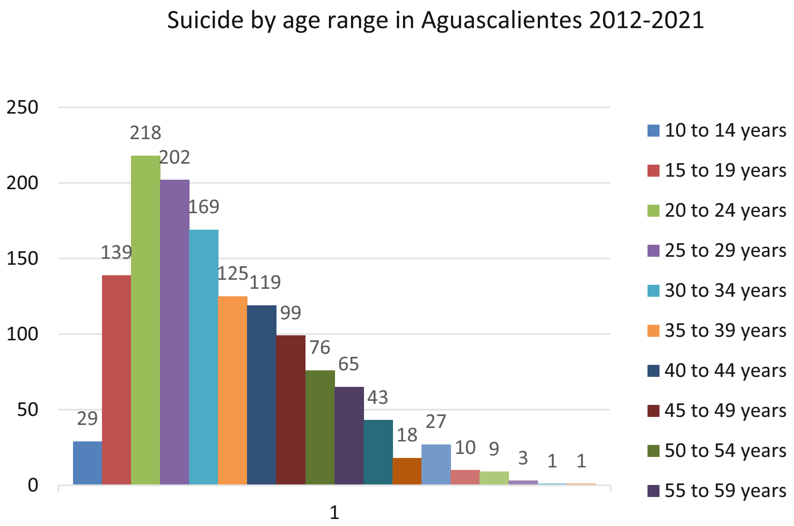

Fig. 1 Suicide by age range [1]

Among the most serious consequences is the social impact, especially related to the economy, since a large number of suicides are carrying out some work activity, and are at a highly productive age [1]. As can be seen in Fig. 1, the ages of the suicides are concentrated especially in the range of 20 and 24 years, with cases decreasing as age increases. This may be since young people are in a phase of high vulnerability, since they experience important changes in their lives and are subject to great emotional changes during this period.

To deal with this problem, different prevention campaigns have been carried out in the state, with the aim of informing and providing tools to the population to avoid suicide. Various suicide prevention programs have also been implemented, such as the Comprehensive Care Program for People at Risk of Suicide, which seeks to provide counseling, therapy, and assistance to people who are at risk of suicide. Another initiative is the Support Program for Suicide Prevention, which offers talks, workshops, and training to students of basic and upper secondary education, in order to guide and prevent suicide cases in Aguascalientes.

On the other hand, as can be seen in Fig. 2, only 29.31% of the people who commit suicide are not working, thus causing a great problem by destabilizing the state's economy, and the health of the companies since 70.69% of suicide people are engaged in some economic activity.

That is why prevention measures are necessary to combat this problem, among which are: the creation of prevention programs in the workplace, where issues such as mental health, work stress, self-care, respect labor, among others; the development of awareness campaigns in work environments to ensure that the working population is aware of the available resources and the importance of suicide prevention; and support for employees in crisis situations, attending to their individual needs and providing professional advice.

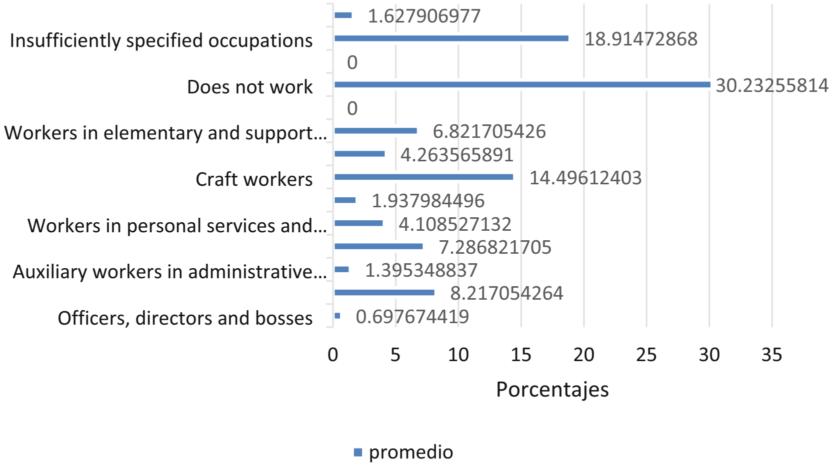

Fig. 2 Average suicides in Aguascalientes 2012–2021 [1]

1.1 Suicide

Suicide, as its definition indicates, is the act by which a person voluntarily puts an end to his own existence [3]. In other words, this person presents the loss of neuroencephalic or cardiorespiratory constants in a definitive and irreversible way [2].

In this study, the characteristics associated with stress and the sociocultural environment experienced by the people surveyed are grouped together, characteristics that, according to Barajas [4], are framed within the factors that lead people to commit suicide.

These stress-associated characteristics include negative mood states, such as sadness, frustration, anxiety, and depression [1]. These states of mind can lead to feelings of despair, which in turn lead to the search for a way out of this situation, which can be suicide. Regarding the sociocultural environment, the lack of social support and the feeling of loneliness are two factors that increase the probability that a person decides to take their own life [1].

In this sense, people who feel isolated and without a support network may feel that suicide is the only way to get out of their situation. In conclusion, stress and the sociocultural environment are important factors that contribute to suicide. This is because these situations can lead to negative moods such as sadness, frustration, anxiety and depression, as well as a lack of social support and a feeling of loneliness. Therefore, it is important to recognize these factors in order to prevent suicide.

1.2 Pattern Recognition

Pattern recognition is a scientific discipline that seeks to classify objects into several categories or classes. The objects can be: images, signals, sounds, or any type of measurement required. Since the 1960s, this discipline has developed thanks to the advancement of technology, ceasing to be just a theoretical part of statistics [5].

The main applications of pattern recognition are: machine vision, character recognition, computer-aided diagnosis, and voice recognition. Testor theory was formulated as one of the independent scientific directions of mathematical cybernetics in the mid-1950s in the former Union of Soviet Socialist Republics (USSR) [3]. A testor is a set of characteristics capable of distinguishing between classes, because no object of a certain class can be confused with one of another class [4].

The testors have been applied in various fields, for example: in medicine it was used to determine factors associated with acute lung injuries related to blood transfusions (TRALI); where they were applied by means of a hybrid evolutionary algorithm [6].

They have also been applied in astronomy for the estimation of stellar parameters [7], as well as in computational sciences, where they have been used to reduce the dimensions of neural network models [8]. Testors are a very useful tool, however, their calculation is a lengthy process that grows exponentially with each of the variables in the matrix to be processed [9].

1.3 Neural Networks

Neural networks are a way of emulating human thinking abilities, such as the ability to memorize and associate facts. They are an artificial and simplified model of the human brain, capable of acquiring knowledge through experience [10].

Neural networks are characterized using neuroscience-based algorithm architecture, allowing computers to emulate the learning and thought processes that occur in our brains. This is achieved using a “neuron”, the basic unit of the neural network, which collects the information and connects with another neuron to pass the information on. The connections between neurons can be modified according to the information that is received, and the information can be stored in these connections.

This allows the neural network to “learn” over time. Neural networks consist of processing units that exchange data or information. They are used to recognize patterns, including images, handwriting, and time sequences (for example, financial trends).

2 Methodology

For the realization of this article, a methodology that combines obtaining typical testors and a neural network classifier was followed (Fig. 3).

The methodology employed in the article started with the selection of relevant data for the study. The data comprised socioeconomic, demographic, geographic, and health-related variables related to access to medical care. Then utilized a machine learning technique to develop a neural network classifier capable of predicting access to healthcare. This classifier was trained on a set of training data and evaluated on a set of test data.

The precision of the classifier was measured and tested to ensure the reliability of the results. Subsequently, statistical analyses were conducted to identify the most relevant variables that could predict access to medical care. The authors used typical testers as a feature reduction mechanism to reduce the number of attributes that needed to be processed. This helped in creating a better classifier and achieving better classification accuracy.

Then used a neural network-based classifier with an input layer containing neurons equal to the number of variables. In the second layer, this value was doubled, and in the third layer, the neurons were reduced to equal the total number of variables. Finally, the output layer used a sigmoid activation function to achieve optimal classification of the data.

A reliability score of 0.7254, indicating that 72.54% of the cases were correctly classified. The most relevant variables in predicting access to medical care were found to be job loss, retirement, pregnancy, and the death of a close friend.

In conclusion, the methodology employed in the article combined typical testers and a neural network classifier to predict access to healthcare and identify the most relevant variables that influenced suicidal behavior at work. The use of typical testers helped in reducing the number of features, and the neural network classifier achieved a good classification of the data.

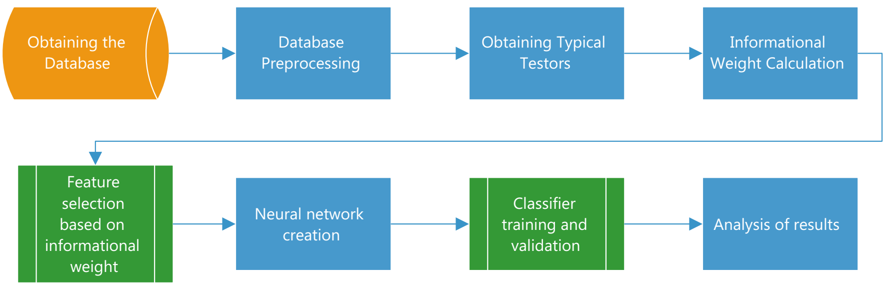

Fig. 3 Methodology

3 Results

As a result of the calculation of the typical testors, a total of 45,125 testors was obtained. Then the informational weight was obtained, resulting in nine characteristics with an informational weight greater than 40%, which can be seen in Table 1.

A neural network-based classifier was created and fed with the set of features with an informative weight greater than 40%. In the neural network, the number of variables was taken as an input layer, creating a neuron for each variable. Subsequently, in the second layer, this value was doubled, and in the third, the neurons were reduced, equaling this number to the total number of variables. To finally use an output layer with a sigmoid activation. This achieves a good classification of the data.

A reliability of 0.7254 was obtained, obtaining the following confusion matrix (Fig. 4):

The precision of the classifier was 0.7254, which means that 72.54% of the cases were classified correctly. In addition, the statistical analysis of the results showed that the most relevant variables in predicting access to medical care were: lose job, retirement, pregnancy and death of a close friend.

Table 1 Informational weight

Informational weight	Feature
94.9394939	Lose job
94.6094609	Retirement
83.2783278	Pregnancy
49.8349835	Death of a close friend
50.7150715	Change employment
74.3674367	Discussions with the couple
44.8844884	Ask for a mortgage
74.0374037	Change of responsibilities at work
41.8041804	Son leaves home
47.5247525	Trouble with the law
44.0044004	Outstanding personal achievements
46.0946095	The couple starts or stops working
55.5555556	The school year begins or ends
44.4444444	Change of address
52.5852585	Change in form or frequency of amusements

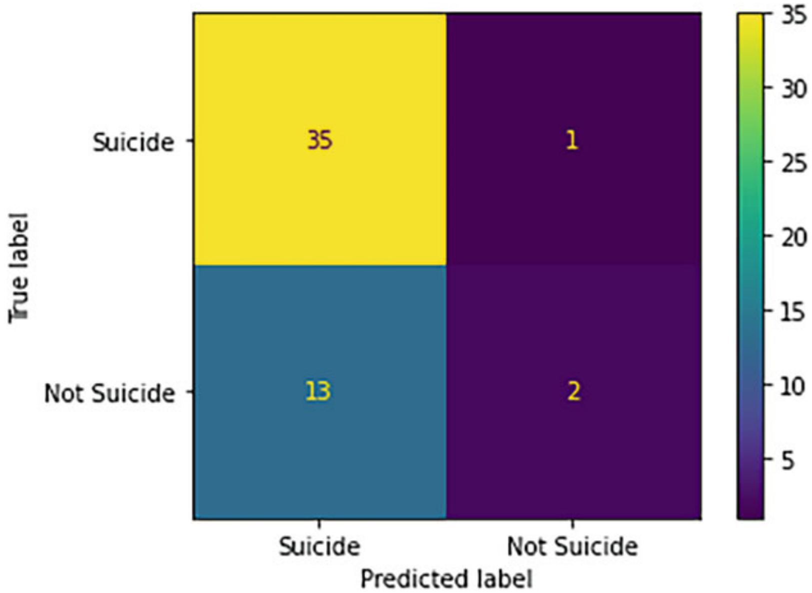

Fig. 4 Confusion matrix

4 Conclusion

At work, the main features that influence the decision to commit suicide are those related to activities that cause work stress, such as job loss, retirement and change of responsibilities, as well as those that have to do with economic aspects such as requesting a mortgage, and those related to the family such as when a child leaves home.

The use of typical testors as a feature reduction mechanism is particularly useful, especially when creating classifiers. With the configuration of doubling the number of neurons of the initial layer, a very favorable result was obtained.

Furthermore, the results highlight the importance of applying dimensionality reduction techniques. This is because, in a reduced number of attributes, better results are obtained in terms of classification precision. On the other hand, it also shows that machine learning algorithms can be useful to identify behavior patterns in the data of people who have attempted suicide.

This allows a better understanding of the factors that are involved in making this decision and allows the creation of strategies to address the problem and prevent and treat suicide. Finally, the use of data mining and machine learning tools is recommended to analyze the data of people who have attempted suicide. This will make it possible to identify patterns of behavior to prevent suicide and offer help to those people who are at risk.

References

1. Instituto Nacional de Estadística y Geografía (2022) Estadísticas Vitales Defunciones generales
2. Campos N (2016) Diplomado en el Protocolo de Actuación (PROL-SMDIFAGS-SUIC/2016)
3. Dmitriev AN, Zhuravlev YI, Krendeleiev FP (1966) On mathematical principles of object and phenomena classification, Discrete Analysis. 3–15
4. Shulcloper JR, Guzmán A, Martínez JF (1999) Enfoque Lógico Combinatorio al Reconocimiento de Patrones. Instituto Politécnico Nacional, Mexico
5. Prandi D, Gauthier JP (2018) Pattern Recognition. In: SpringerBriefs in Mathematics
6. Torres MD, Torres A, Cuellar F, et al (2014) Evolutionary computation in the identification of risk factors. Case of TRALI
7. Santos JÁ, Carrasco A, Martínez JF (2004) Selección de Características usando Testores Típicos aplicada a la Estimación de Parámetros Estelares. Comput y Sist 8:15–23
8. Vázquez RA, Godoy-Calderón S (2007) Using testor theory to reduce the dimension of neural network models. Spec Issue Neural Networks Assoc Memories 28:93–103
9. Alganza YS, Porrata AP (2003) Lex: Un nuevo algoritmo para el calculo de los testores tipicos. Ciencias Mat 21:
10. Matich DJ (2001) Redes Neuronales: Conceptos Básicos y Aplicaciones. Historia Santiago 55

Method for Improving the Control of Suppliers Aiming at Operational Excellence

José Cristiano Pereira and Carlos Alberto de Carvalho Junior

Abstract Perfect control over the quality of suppliers is essential for any organization that seeks operational excellence, since failures in it can cause problems in product quality, delays in production, financial loss, and disrepute in the market. Many companies have problems with quality because they have not created or followed a model that allows them effective control of information about their key suppliers. When companies do not adequately control their suppliers, the number of nonconformities increases and the number of customer complaints also increase, impacting the company's revenue. This fact was observed in a company in the aviation sector dealing with high technology and a broad base of suppliers. This study aims to present a method to optimize suppliers' control process to help quality managers in the aviation field. It adopted the construction theory approach from case study research. The authors combined data from an in-depth literature review about supplier control, archives, interviews, and observations in the studied company. The results show the importance of the relationship between the company, supplier and complement the previous studies on supplier control. The contribution is significant since the proposed method allows process optimization and can be used by companies of all sizes. Although conducted in a specific company, it can be generalized to other industries whose quality is affected by a lack of effective supplier control, which may result in waste, rework, and unnecessary resource consumption. The study can change the practice and thoughts of professionals dealing with supplier control in companies' operations.

Keywords Supplier control · Quality excellence · Organizational sustainability

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1 Introduction

Amid the evolution of companies and the diversification of the same item or service, a company that aims to remain alive and robust within an increasingly competitive market must value the quality of the product/service that will reach the customer, instigating the loyalty of that customer and potential customers. Quality is nothing more and nothing less than meeting the needs of the moment or routine in the activity in which the customer will use the item. However, quality is intertwined with several characteristics particular to each customer, and it can often be linked to price, brand size, resistance, and aesthetics. One of the tasks of companies is to seek to meet customers' needs and ensure that their product/service has the quality and that the supply of materials and inputs is from suppliers that value quality, deadlines, and characteristics established in the contract.

One way to seek control over what is received as a supply is by implementing a supplier control that meets the company's needs for producing a product or employing a service. This will allow the company and its managers to have greater security in the development of your product and be prepared to act when necessary. Such control will also affect the financial life of a company. Consequently, delays or non-compliant materials can force managers to make hasty decisions, possibly increasing the cost of the product and decreasing the profit margin and quality of the product or service to the customer, which in some cases can directly affect the company's morale in the market.

The quality standards establish that the company's managers must analyze, in an organized way, the most significant possible number of suppliers able to meet the expected requirements of the company according to the needs and forecasts of demand and going through the stages of initial assessment, performance monitoring, and reassessment.

A specific company identified an opportunity to improve the supplier control process, to reduce the number of non-conformities. Given this context, a study was conducted in this company, aiming to improve the method of controlling suppliers and consequently reduce costs and improve quality. This work proposes an optimized method to control suppliers to reduce the number of non-conformities.

The study responds to two research questions.

Research Question 1: What factors to consider when choosing the ideal method to control suppliers to cause the least possible impact on the quality of the product/service?

Research Question 2: How to operationalize the model in a company?

The study is structured as follows: Section 1 presents the introduction. Section 2 presents a literature review on topics related to supplier control, quality excellence, and organizational sustainability. Section 3 presents the methodology and steps taken to deepen the research and development of the proposed method. In Sect. 4, the results are presented. In Sect. 5, results are discussed. Section 6 presents the conclusion. In the end, future studies on the subject will be suggested.

2 Supplier Control

Meirelles [1] observed that the purchasing sector was identified from the point of view of managers as an essential area for companies. It is linked to important issues that impact the final quality of products and services, in addition to being responsible for 50% of an organization's expenses. According to the managers, the supplier management process contributed to increasing the transparency of the purchasing sector, thereby reducing the compliance risk in the sector. It was reported that after this implementation, company X and the other 3 obtained a reduction in failures and the negative impact of processes and products, thus becoming a competitive potential. The study was applied in 3 companies from different branches, which allows validation that the practice can be implemented in organizations from different branches that seek control over their supply. It also demonstrates the view of the managers consulted in the study. The purchasing sector tends to affect the final quality of the product or service to be offered, in addition to being responsible for half of the expenses incurred by organizations. The study by Gallear [2] aimed to examine the influence caused by current supplier selection and evaluation routines and the managerial attitude towards relational and performance risks to form buyer-supplier partnerships in the future based on the theory of relational and evolutionary economics. The analysis was carried out on top of 156 questionnaires from senior executives and supply/logistics managers of companies in the United Kingdom. This made it possible to understand that controlling suppliers is essential not only for evaluating suppliers and their performance. It can also be used to create partnerships that may be important for the evolution and development of the company and also understand the risks that the partnership may bring in the future.

3 Excellence in Quality

A study by Martin et al. [3] aimed to introduce competency-based terminology and describe the general competencies of quality management work in organizations, creating a framework of competencies that allows understanding of what is necessary for a quality manager to perform his function. A survey was carried out where 33 professionals in the area of quality management were selected. A framework of quality management competencies is presented, incorporating four main dimensions: the human dimension, the methods and processes, the conceptual dimension, and the contextual competence dimension. The conclusion is that it is essential to focus on the four dimensions and even obtain the dimension of contextual competence, which should be added to the initial conceptual structure. The study also identifies four generic quality management responsibilities derived from the analysis: centralized and strategic, centralized and operational, and strategic location. The studies used for the theoretical basis on excellence in quality demonstrated some necessary measures to be taken in the search for excellence in quality, such as changing the employees' thinking and breaking paradigms that allowed managers to have a new vision of the organization. The data generated with these tools are related to the method for quality control of suppliers in this study, as they can be stored in a database that will make it possible to evaluate and reassess suppliers, in addition to protecting companies with information obtained by their Providers.

4 Supplier Control and Organizational Sustainability

For Saeed and Kersten [4], with the external pressures and demands made by customers nowadays, the demand to incorporate sustainable issues (environmental and social causes) in supply chain management has become ever more significant. According to Lima et al. [5], with the increasing development and evolution of Industry 4.0 technology in the global scenario, environmental and sustainability issues have already become indispensable in the race for organizational competitiveness. The study by Claro et al. [6] says that the sustainable development of an organization must meet the needs obtained in the present without compromising the future, having a vision on analysis of the interests of future generations. The study conducted by Pereira [7] dealt with management technologies and organizational sustainability in small and medium-sized enterprises. It aimed at analyzing the management technologies and the dimensions and components of technological capability as factors of organizational sustainability in small and medium-sized enterprises. At first, a consultation was made with the recent literature to create a theoretical knowledge base on the subject. Subsequently, a deductive method was used to build systemic concepts and hypotheses. The data was collected from 170 municipalities with informal industrial and industrial service provisions. It was observed that supplying small and medium-sized companies with technological tools for management proved to be a constant challenge, however relevant for organizational sustainability and sustainable economic development. There were significant advances in the rate of entrepreneurs in the initial stage of the period compared to the other countries. Pagliuso's [8] study dealt with the relationship between management reference models, sustainability, and organizational culture. Its objective is to investigate whether the hypothesis of adopting management reference models focused on sustainability contributes in any way so that organizations internalize them as an organizational assumption. The research took into account multiple case studies. To capture the data, three organizations from the industrial sector with relevance in their activity areas and a history of implementing management reference models and publishing sustainability reports participated. The research was conducted on management reference models, sustainability, and organizational culture and their intersections. The research was carried out by fieldwork with interviews with leaders and rounds of conversations with people without leadership positions, and analyses of specific documentation of each organization and their published reports.

A study conducted in Qatar by Nawaz and Koç [9] aimed to explore the most sustainable organizations' organizational sustainability issues, functional areas, and best practices. With the results obtained in the study, a framework is proposed that enables theoretical support. The functional areas of 'operational and business excellence' reflect sustainability in modern business operations. While some of these functional areas apply to any business, regardless of whether it is sustainable, organizational activities in these functions significantly impact the economic development potential of the firm, which is often neglected in conventional sustainability management models. By performing well in these areas, most companies can achieve the organization's primary goal, profit. However, how organizations obtain this profit is critical because it makes them different and unique from other organizations, being more conscious and responsible in their actions. Other benefits that can be obtained with the practice are minimizing operational errors, increased business opportunities, and greater customer satisfaction.

The studies demonstrated the importance of sustainability in an organization, showing that it is indispensable that companies that seek excellence in the market should give due attention to the subject. Such achievements allow the company to be well-seen in front of others, thus creating new business opportunities and customer satisfaction. This information is interconnected to the proposal of a new method for supplier quality control because the way companies deal with this subject tends to affect the company's financial and moral results in the market, which, consequently, may cause customer dissatisfaction. Thus, searching and storing constant information is essential for any organization that seeks success in its market.

Lou et al. [10] studied supplier selection into the framework of interorganizational control systems. They investigated the impact of different combinations of supplier selection. Ghadimi et al. [11] proposed a Multi-Agent Systems (MASs) approach for addressing sustainable supplier evaluation and selection process to provide a proper communication channel, structured information exchange and visibility among suppliers and manufacturers. Zhou and Li [12] study demosntrated that the supply chain information sharing has noteworthy positive impact on quality management practices and supplier specific investment; and that quality management practices and supplier specific investment have significant positive impact on both market share performance and innovation performance. Duque-Uribe et al. [13] presented a systematic literature review and a framework for identifying the supply chain management practices that may contribute to sustainable performance in hospitals. Abdel-Baset et al. [14] studied a proactive approach called green supply chain management(GSCM) They used a robust ranking technique with neutrosophic set to handle practices and performances in GSCM. Danese et al. [15] investigated how well-defined configurations of monitoring and collaboration can be characterised in terms of drivers and enablers. The authors identified what drivers and enablers are important and distinctive for the different configurations of supplier sustainability practices.

5 Methodology

The study adopted the approach of building theory from Case Study Research as proposed by Eisenhardt and Hancock et al. [16, 17] and was carried out in an aircraft component overhaul company. It is classified as applied research, dedicated to generating knowledge to solve specific problems and directed to practical application in a particular situation. The research is qualitative, based on the interpretation of the collected data and the observation of the studied organization, considering the context in which they are inserted. As for the objective, it is classified as exploratory research, providing greater familiarity with the problem object of the research and a greater understanding of the research questions. For this purpose, the procedure adopted is the qualitative case study to understand the factors considered by the manager of an organization, taking into account the context in which it is inserted.

5.1 *Selecting the Population and Sample*

The study adopted the construct theory approach from case study research. It combined data from files, interviews, and observations conducted in the quality area of the company where the case study was conducted. The sample for the study was the supplier control process. The number of stakeholders participating in the study is listed in Table 1. These stakeholders were selected based on their expertise in a specific domain.

5.2 *Instruments and Tools Used*

The authors interviewed the stakeholders to prepare a mind map of the supplier control process at the time of the study. Based on the current process mind map and on the literature search, a new mind map with new elements to optimize the process was prepared.

Table 1 Stakeholders participating in the study

Area	Function	Number of participants	Experience in years
Quality	Quality engineer	1	35
Quality	Quality specialist	1	5
Purchase	Purchaser	1	10
Quality	Quality specialist	1	2
Quality	Quality intern	1	2

5.3 Data Collection

The following are the steps used to collect the data needed to optimize the model used in the company: 1. Analysis of the theoretical framework and updated literature, using the keywords: Supplier Control, Quality Excellence and Operational Sustainability. 2. Search for data and information about the method used by the company for supplier control. 3. Based on the literature review and analysis of the model used, define the needed improvements. 4. Preparation of Survey for validation of the data proposed in the new method.

5.4 Data Analysis and Actions

The initial mind map was prepared with the help of the process stakeholders. A review of the supplier control literature and the procedure in use at the company made it possible to optimize the existing process and prepare the modified mind map. The study was carried out in a company in the aviation sector. Information was captured on the methods used by the company to control the quality of its suppliers, and through these data, a mind mapping of the method used by the company was created. Then, the second stage began: a search for information in the literature about the methods currently used in companies. Then some items were selected that have the potential to refine a new supply control model.

6 Results

This chapter presents the method that the studied company used for the quality control of its suppliers and a new updated method that aims at the excellence of the process. Next, a proposal for surveys was presented to validate the new method for controlling suppliers. Figure 1 shows the current process, where the company's quality sector performs an on-site audit, visiting its suppliers' facilities to carry out audits that allow generating data from the supplier, data that will allow analyzing whether the supplier complies with the pre-established requirements of the company. The quality sector still seeks information from the supplier through e-mail surveys, asking critical questions about the characteristics and requirements expected by the company and asking the supplier for the appropriate quality certificates. The company's receiving sector receives the product and necessary documents, performs inspections in the sector, creating data for analysis based on performance metrics. For the analysis of performance metrics, product quality, documents sent, and delivery time are evaluated. Finally, all data from audit reports, quality certificates, surveys, and performance metrics are stored in a database, which allows the reassessment of the supplier and the protection of essential information for the company.

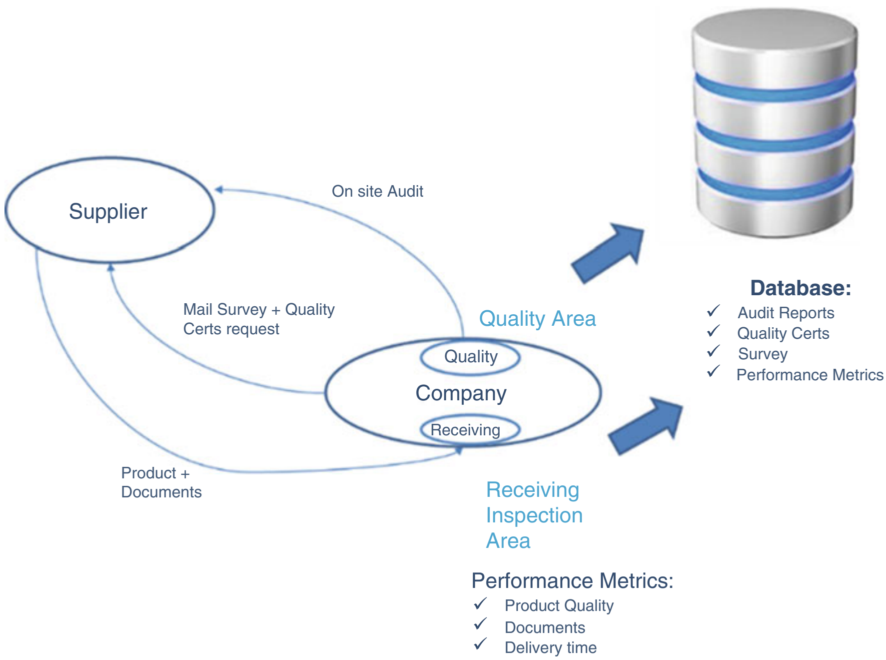

Fig. 1 Current process mind map

Figure 2 shows the optimized model. The proposed method can be validated through a survey conducted by professionals who have had contact with the area. In this new method, the quality sector performs the on-site audit and seeks to obtain information on the supplier's financial reports. Visits to the supplier's facilities occur not only for the audit but also to understand the organization's functioning better; performance meetings are held, discussions with other clients, research in the industry's database, evaluation of samples, surveys and request of certifications. The receiving sector, on the other hand, is responsible for carrying out inspections of the material received and, on top of that, performs a performance analysis, attesting to the quality of the product, verifying the necessary documents and that the material was delivered in the form and deadline established. Finally, audit reports, quality certificates, survey results, used performance metrics, financial reports, performance meetings, discussion reports with other clients, and research reports in the industry database are stored in the database.

To validate and customize the model, a company can use a survey to be answered by professionals responsible for the quality and receiving areas. Key questions to be answered are listed in Table 2.

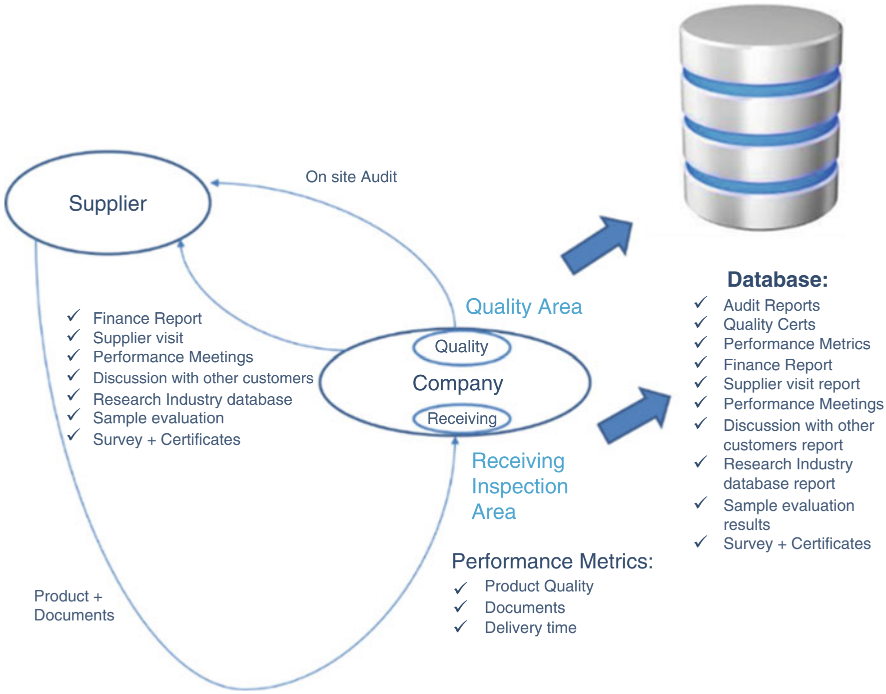

Fig. 2 Optimized model mind map

Table 2 Survey questions

Factors	Questions
VISITING A SUPPLIER	What is the importance of visiting a supplier?
QUALITY AUDITS	How important is it to carry out quality audits at supplier's facilities?
SURVEYS	How important is it to conduct surveys by mail from the supplier?
SUPPLIER CERTIFICATIONS	How important is it to ask for supplier certifications?
DISCUSSIONS WITH OTHER VENDORS	How important is it to hold discussions with other vendors?
INDUSTRY DATABASE SEARCHES	How important is it to conduct industry database searches on the supplier?
SAMPLE ANALYSIS	How important is it to carry out sample analysis from the supplier?
SUPPLIER'S PERFORMANCE METRICS	How important is it to evaluate a supplier's performance metrics?
SUPPLIERS' FINANCIAL REPORTS	How important is it to analyze suppliers' financial reports?

7 Discussion of Results

The results show the importance of the relationship between the company and the supplier and complement the previous studies on supplier control. It is essential to obtain as much information exchange as possible, and the company must always store each piece of data obtained in order to evaluate if the relationship between the two parties is generating the expected results. It is of great importance that the company seeks certified and qualified suppliers to deliver what is expected, not forgetting to observe if the supplier gives importance to areas such as excellence in quality and organizational sustainability. On organizational sustainability, environmental and social causes are also areas that affect the business. Considering that customers tend to feel uncomfortable with some situations in which the company or the supplier may be involved, it affects the company's image and morale in the market, so it is essential to analyze the compatibility between the company's values and the supplier. It is of great importance that a company seeking operational excellence in its process of quality control of suppliers has a method or model to be followed so that the organization as a whole can have an alignment of thoughts so that the process has excellence. Besides having a method, this method must be updated with refined information that must later be stored in a database so that the company always has information in its possession that enables it to control the quality of its supply.

8 Conclusion

As mentioned in the introduction, supplier control is essential in every company that has a production process since failures or problems at this stage can cause serious problems for the logistics and production sector. Delays in supply, or the sending of materials that are not in accordance or outside the required quantity or validity, subsequently affect the entire logistics process and production planning and may cause, in some cases, irritation to customers, breach of contracts, and discredit the company's moral in the market.

This study was conducted in a company in the aviation sector. An analysis of the current literature was conducted to help in the search for improvements and refinement of the supplier control process. In response to the questions presented in the introduction, "*What factors to consider when choosing the ideal method to control suppliers to cause the least possible impact on product/service quality?*" *and* "*How to operationalize the model in a company?*" Knowing what is sought and understanding the organization's needs are very important. With this, the organization's managers involved in the supply process must define the factors to be considered in controlling suppliers. Everyone involved must know the challenge to be met and follow the planned guidelines so that the organization can seek operational excellence. As factors to consider the choice of the ideal method, managers must obtain as much information as possible and the conviction of the expected characteristics of their supply. To this end, the quality, receiving, and purchasing sectors must be integrated to exchange knowledge and create metrics and parameters to be followed. The managers should also seek to know if the professionals in the organization's sectors can perform operations such as inspection of the material received, on-site audits, and search for information from the supplier. Such achievements will allow managers to adapt the method presented in this study according to their organization's needs, enabling the search for excellence in the supplier quality control process. The company's characteristics and needs must be defined for the operationalization of the model in a company. The managers must integrate the involved sectors, such as quality, which will seek information from the supplier by performing on-site audits, mail surveys, and searching for supplier quality certifications. The receiving sector must perform sample inspection according to the established metrics, such as product quality, documentation, and delivery time. All the information collected must have a secure database for storage because it will allow the company to control the process and the information exchanged with the supplier, which will enable the reevaluation of suppliers and contracts, in addition to protecting the company from possible future problems in the relationship with the supplier. As a contribution, the study presents a method to be used by companies of all sizes, whether or not they have a pre-defined method defined for their supplier control. It can be used or adapted based on their needs in search of operational excellence. Managers can better understand how and what is needed to properly operationalize the organization's routine. Moreover, in cases of adaptations, a way to validate the data and improvements added to the method was presented. It allows seeking information in the field with professionals who have or have had experience with supply.

As a suggestion for future studies, the field application of the new method of supplier control is recommended. It should be adapted to the organization's needs to which the new method will be applied. This will generate data during and after the implementation of the new model, showing the impacts caused by product quality, the emergence of non-conformities, the relationship with the supplier, customer satisfaction, and operation costs.

References

1. Meirelles, Junior, Julio Candido et al. Controladoria estratégica e gestão de fornecedores. Brazilian Journal of Development, v. 7, n. 4, p. 39239–39257, 2021. 2.
2. Gallear, David et al. Relationship between supplier selection and evaluation routines, risk perception and propensity to formbuyer–supplier partnerships. Production Planning & Control, p. 1–17, 2021.
3. Martin, J., Elg, M., Gremyr, I., & Wallo, A. (2021). Towards a quality management competence framework: exploring needed competencies in quality management. Total Quality Management & Business Excellence, 32(3–4), 359–378.

4. Saeed, Muhammad Amad; Kersten, Wolfgang. Drivers of sustainable supply chain management: identification and classification. Sustainability, v. 11, n. 4, p. 1137, 2019.
5. Lima, Fabricio Pacheco; Seleme, Robson; Cleto, Marcelo Gechele. Indústria 4.0 e a Sustentabilidade Organizacional. Revista Livre de Sustentabilidade e Empreendedorismo, v. 7, n. 2, p. 87–101, 2022.
6. De Oliveira Claro, Priscila Borin; Claro, Danny Pimentel; Amâncio, Robson. Entendendo o conceito de sustentabilidade nas organizações. Revista de Administração-RAUSP, v. 43, n. 4, p. 289–300, 2008.
7. Pereira, Ilmar Polary. Tecnologias de gestão e sustentabilidade organizacional em pequenas e médias empresas – pmes. Brazilian Journal of Business, v. 4, n. 1, p. 352–370, 2022.
8. Pagliuso, Antonio Tadeu. As relações entre modelos de referência à gestão, sustentabilidade e cultura organizacional: um estudo de casos múltiplos. 2022. Tese de Doutorado.
9. Nawaz, W., & Koç, M. (2019). Exploring organizational sustainability: Themes, functional areas, and best practices. Sustainability, 11(16), 4307.
10. Lou, Z., Ye, A., Mao, J., & Zhang, C. (2022). Supplier selection, control mechanisms, and firm innovation: Configuration analysis based on fsQCA. Journal of Business Research, 139, 81
11. Ghadimi, P., Wang, C., Lim, M. K., & Heavey, C. (2019). Intelligent sustainable supplier selection using multi-agent technology: Theory and application for Industry 4.0 supply chains. Computers & Industrial Engineering, 127, 588–600.
12. Zhou, H., & Li, L. (2020). The impact of supply chain practices and quality management on firm performance: Evidence from China's small and medium manufacturing enterprises. International Journal of Production Economics, 230, 107816.
13. Duque-Uribe, V., Sarache, W., & Gutiérrez, E. V. (2019). Sustainable supply chain management practices and sustainable performance in hospitals: a systematic review and integrative framework. Sustainability, 11(21), 5949.
14. Abdel-Baset, M., Chang, V., & Gamal, A. (2019). Evaluation of the green supply chain management practices: A novel neutrosophic approach. Computers in Industry, 108(1), 210–220.
15. Danese, P., Lion, A., & Vinelli, A. (2019). Drivers and enablers of supplier sustainability practices: a survey-based analysis. International Journal of Production Research, 57(7), 2034–2056.
16. Eisenhardt, K. M. (1989). Building theories from case study research. Academy of management review, 14(4), 532–550.
17. Hancock, D. R., Algozzine, B., & Lim, J. H. (2021). Doing case study research: A practical guide for beginning researchers.

Research on Potential Usage of Residual Biomass in Marine Ports

António Cardoso, Margarita Robaina, and João Matias

Abstract European ports authorities are being forced to challenge their traditional approach to energy usage and how efficiently they manage energy within the port itself. Until recently, ports authorities did not engage as much with energy trading, generation, or purchase beyond the typical consumption, but now, there is an external pressure for the authorities actively engage with energy management within the ports. Port authorities are starting to actively engage and dictate new sustainable energy policies for the industrial cluster and itself, encouraging the use of renewable energy, solutions for carbon management and raising energy conservation. The objective of this paper is to evidence the role of Maritime Ports in decarbonization, showing, through case studies, the different strategies of European Maritime Ports in adopting "clean" technologies to produce electricity and also to evidence the role of the use of agroforestry biomass and urban solid waste in the decarbonization of European ports. As fossil fuels will become less suitable, whether for financial or environmental reasons, energy-dense fuels will become less in demand and supply, and as such, using energy to vectorize biomass will become a necessity.

Keywords Marine ports · Biomass · Renewable energy · Decarbonization · Energy sustainable technologies · Energy production and storage

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1 Introduction

In seaports are concentrated several activities that consume a lot of energy, as for instance transportation and cargo handling, logistics, industrial clusters, and energy production. Cargo transportation and handling refers to the use of port infrastructure, such as construction, operation and maintenance, cargo handling operations, and loading and unloading activities, which may include government agencies and organizations, military activities, and passenger traffic [26]. In recent decades there has been a need to understand and monitor port activities to find solutions that promote their environmental sustainability and, consequently, improve the management and use of energy sources. However, few port authorities currently actively seek strategies for better energy and environmental management. This management involves planning, coordinating and facilitating the development of economic activities within the port and giving greater weight to its sustainability [18].

The achievement of UN Sustainable Goal 7 (Ensure access to affordable, reliable, sustainable, and modern energy for all) can be supported by improving energy efficiency across the maritime sector (including ports), through the objective of double the global rate of improvement in energy efficiency, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all [9].

For ports, energy efficiency is currently a highly important objective, as it has the dual environmental and energy/economic benefits, through the considerable energy savings. Thus, ports have been involved in projects related to energy saving and the use of renewable energies, namely through the European Organization of Seaports [5]. Since 2016, environmental reports have been prepared by ports, to promote and improve the interaction of European ports and to increase the transparency and responsibility of the port sector concerning environmental issues. In addition, these reports aim to raise awareness of environmental protection, knowledge sharing and cooperation between ports to improve environmental, logistics and energy management. The assessment is based on environmental management and monitoring indicators in priority areas [18].

European ports authorities are being forced to challenge their traditional approach to energy usage and how efficiently they manage energy within the port itself. Until recently, ports authorities did not engage as much with energy trading, generation, or purchase beyond the typical consumption, but now, there is external pressure for the authorities actively engage with energy management within the ports. Starting by monitoring and coordinating energy consumption within the port and industrial cluster allows for plans on optimization for energy consumption to be designed. Port authorities are starting to actively engage and dictate new sustainable energy policies for the industrial cluster and itself, encouraging the use of renewable energy, solutions for carbon management and raising energy conservation [1]. In this context, the objective of this paper is to evidence the role of Maritime Ports in decarbonization, showing, through case studies, the different strategies of European

Maritime Ports in adopting "clean" technologies to produce electricity and to evidence the role of the use of agroforestry biomass and urban solid waste in the decarbonization of European ports.

2 Literature Overview

Energy Consumption Forecasts in Ports and the Role of Energy Efficiency Maritime transport is responsible for about 90% of all the exchange of goods worldwide, which reveals the importance of this sector [9]. At European level, maritime transport is responsible for 75% of the exchange of goods. Maritime transport is increasing, which is directly related to the increase in the world economy and international commercial exchanges between the various countries. However, this growth is higher than the rate of economy, rising issues related to adverse impacts on the environment and human health, caused by atmospheric emissions resulting from the combustion of fuel by ships [8]. Demand for maritime trade is estimated to grow by 39% by 2050. However, energy use per ton-mile is predicted to decrease by 35–40% on average by 2050 on all projected routes, due to the application of energy efficiency measures, improvements in the hull and machinery and speed reduction [4].

The activities that take place within seaports include not only maritime transport within the port, but also other sources that contribute to air pollution, which are strongly associated with the use of fossil fuels [17]. Port activity has other associated emission sources, such as the circulation of light vehicles and trucks. These emissions are regulated by Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007, in the case of light vehicles, and by Regulation (EC) No 595/2009 of the European Parliament and of the Council of 18 June 2009 [19]. Reference should also be made to Directive of the European Parliament and of the Council of 22 October 2014 – on the creation of an infrastructure for alternative fuels [17].

A survey conducted by Wilmsmeier et al. [27] for the Economic Commission for Latin America and the Caribbean (CEPAL) on energy consumption and container terminal efficiency, indicates that a low number of publications exist on this topic and in practice, ports do not fully analyze in detail their energy consumption. The authors also prepared a table (Table 1) highlighting the corresponding machinery and fuel used in each one. Every machine used to process containers has a diesel and an electrical version. The activities were divided between vertical and horizontal handling operations of the containers, buildings within the port, lighting, and reefer (colling or freezing cargo). Only vertical and horizontal handling of the containers utilize diesel as a source of energy, while buildings, lighting and reefer only consume electrical energy. From the terminals studied between 2012 and 2015, 70% of the total energy consumed had diesel as energy source and half of the diesel is consumed in the horizontal operations. Economies of scale play a key role in energy efficiency with terminals that have less than 100,000 container movements per year consuming

Table 1 Energy consumers inside a container terminal with the corresponding fuel source

Energy consumers	Diesel	Petrol	Natural gas	Electricity
Ships-to-shore cranes	x			x
Mobile cranes	x			x
Rail-mounted gantry cranes	x			x
Rubber-tyred gantry cranes	x			x
Reach stackers	x			x
Straddle carriers	x			x
Tracto-trailer units and lorries	x		x	x
Generators	x		x	
Buildings				x
Lighting				x
Reefer containers				x
Other port vehicles	x	x	x	x

Source: Adapted from Wilmsmeier et al. [27]

more than the double of the diesel per container than terminals with more than 500,000 movements. Reefer consumes most of the electrical energy and its efficiency is highly dependent on the infrastructure to transmit energy to the terminals and not from how efficiently the port authorities handle this type of cargo [27].

Sdoukopoulos et al. [24] presented a study on the state of practice of energy efficiency in European marine ports, highlighting measures to improve their efficiency: full or semi-automation and/or eco-driving of the relevant terminal equipment; dynamic lighting system; hybridization, electrification and use of alternative fuels for port vehicles and vessels; green building standards for terminal offices; warehouses that do self-production; use of thermal energy for cooling and heating in passenger terminals; and energy consumption monitoring and recording systems. According to the authors, the measures implemented to improve efficiency may offset the increase in port energy consumption in the coming decades.

2.1 Studies About Renewable Energy Sources in Ports

European marine ports have become private investors in Renewable Energy Sources (RES) as regulations concerning energy policies tightens and as energy prices rise. Combinations of solar and wind energy are a promising investment for marine ports since they use the large area of rooftops and unused space with the strong winds typically present in shore lands. Similar systems exist in the port of Cartagena [6], Aegean [13] and Igoumenitsa [14] with good economic returns and energy production exceeding the energy demand, with the authors proposing to inject the excess energy into the grid. In the port of Alexandria, wind was coupled with hydrogen fuel cells for storing the excess energy production instead of injecting to the electrical grid. This results in a higher financial feasibility since energy can have a big discrepancy between buy and sell prices [21].

In the port of Naples, a comparison was made between two energy production units that utilizes waves. ISWEC, a floating device, performs worse than Rewec3, a system that utilizes reinforced concrete walls, typically already built-in marine ports, and adapts them for energy production. Both systems have technical issues and can cause public outcry for some issues such a water use and environmental aspects [15].

2.2 Energy Transition in Seaports

There are several energy options identified in the transition to more sustainable energy consumption and production in ports. From solar and wind generation technologies (onshore and offshore), through hydrogen, biomass, wave energy and side shore electricity generation, to the development of Smart Grids, Renewable Energy Communities, and the trend towards electrification, European marine ports are starting to be innovative and proactive in this area, both in research and in implementation.

Research on the theoretical implementation of smart grids on marine ports reveals a better energy efficiency than the traditional single entity effort to reduce its carbon footprint. This is possible using tools such as peak shaving, power sharing, energy storage and buy and sell energy to and from the grid depending on prices. Also, a higher energy storage capability correlates to higher costs saving. An individual analysis is needed for each port since the financial value of the smart grids depends on the size and energy usage of the port. Even if the technology is profitable, the port authority should try to convince the neighborhood to get covered from their smart grid since it will help to gather more investment from private stakeholders and investors [10].

Renewable energy cooperatives, organizations of private individuals who collectively invest and own enterprises, can facilitate the energy transition in ports. Hentschel et al. [7] studied this topic in a theoretical exploration of Rotterdam port within an industrial cluster. When cooperatives successfully establish themselves in ports, companies in the industrial campus, with high demand for energy, could benefit from a lower cost of energy and, therefore, they show interest in joining these cooperatives. In addition, port authorities are also interested in joining, as energy saving is always beneficial for any seaport. Cooperatives can help alleviate the investment costs of seaports, allowing for much lower risk when investing in innovative technologies within the port.

An assessment made by Winkel et al. [28] on side shore electricity generation in Europe suggests creating tax exemptions to help them becoming more feasible. European marine ports are being regulated into deploying side shore electricity, and taking ports geographical conditions, it is an obvious strategy for European marine ports. Even so, it is necessary to create a lot of infrastructure, but as these do not have a predictable return, the number of interested investors is exceptionally low and the financial burden will certainly fall on the ports. However, there are some opportunities to implement pilot projects, as government and social support could help alleviate some of the costs.

Electrification is now a prominent trend in shipping, but development needs to be accelerated. Increased fleet electrification will strongly contribute to a more sustainable maritime transport [11]. As a power hub, a port's electricity demand, facilitated by the grid, will vary over time. The electrification of the transportation sector increases the need for demand-side management and energy storage to provide flexibility and peak load reduction. Digitization will be the enabler and opens possibilities for innovative system solutions, intelligent control, and new business models. A port can now develop energy hub capabilities where energy demands and distribution can be coordinated by digital means, providing information on the timing and volumes of energy required [11].

In 2019, 53% of European ports had electricity supply through high voltage Onshore Power Supply (OPS). In 96% of ports equipped with OPS, 16% of electricity is supplied through mobile installations. It is estimated that between 2022, 29% of ports will have OPS systems [18]. Moreira [18] describes solutions adopted by ports, including those related to the lighting system like the installation of LED lighting, allowing the adoption of an intelligent control system so the LED lights can be turned on/off automatically. This measure can be extended to terminal operation systems to limit lighting only to areas where operations are taking place. Another measure is to implement management and control systems that help to rationalize the terminal's logistics, which increases storage capacity and reduces the cost of handling containers by 5%.

European marine ports have started monitoring energy consumption and are now investing to improve energy usage with techniques such as peak power shaving, electrification of port operations, energy recuperation from vertical movements, improving lighting and thermal properties of the port facilities and other more immediate solutions such as RES. Overall, European ports are in different states of development. While sophisticated ports have already implemented solutions for energy efficiency issues, others still have a long way ahead.

3 Residual Biomass Usage in Marine Ports

The use of biomass and waste is proving to be a viable solution for the decarbonization of ports. When comparing the use of coal and biomass for energy production, the use of biomass emits less Greenhouse Gases (GHG), except when there is a high dependence on trucks based on fossil energy for the transport of biomass. Using biomass combined with coal, even in existing coal plants, will help to decarbonize energy use in seaports [2]. European marine port authorities can create integration by making it a clear goal and by extending their influence to facilitate, create and coordinate new flows for the supply chain, by developing a bio-industry cluster and executing value-added activities to the biofuel and by acting as general source of information and knowledge [25].

Research on the supply chain of overseas biomass, waste and residues and its role in decarbonization indicates that it may play a significant role, especially if the port is burning coal for energy production [16]. Ports that are also affected by national and international policies that limit the volume of importing coal would highly benefit from using biomass with coal and progressively replacing it. Current EU policies facilitate and stimulate sea-based biomass supply chains, various mixes of biomass can be sourced but there are still several aspects that slows down the demand and supply of biomass. Lack of knowledge on biomass and its use, failing to correctly assess the carbon footprint when choosing the biomass source, low value and diminished profit, lack of interest by cargo companies and insufficient infrastructure are examples of key challenges that needs to be overcome. Mańkowska et al. [16] mention a dedicated biomass terminal as a solution for solving some challenges. Also, energy suppliers should change the biomass selection criteria considering the environmental impact relative to the port and ports authorities should facilitate biomass supply and mobilization between international and local ports.

Rentizelas et al. [20] performed a techno-economic analysis on biomass torrefaction of palm kernel shells originated from Malaysia in the UK to later be used with coal in a co-firing unit, in which different fuel sources are mixed, usually it refers to using coal and biomass. Although this technique is not a sustainable form of energy production, allows for a decarbonization and lesser fossil fuel demand and usage. It compared the tradeoff between biomass torrefaction before shipping, which is more efficiently to transport, with the lower capital investment needed for the torrefaction facility and power plant modifications. Co-firing coal and biomass was not profitable, with a ratio of 1:1 given the best economic outcome. In contrast, burning with 100% biomass was deem profitable under the current UK support for co-firing.

Sanders et al. [22] described on the development of bio-commodities and the role of European ports in its chain, studying bio-commodities such as biodiesel, pure plant oil, bioethanol, pyrolysis oil, torrefaction pallets, wood pallets, bio syngas, biogas, rapeseed & soybeans, rape cake & soy cake, cereals grains, crude protein or protein hydrolysates or crude minerals. Each type of biomass has a unique pre-treatment process to be made in exporting marine ports and the same for the after-treatment in importing port. For lignocellulose, the pre-treatment would be densification into pyrolysis oil, torrefaction pallets and hydrothermal upgrading biocrude to later be processed into Fisher-Tropsch diesel in importing ports. Seeds and beans are itself a bio-commodity with no pre-treatment required in exporting marine ports and requiring only refinery and conversion at importing ports. Sugar, starch, leaf, algae, and manure require refinery and conversion as a pre-treatment in exporting ports, and the resulting bio-commodities varies between ethanol and proteins. Dehydration, hydrolyzation and hydrothermal upgrading are possible post-treatments in importing ports.

Costs for biomass supply chains via maritime transport are higher for Europe, USA and developing countries due to trade imbalance in the regions, pending ports, lower trade volumes, travel distance and capability as well as shipping connectivity [29]. Infrastructures to effectively manage exporting biomass to achieve better economies of scale and higher power of negotiation are necessary. To decrease the expenses of exporting while preserving the quality of the raw material, effective handling, storage, procedures, and transportation in large volume is required [29].

An assessment on biomass supply chain using Data Envelopment Analysis, by Costa Melo et al. [3], compared 3 scenarios for shipping wood biomass from Brazil to the UK to later be converted into electricity. In one scenario, wood logs were directly shipped, in another, wood logs were converted into pallets, shipped, torrefied, and then converted to electricity, and in the last scenario, wood logs were converted and torrefied and only then were shipped. In both scenarios, both facilities to palletize and torrefied, were not part of the exporting port, and as such, biomass was transported from the source to the facilities, then transported to the port. Economic viability could be higher if the pre-treatment facility of biomass were integrated within the exporting port. Adjacent infrastructure plays a essential role, as transporting biomass by train is simply both more energic and economically feasible than by truck. Biomass palletization is always preferable to transport biomass overseas, while torrefying it may not be as feasibly.

In a study of deep decarbonization pathways for the industrial cluster in the Port of Rotterdam, Samadi et al. [23], presented two proposals for a scenario where European ports reduced more than 90% of GHG emissions since 1990. Two systems were proposed, with Hydrogen either being the product or the source for some of the processes within the systems. In one proposal, no biomass was used, while in the other, biomass was used in a Fischer-Tropsch reactor to produce waxes for a hydrocracker process. Waste was used in cogeneration of steam and electricity. For this scenario, a large, sustainable, and constant feed of biomass was assumed. Since Hydrogen was the both the product and source, water electrolysis was the larger energy consumer. In this scenario, the energy needs of the port and industrial cluster will not be fulfilled and instead, the port will focus on exporting Hydrogen and carbon-based fuels and products. If the goal were not Hydrogen production but instead energy production, using biomass and waste combined with solar and wind energy would be enough energy for the port's operations. In the end, a few challenges were mentioned: the number of changes need to the port infrastructure, need for new products and industrial activities within the port, being able to be couple with other RES, and both the higher investment cost and higher risk for early investors.

4 Proposed Biomass Integration in Marine Ports

Both residual solid waste and/or biomass can be used directly in an energy production unit, usually by combustion, or by processing it into biofuels. The diagrams presented in Fig. 1 describes the energy and mass transfers, in the case A), we directly convert both the residual waste from port operations, companies cluster, ships and the local community and biomass produced in the port or in the local community and/or imported by ships to energy, further improving the sustainability of the port as whole by using the energy produced to sustain the energy demands of the port operations. Using residual waste and biomasses from the local community gives a pathway to convert low value community resources into a higher, universal,

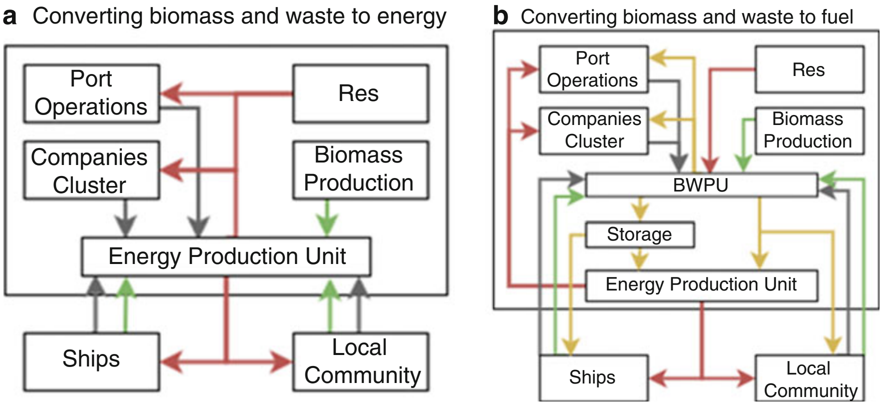

Fig. 1 Diagram of the proposed system. BWPU biomass/waste processing unit. Red: Energy; Green: Biomass; Yellow: Fuel; Grey: Waste

and accessible form of energy (electricity). The energy generated can then be used to maintain port operations, to accommodate the companies cluster energy demand and/or inject and sell energy into the national grid. The allocation of energy should be decided by the port operator based on financial calculations, local preferences, and legislation.

In case B), a more complex diagram emerges by first processing low energy dense fuels to a higher one, making it easy to store. Since biomass/waste processing requires energy, using it from RES or the national grid at a lower rate, usually at night, returns a lower energy production cost and as such, the economic feasibility of the system improves. The fuel produced can then be sold to ships, to the local community or to the business cluster or directly used to produce energy. The fuel can also be stored to be used in an energy peak demand situation. Moreover, storing fuel gives the opportunity to store excess energy from RES, competing with other forms of energy storage. Converting biomass and residual waste into fuel also gives a higher flexibility to the port operators for handling energy demands and productions, but at the cost of lower energy yields and higher investment costs compared to combustion. In addition, processing units are not yet a fully mature technology and higher investment and O&M costs are expected. Nevertheless, a correct management of biofuel and energy can give a higher economical return by adjusting the fraction at each is sold. A proposed system similar to the B) case has been deployed in a case study for the port of Copenhagen-Malmö by Karimpour et al. [12]. Ships waste and biomass were converted into biogas to later be converted into electricity. Overall, the project is a solution for disposing of waste from the shipping industry while simultaneously generating energy for it, constituting a solution for energy based on circular economy. Both systems are compatible with co-firing technique and in case A) co-firing can be achieved by mixing coal and biomass/waste and in case B) by mixing the output fuel with an equivalent fossil fuel, biogas with natural gas and bioliquid with petrol based liquid fuels and charcoal with coal.

5 Conclusions

Marine ports in Europe are changing how to handle energy consumption and carbon footprint because of stringent legislation and regulation towards higher energy efficiency. Ports authorities shifted from being energy consumers to having an active position on how energy is handled between all parties involved in the port eco-system. This is achieved not only by monitoring and categorizing energy flows but also by dictating measures and creating plans to reduce the overall port's carbon footprint. Simpler methods such as electrification, upgraded lighting, investing in renewable energy, and substituting older equipment are becoming insufficient to meet the new imposed goals of energy handling within ports. As fossil fuels become untenable, both financial and in quantity, using energy to vectorize biomass will be an option for replacing current fuels and as a form of maintaining the status quo on how humans handle energy, especially in the transport sector. As such, biomass will become more relevant in highly regulated territories, such as Europe, since they need to reduce fossils dependencies and eventually, as regulations tighten, petrochemicals industries in marine ports will focus on transforming high quantities of cheap transported biomass into high density fuels and its byproducts to later be sold at higher prices for local communities or to export.

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References

1. Acciaro, M., Ghiara, H., & Cusano, I. (2014). Energy management in seaports: A new role for port authorities. Energy Policy, 71, pp. 4–12. https://doi.org/10.1016/j.enpol.2014.04.013
2. Beagle, E. & Belmont, E. (2019). Comparative life cycle assessment of biomass utilization for electricity generation in the European Union and the United States. Energy Policy (Vol. 128, pp. 267–275). https://doi.org/10.1016/j.enpol.2019.01.006
3. Costa Melo, I., Rentizelas, A., Alves Junior, P., Campoli, J. & do Nascimento Rebelatto, D. (2018). An assessment of biomass supply chain: a DEA application. Athens Journal of Sciences, 5 (2). pp. 125-140. https://doi.org/10.30958/ajs.5-2-2
4. DNV GL (2019). Maritime Forecast to 2050 - Energy Transition Outlook 2019. https://sustainableworldports.org/wp-content/uploads/DNV-GL_2019_Maritime-forecast-to-2050-Energy-transition-Outlook-2019-report.pdf
5. ESPO (2019) - ESPO Environmental Report, EcoPortsinSights https://www.espo.be/media/Environmental%20Report-2019%20FINAL.pdf
6. Gutierrez-Romero, J. E., Esteve-Pérez, J., & Zamora, B. (2019). Implementing Onshore Power Supply from renewable energy sources for requirements of ships at berth. Applied Energy, 255, 113883. https://doi.org/10.1016/j.apenergy.2019.113883
7. Hentschel, M., Ketter, W., & Collins, J. (2018). Renewable energy cooperatives: Facilitating the energy transition at the Port of Rotterdam. Energy Policy (Vol. 121, pp. 61–69). Elsevier BV. https://doi.org/10.1016/j.enpol.2018.06.014

8. Hua, J., Wu, Y., Chen, H. (2017). Alternative fuel for sustainable shipping across the Taiwan Strait. Transportation Research Part D 52, 254-276. https://doi.org/10.1016/j.trd.2017.03.01
9. IMO (International Maritime Organization), (2021) in https://www.hellenicshippingnews.com/energy-efficiency-in-ports-to-support-maritime-decarbonization/. Accessed in November 2021.
10. Iris, Ç., & Lam, J. (2021). Optimal energy management and operations planning in seaports with smart grid while harnessing renewable energy under uncertainty. Omega (Vol. 103, p. 102445). https://doi.org/10.1016/j.omega.2021.102445
11. Lind, M., Pettersson, S., Karlsson, J., Steijaert, B., Hermansson, P., Haraldson, S., Axell, M., and Zerem, A. (2020). Sustainable Ports as Energy Hubs. The Maritime Executive. https://www.maritime-executive.com/editorials/sustainable-ports-as-energy-hubs
12. Karimpour, R., Ballini, F. & Ölcer, A. I. (2019). Circular economy approach to facilitate the transition of the port cities into self-sustainable energy ports—a case study in Copenhagen-Malmö Port (CMP). WMU Journal of Maritime Affairs (Vol. 18, Issue 2, pp. 225–247). https://doi.org/10.1007/s13437-019-00170-2
13. Kotrikla, A. M., Lilas, T., & Nikitakos, N. (2017). Abatement of air pollution at an aegean Island port utilizing shore side electricity and renewable energy. Marine Policy (Vol. 75, pp. 238–248). https://doi.org/10.1016/j.marpol.2016.01.026
14. Kotrikla A.M, Nikitakos N., Th. Lilas. (2015). Shore Side Electricity and Renewable Energy Potential at Igoumenitsa Port, European Conference on Shipping, Intermodalism & Ports – ECONSHIP 2015 "Shipping and Ports at Crossroads: Competition, Global Sourcing and Regulatory Challenges", 24-27 June, Chios, Greece.
15. Lazaroiu, C. & Roscia, M. (2017). Sustainable port through sea wave energy converter. 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA). IEEE. https://doi.org/10.1109/icrera.2017.8191103
16. Mańkowska, M., Pluciński, M. & Kotowska, I. (2021). Biomass Sea-Based Supply Chains and the Secondary Ports in the Era of Decarbonization. Energies (Vol. 14, Issue 7, p. 1796). MDPI AG. https://doi.org/10.3390/en14071796
17. Monteiro, A., Lopes, M. Borrego, C., Neves, A., Sorte, S. and Russo, M. (2019). Mitigação de emissões marítimas e portuárias: Linhas orientadoras. UA Editora - Universidade de Aveiro 1ª edição. ISBN: 978-972-789-607-3
18. Moreira, M. (2020). Pré-Avaliação da Produção de Energia Elétrica através de Dispositivos de Extração de Energia das Ondas no Quebramar Norte do Porto de Leixões, Dissertação de Mestrado em Engenharia Civil, Faculdade de Engenharia – Universidade do Porto. https://repositorio-aberto.up.pt/bitstream/10216/130826/2/433302.pdf
19. NABU. (2015). Clean Air in Ports. Berlim, Germany: German Nature and Biodiversity Conservation Union.
20. Rentizelas, Athanasios & Li, Jun. (2016). Techno-economic and carbon emissions analysis of biomass torrefaction downstream in international bioenergy supply chains for co-firing.
21. Sadek, I., & Elgohary, M. (2019). Assessment of renewable energy supply for green ports with a case study. Environmental Science and Pollution Research (Vol. 27, Issue 5, pp. 5547–5558). Springer Science and Business Media LLC. https://doi.org/10.1007/s11356-019-07150-2
22. Sanders, J., Annevelink, B. & van der Hoeven, D. (2009). The development of biocommodities and the role of North West European ports in biomass chains. Biofuels, Bioproducts and Biorefining (Vol. 3, Issue 3, pp. 395–409). Wiley. https://doi.org/10.1002/bbb.146
23. Samadi, S., Schneider, C., & Lechtenböhmer, S. (2018). Deep decarbonisation pathways for the industrial cluster of the Port of Rotterdam. 2018 ECEEE Industrial Summer Study on Industrial Efficiency: Leading the Low-Carbon Transition, Kalkscheune, Berlin, Germany.
24. Sdoukopoulos, E., Boile, M., Tromaras, A., & Anastasiadis, N. (2019). Energy Efficiency in European Ports: State-Of-Practice and Insights on the Way Forward. Sustainability (Vol. 11, Issue 18, p. 4952). MDPI AG. https://doi.org/10.3390/su11184952
25. Stevens, L. & Vis, I. (2015). Port supply chain integration: analyzing biofuel supply chains. Maritime Policy & Management (Vol. 43, Issue 3, pp. 261–279). Informa UK Limited. https://doi.org/10.1080/03088839.2015.1050078

26. Theo Notteboom, Athanasios Pallis and Jean-Paul Rodrigue (2022) Port Economics, Management and Policy, New York: Routledge, 624 pages / 218 illustrations. ISBN 9780367331559
27. Wilmsmeier, G.; Spengler, T. Energy Consumption and Container Terminal Efficiency. (2016). Available online: http://hdl.handle.net/11362/40928. Accessed on 19 November 2021.
28. Winkel, R., Weddige, U., Johnsen, D., Hoen, V., & Papaefthimiou, S. (2016). Shore Side Electricity in Europe: Potential and environmental benefits. Energy Policy, 88, 584–593. https://doi.org/10.1016/j.enpol.2015.07.013
29. Zahraee, S., Rahimpour, S., Shiwakoti, N. & Stasinopoulos, P. (2021). Particle-Gaseous pollutant emissions and cost of global biomass supply chain via maritime transportation: Full-scale synergy model. Applied Energy (Vol. 303, p. 117687). https://doi.org/10.1016/j.apenergy.2021.117687

Optimisation Models for Scheduling Extraordinary University Exams with a Minimum Rest Time Between Consecutive Exams

Ana Esteso, M. M. E. Alemany, Elena Tarín, and Ángel Ortiz

Abstract The scheduling extraordinary exams problem has specific characteristics that make the models for scheduling ordinary exams inapplicable. Some of these characteristics are that exams are only scheduled for subjects requested by students and the impossibility of overlapping exams requested by the same student. This paper proposes an optimisation tool for scheduling extraordinary university exams based on two mixed integer linear programming (MILP) models. The first aims to schedule the most demanded subjects first to leave more correction time for the subjects with more students. It also ensures a minimum rest time between two consecutive exams for all students to improve their academic performance. If all students cannot reach the defined minimum rest time, the model will be unfeasible. In this case, it is possible to decrease the minimum rest time to a lower limit to find a feasible solution. If a feasible solution is not found, a second MILP model is proposed for scheduling exams without considering the requirement for time off between exams but minimising the number of non-compliances with this requirement. These models are applied to the School of Industrial Engineering of the Universitat Politècnica de València (Spain). It is concluded that achieving a schedule that ensures the minimum rest time set by the school for all students is infeasible. Therefore, the second model is solved. The solution shows that the average rest time between two consecutive exams increases considerably compared to the first model, ensuring compliance with the minimum rest time set for 93% of the students.

Keywords Exam Scheduling · Rest Requirement · Extraordinary Exam · Optimisation

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1 Introduction

The exam schedule is a simple problem in small educational institutions, where the most efficient way to perform this process is manually [1]. However, the problem becomes complex when considering large institutions such as universities with many degree programmes, many students enrolled, and limited resources such as classrooms, professors, or exam time slots [2].

There are several exact [3, 4] and heuristic [5, 6] approaches to solving the exam scheduling problem under different constraints (see [1] for a review of models for exam scheduling). Most existing approaches focus on scheduling ordinary exams that take place during or at the end of a subject and are open to all students enrolled in the subject. When scheduling ordinary exams, it is only necessary to ensure no overlap between exams of subjects of the same year and degree.

However, to the best of our knowledge, there are no models for scheduling extraordinary exams, understood as assessment acts that a student can carry out upon formal request after having failed a subject in its ordinary assessment. To attend an extraordinary exam, students must meet several requirements defined by each university. For example, the Universitat Politècnica de València (Spain) establishes "*the possibility of extraordinary assessment acts, outside the general established deadlines, for students who, being enrolled for all the credits required to complete the degree (except for the final project), lack only a maximum of 20 ECTS in the case of Bachelor's degrees and 10.5 ECTS in the case of Master's degrees to complete their studies, and have taken the ordinary exams in the previous call*" [7].

The particularity of the scheduling of extraordinary exams is that, unlike the scheduling of ordinary exams, it is not necessary to schedule exams for all subjects offered by the institution, but only those students have requested. The complexity lies in that students may apply for exams in subjects from different years of their degree. It must be ensured that there is no overlap between two or more exams requested by the same student. In addition, limited time is available to complete the extraordinary exams. Due to these particularities, it is not possible to use the existing models in the literature for the scheduling of ordinary exams in order to schedule extraordinary exams.

To fill this gap in the literature, this paper proposes a Mixed Integer Linear Programming (MILP) model for scheduling extraordinary exams. It considers that it must ensure a minimum rest time between two consecutive exams for each student. As the latter requirement may render the problem unsolvable, an extension to this model is also proposed in which the minimum rest time between two consecutive exams for each student is allowed to be violated, and the number of times this occurs is minimised. The models are validated by applying to the School of Industrial Engineering (ETSII) at the Universitat Politècnica de València (UPV) in Spain.

The rest of the paper is structured as follows. Section 2 describes the problem of scheduling extraordinary exams. Sections 3 and 4 formulate the MILP models for the scheduling of extraordinary exams with a minimum rest time between two consecutive exams and the scheduling of extraordinary exams with the minimisation of the number of times the minimum rest time between two consecutive exams is not met, respectively. Section 5 shows the results obtained with both models and their computational efficiency. Finally, Sect. 6 presents the main conclusions obtained as well as future lines of research.

2 Problem Description

The problem addressed in this paper is the scheduling of extraordinary exams in a university school. This problem consists of defining the time segments on which the extraordinary exams are to be held, ensuring that there is no overlapping of exams for any students. The process of scheduling extraordinary exams begins when the students interested in taking this option formally request the extraordinary exam from the Secretary's Office of the University School to which they belong. The Secretary's Office checks which students meet the requirements to take this type of exam and draws up lists of the subjects that must be scheduled for an extraordinary exam and of the students who request the extraordinary exam for each subject. For this reason, the subjects in which extraordinary exams must be offered vary from year to year. Therefore, it is not possible to reuse schedules as they must be defined each time for the data available for that year. With this information, the extraordinary exams are scheduled considering the following assumptions:

– The number of scheduled exams depends on the subjects that at least one student has formally requested.
– The number of students requesting the extraordinary exam for each subject can differ.
– Students can apply to take exams in a different number of subjects.
– Only one extraordinary exam per requested subject should be scheduled.
– There is a predefined date range in which the scheduling of extraordinary exams is allowed and delimited by the scheduling horizon.
– The scheduling horizon is divided into time segments in which an exam can be scheduled.
– Extraordinary exams of two subjects requested by the same student cannot be scheduled at the same time segment to ensure that all students can take all the exams from their requested subjects.
– Where possible, it should be ensured that there is a minimum rest interval between two extraordinary exams taken by the same student. This requirement tries to improve the academic performance of students.
– The qualifications for exams should be published at a fixed time interval after the end of the predefined date range for scheduling the extraordinary exams. For this reason, assigning earlier dates to subjects with more students is desirable to give teachers more time to correct exams.

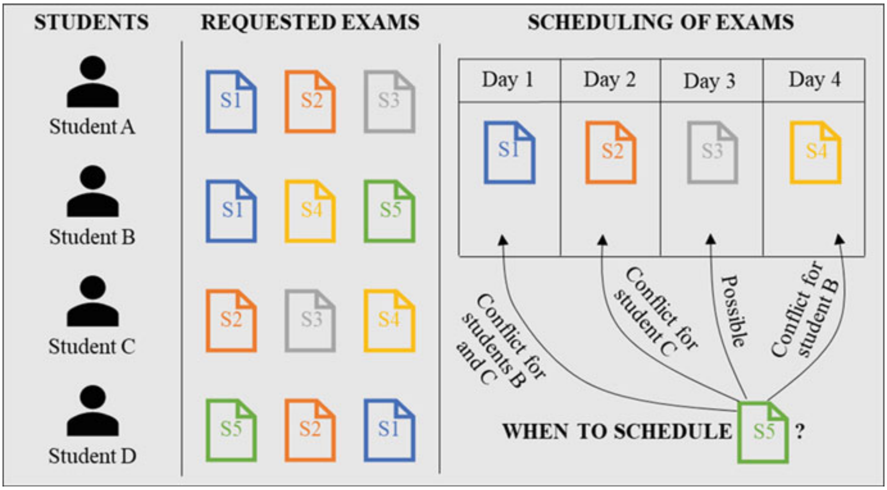

Fig. 1 Example of the problem of scheduling extraordinary exams

An elementary example is shown in Fig. 1 to show the complexity of the problem. Suppose four students apply to take extraordinary exams, and there are only 4 days to schedule them. It is possible to schedule more than one exam per day but only one per day for each student. Student A applies for subjects S1, S2 and S3; student B for subjects S1, S4 and S5; student C for subjects S2, S3 and S4; and student D for subjects S1, S2 and S5. It is possible to schedule the exams of subjects S1, S2, S3 and S4 on the different days that make up the scheduling horizon to avoid conflicts for all students. However, it is only possible to schedule the S5 exam on the same day as the S3 exam, as the other days would create conflicts for at least one student.

Due to the short scheduling horizon and the fact that students apply for exams in different subject combinations, offering a schedule without producing exam overlaps for all students is complex. This complexity substantially grows as the number of students requesting extraordinary exams and of subjects requested increases.

To address this problem, first, it is proposed a MILP model for Extraordinary Exam Scheduling (EES) with Rest Requirement (RR), hereafter referred to as EES-RR-MILP model. However, since the number of extraordinary exams to be included in the scheduling horizon varies according to the number of subjects requested, it may not be possible to ensure a minimum rest interval between exams if the number of subjects is elevated. For this case, a second model is defined that minimises the Non-compliance with the Rest Requirement (NRR), hereafter referred to as EES-NRR-MILP model.

3 EES-RR-MILP Model Formulation

Table 1 shows the nomenclature used to formulate the EES-RR-MILP model.

3.1 Objective Function

The objective Z_1 minimises the result of multiplying the time segment in which an exam is scheduled by the number of students who must take this exam (1). This way, the exams with the most significant number of students will be scheduled first, thus offering more correction time to teachers with more exams. This objective also tends to schedule all exams as early as possible.

$$Min\, Z_1 = \sum_{a=1}^{A} \sum_{p=1}^{P} ns_a * p * Y_{ap} \tag{1}$$

3.2 Constraints

The model is subject to the following constraints. The exam of a subject can only be scheduled in a time segment (2). It ensures that all subjects have an assigned time segment for the exam.

Table 1 EES-RR-MILP Model Nomenclature

Indexes	
p, p'	Time segment ($p = 1, \ldots, P$).
a, a'	Subject ($a = 1, \ldots, A$).
s	Student requesting an extraordinary exam ($s = 1, \ldots, S$).
Set of indexes	
AS_s	Set of subjects for which the student s has requested extraordinary exam
Parameters	
ns_a	Number of students requesting the extraordinary exam of the subject a.
ne	Number of time segments
$dmin$	Minimum rest time segments required between consecutive exams of a student
Decision variables	
Y_{ap}	Binary variable with a value of one if the exam of the subject a is scheduled in time segment p, and zero otherwise.
YS_{sap}	Binary variable with a value of one if the student s takes the subject exam a in time segment p, and zero otherwise.
$Pmax$	Time segment in which the last extraordinary exam is scheduled.

$$\sum_{p=1}^{P} Y_{ap} = 1 \qquad \forall a \tag{2}$$

The latest time segment with a scheduled exam corresponds to the time segment in which the last exam on the horizon is scheduled and must be earlier than or equal to the last segment of the horizon (3).

$$p * Y_{ap} \leq Pmax \leq ne \qquad \forall a, p \tag{3}$$

If a student has applied to take an exam in a subject, they must take it in the time segment scheduled for the subject (4).

$$YS_{sap} = Y_{ap} \qquad \forall s, a \in AS_s, p \tag{4}$$

No more than one exam can be scheduled for each student in the same time segment (5). It ensures that all students can take all requested subjects without overlapping them.

$$\sum_{a \in AS_s} YS_{sap} \leq 1 \qquad \forall s, p \tag{5}$$

A minimum time interval between two consecutive exams requested by the same student must be ensured (6)–(7).

$$\sum_{a \in AS_s} \sum_{p' \geq p}^{p'+dmin} YS_{sap'} \leq 1 \qquad \forall s, p \leq ne - dmin \tag{6}$$

$$\sum_{a \in AS_s} \sum_{p' \geq p}^{P} YS_{sap'} \leq 1 \qquad \forall s, p > ne - dmin \tag{7}$$

Finally, the considered decision variables' nature is defined (8).

$$\begin{array}{cc} Y_{ap}, YS_{sap} & BINARY \\ Pmax & INTEGER \end{array} \tag{8}$$

4 EES-NRR-MILP Model Formulation

The EES-RR-MILP Model can give rise to feasibility problems when it is impossible to guarantee the minimum rest interval between exams for students who have applied for more than one subject since few days are usually dedicated to these exams. Each student may apply for exams in different subjects, and it is also necessary to guarantee that all exams in the same subject occur at the same place and time.

To solve this problem, the EES-NRR-MILP Model is presented as an extension of the EES-RR-MILP Model. In this novel model, the minimum rest time between exams is allowed to be breached, and it is minimised the number of times this requirement is failed. Table 2 presents the complementary nomenclature for the EES-NRR-MILP Model.

4.1 Objective Function

The objective Z_2 minimises the number of times it is not possible to respect the established minimum interval between exams for students (9). This objective aims for maximum student satisfaction and will only be optimised when it is unfeasible to ensure the minimum interval between exams for all students.

$$Min\ \ Z_2 = \sum_{s=1}^{S} \sum_{a \in AS_s} \sum_{a' \in AS_s} \frac{YSA_{saa'}}{2} \tag{9}$$

Table 2 Additional Nomenclature for EES-NRR-MILP Model

Decision variables	
$YSA_{saa'}$	Binary variable with a value of one if the minimum required distance between the exam of subject a and a′ for student s is not met, and zero otherwise.
$T^{+}_{saa'}$	Number of time segments between subject a and subject a′ taken by student s if the exam of subject a′ is scheduled BEFORE the exam of subject a.
$T^{-}_{saa'}$	Number of time segments between subject a and subject a′ taken by student s if the exam of subject a′ is scheduled AFTER the exam of subject a.
$YT^{+}_{saa'}$	Binary variable with a value of one if the exam of subject a′ is scheduled BEFORE the exam of the subject a for student s, and zero otherwise. Variable related to the variable $T^{+}_{saa'}$
$YT^{-}_{saa'}$	Binary variable with a value of one if the exam of subject a′ is scheduled AFTER the exam of the subject a for student s, and zero otherwise. Variable related to the variable $T^{-}_{saa'}$

4.2 Constraints

This model is subject to constraints (2)–(5), (8) and the constraints defined in this section. The constraint (10) calculated the time between two exams required by the same student, so its value is stored in the variable $T^{+}_{saa'}$ when the exam of subject a′ is scheduled before exam a, and it is stored in the variable $T^{-}_{saa'}$ otherwise.

$$\left(\sum_{p=1}^{P} p * YS_{sap} - \sum_{p'=1}^{P} p' * YS_{sa'p'}\right) = T^{+}_{saa'} - T^{-}_{saa'} \quad \forall s,\ a \in AS_s,\ a' \in AS_s \ where\ a' \neq a \tag{10}$$

Therefore, only one of the variables capturing the time between exams can have a positive value. To model this, the binary variables $YT^{+}_{saa'}$ and $YT^{-}_{saa'}$ are used so that when the time between two exams is captured in the variable $T^{+}_{saa'}$, its assigned binary variable $Y^{+}_{saa'}$ will take value one (11)–(12). Variables $T^{-}_{saa'}$ and $YT^{-}_{saa'}$ will have the same relationship between them (13)–(14). Finally, it must be ensured that only one of the binary variables can take value one if the student takes both exams (15).

$$T^{+}_{saa'} \leq ne * YT^{+}_{saa'} \qquad \forall s, a \in AS_s, a' \in AS_s \ where\ a' \neq a \tag{11}$$

$$T^{+}_{saa'} \geq YT^{+}_{saa'} \qquad \forall s, a \in AS_s, a' \in AS_s \ where\ a' \neq a \tag{12}$$

$$T^{-}_{saa'} \leq ne * YT^{-}_{saa'} \qquad \forall s, a \in AS_s, a' \in AS_s \ where\ a' \neq a \tag{13}$$

$$T^{-}_{saa'} \geq YT^{-}_{saa'} \qquad \forall s, a \in AS_s, a' \in AS_s \ where\ a' \neq a \tag{14}$$

$$YT^{+}_{saa'} + YT^{-}_{saa'} \leq 1 \qquad \forall s, a \in AS_s, a' \in AS_s \ where\ a' \neq a \tag{15}$$

The binary variable $YSA_{saa'}$ must take a value of one when the exams of subjects a and a′ are less than the minimum time between exams *dmin* and exams are from different subjects (16)–(17).

$$dmin - T^{+}_{saa'} - T^{-}_{saa'} \leq YSA_{saa'} * ne \qquad \forall s, a \in AS_s, a' \in AS_s \ where\ a' \neq a \tag{16}$$

$$YSA_{saa'} = 0 \qquad \forall s, a \in AS_s, a' = a \tag{17}$$

Finally, the nature of the new variables in this model is defined (17).

$$\begin{array}{ll} YSA_{saa'}, YT^{+}_{saa'}, YT^{-}_{saa'} & BINARY \\ T^{+}_{saa'}, T^{-}_{saa'} & INTEGER \end{array} \tag{18}$$

5 Application of the Models to the ETSII of the UPV

The data corresponding to the May 2022 call for extraordinary exams of the ETSII at the UPV was used to validate the models. A total of 90 students from five degrees applied to take at least one subject by means of extraordinary exams.

Figure 2a shows the number of exams from different subjects requested by students. Students applied for between one and four subjects, with an average of 1.97 subjects per student. Students request exams for 43 subjects.

Figure 2b displays the number of students that have requested each exam. For example, in 18 exams, only one student (who may be different for each subject) will be examined. Similarly, in 11 exams, only two students (who may be different for each exam) will be examined. The number of students requesting exams for each subject ranged from one student to 28 students, with an average of 4.12 students per subject (Fig. 2b). It is worth noting that more than 67% of subjects were requested by one or two students, while more than three students requested the rest.

The exams for these subjects were to be scheduled in ten-time segments (corresponding to 5 days in morning or afternoon shifts). In addition, it is considered that there should be a minimum rest time between two consecutive exams of two-time segments for all students. It means that all students must have two-time segments without exams between one exam and another.

First, the EES-RR-MILP model is applied to this dataset. However, there is no feasible solution when solving the model by ensuring the minimum rest time of two segments between two consecutive exams. Therefore, the model is solved for two other scenarios where the minimum rest time between two consecutive exams varies from zero to one time segments. When the rest time is zero, exams can be scheduled in two consecutive segments but not in the same segment.

Table 3 compares the results of these scenarios. An analysis of the results shows that the allocation of exams to each time segment is similar in both scenarios so that the combinations of subjects scheduled in the same time segment coincide in both scenarios. This paper does not show these scheduling results due to a lack of space.

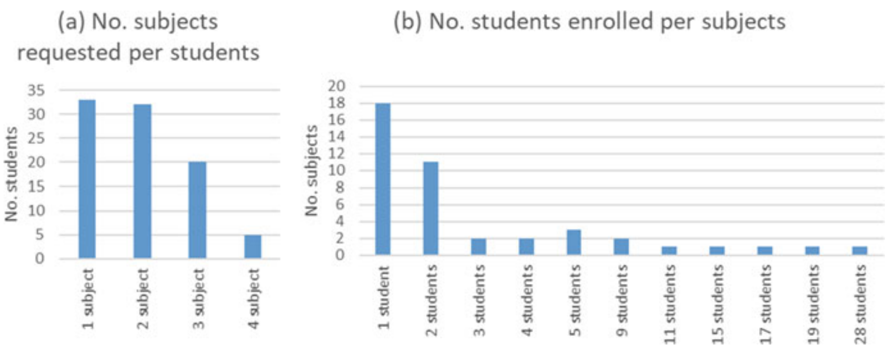

Fig. 2 Data on subjects and students of the ETSII at the UPV

Table 3 Results for EES-RR-MILP Model

Scenario	A	B	C
Minimum rest time between two consecutive exams (dmin)	2	1	0
Feasible?	No	Yes	Yes
Last time segment with a scheduled exam	–	9	5
Number of time segments with scheduled exams	–	5	5
Average number of students per time segment with exams scheduled	–	35.4	35.4
Average number of exams per time segment with exams scheduled	–	8.6	8.6
Average time available for teachers to correct exams (in days)	–	8.2	8.9
Average rest time between two consecutive exams (in time segments)	–	1.4	0.2

Table 4 Frequency of exams for EES-RR-MILP Model

	Time segment									
Scenario	1	2	3	4	5	6	7	8	9	10
B (dmin = 1)	X		X		X		X		X	
C (dmin = 0)	X	X	X	X	X					

The main difference between the schedules obtained for scenarios B and C is that scenario B schedules exams in alternating time segments, while scenario C schedules exams in consecutive time segments (Table 4). It impacts the time teachers have to mark exams, which is slightly higher in scenario C, and the average rest time between exams, which decreases substantially in this scenario.

In addition, as an example, the optimal exam schedule proposed by the model for scenario B is shown in Table 5. This schedule would be the result offered by the model to the decision-maker and could be used by the university institution.

ETSII aims to offer students a schedule of extraordinary exams with at least a minimum rest time of two-time segments between two consecutive exams. As shown in Table 3, it is impossible to offer this minimum rest time to all students since this scenario was unfeasible in the resolution of the EES-RR-MILP model. However, it is intuited from Table 5 that it may be possible to reschedule the exams and offer the two-time-segment rest to some of the students.

To test this, the EES-NRR-MILP model minimises the number of times the students are not guaranteed a rest of two-time segments. Table 6 compares the results of this run with those obtained with the EES-RR-MILP model.

The results show that minimising the number of times the minimum rest time for students is not respected is beneficial for most of the indicators analysed. In this case, a more significant number of time segments would be devoted to taking extraordinary exams. However, the time devoted to taking exams would only be spread over one time segment. In addition, fewer students on average would be examined, and fewer exams would be scheduled on average in each time segment.

Teachers would have, on average, a similar amount of time to mark exams, 7.5 days, as opposed to the 8.2 days offered by the model with the hard constraint of respecting the minimum rest time (EES-RR-MILP). On the other hand, students

Table 5 Optimal Extraordinary Exams Scheduling for EES-RR-MILP Model with dmin = 1

Day	Segment	Subject(s)	Student(s) with a scheduled exam
1	Morning	3, 11, 13, 14, 16, 17, 20, 24, 27, 34, 37, 43	1, 3, 5, 6, 7, 8, 10, 11, 13, 14, 15, 16, 17, 18, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 34, 35, 37, 39, 41, 42, 43, 44, 46, 47, 48, 49, 50, 52, 53, 55, 57, 58, 59, 60, 61, 62, 63, 64, 66, 67, 70, 71, 72, 74, 75, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 88, 90
	Afternoon		
2	Morning	2, 5, 6, 8, 12, 18, 21, 23, 25, 26, 32, 35, 38, 39, 40	1, 3, 4, 5, 6, 8, 9, 11, 12, 14, 15, 17, 19, 20, 21, 24, 25, 26, 30, 32, 34, 35, 36, 40, 42, 43, 46, 47, 48, 49, 52, 54, 56, 57, 58, 59, 60, 63, 64, 65, 68, 69, 70, 71, 72, 73, 74, 76, 78, 79, 80, 82, 84, 85, 87, 89, 90
	Afternoon		
3	Morning	1, 7, 10, 19, 22, 28, 30, 33, 36, 41	1, 2, 3, 8, 10, 15, 24, 25, 26, 31, 33, 36, 38, 43, 45, 47, 51, 56, 59, 60, 61, 62, 64, 65, 70, 71, 72, 74, 76, 81, 83, 84, 90
	Afternoon		
4	Morning	9, 15, 29, 31, 42	9, 10, 18, 21, 33, 34, 35, 61, 65, 69, 70, 84
	Afternoon		
5	Morning	4	1, 11, 28, 34, 35
	Afternoon		

Table 6 Results for EES-NRR-MILP Model

Model	EES-RR-MILP	EES-RR-MILP	EES-NRR-MILP
Minimum rest time between two consecutive exams (dmin)	2	1	2
Feasible?	No	Yes	Yes
Last time segment with a scheduled exam	–	9	10
Number of time segments with scheduled exams	–	5	9
Average number of students per time segment with exams scheduled	–	35.4	19.7
Average number of exams per time segment with exams scheduled	–	8.6	4.8
Average time available for teachers to correct exams (in days)	–	8.2	7.5
Average rest time between two consecutive exams (in time segments)	–	1.4	3.1
Number of times the minimum rest time between two consecutive exams is not respected	–	–	3
Number of students affected	–	–	3
Rest time allocated to cases where minimum rest time is not respected (in time segments)	–	–	1, 0, 0

would benefit fully, having, on average, 3.1 segment times (equivalent to 1.5 days) of rest between two consecutive exams.

In this case, this would imply that the minimum time between two consecutive exams would be breached on three occasions, affecting three students. This adverse effect is minimal compared to the advantages of this approach. The main advantage is that the average rest time enjoyed by students increases by more than 100%. The students affected by the non-compliance of the minimum rest also enjoy this advantage since they requested exams for more than two subjects. Thus, they would have a rest of less than two-time segments between two exams and a rest of more than two-time segments between the rest of their exams.

5.1 Computational Efficiency

The models have been implemented using Pyomo, a Python-based optimisation modelling environment, and solved using the solver Gurobi Optimisation 9.1.1. The model imported input data through databases generated with .tab files. A laptop with an Intel® Core™ i7-7500U CPU @ 2.70 GHz 2.90 GHz processor, an installed RAM of 8.00 GB, and an operative system of 64 bits obtained all results.

Table 7 shows the models' size in their application to the case study of the scheduling of extraordinary exams at the ETSII of the UPV. The number of integer variables, binary variables and constraints created quantifies the models' size. This table also includes information on the feasibility and resolution time of the different scenarios.

In all model runs except for the EES-RR-MILP model with a minimum rest time between two consecutive exams of two segments, which proved to be infeasible, the optimal solution was found in less than 6 seconds.

Table 7 Computational efficiency

Model - Scenario	Feasible?	Integer variables	Binary variables	Constraints	Resolution time (seconds)
EES-RR-MILP with dmin = 0	Yes	1	2200	4045	2.24
EES-RR-MILP with dmin = 1	Yes	1	2200	4045	2.25
EES-RR-MILP with dmin = 2	No	1	2200	4045	–
EES-NRR-MILP with dmin = 2	Yes	489	2932	5097	5.41

6 Conclusions

This paper has proposed two MILP models for the scheduling of extraordinary exams. The EES-RR-MILP model allows for the scheduling of extraordinary exams requested by students, considering that two exams should not overlap for the same student and that there should be a minimum time devoted to rests between two consecutive exams for each student.

This model may give rise to feasibility problems in cases where it is impossible to schedule exams while ensuring rest between them. To solve this problem, the EES-NRR-MILP model is proposed. It allows the scheduling of the extraordinary exams requested by the students taking into account that it is possible to schedule the exams without guaranteeing rests between them but minimising the number of occasions when the minimum rest requirement between two exams is not met.

The models are applied to the case of the ETSII at the UPV, concluding that it is preferable to use the second model since it offers students longer rests without affecting teachers' exam marking time.

In the future, these models could be extended by transforming them into a multi-objective model in which multiple objectives are optimised, such as maximising the rest time between exams or the time available for marking exams, among others. Furthermore, the model could be extended to include new constraints, such as the availability of teachers for exam invigilation.

References

1. Gashgari R, Alhashimi L, Obaid R, et al (2018) A Survey on Exam Scheduling Techniques. In: 2018 1st International Conference on Computer Applications & Information Security (ICCAIS). IEEE, pp 1–5
2. Goli A, Tirkolaee EB, Mahdavi I, Zamani M (2019) Solving a University Exam Scheduling Problem Using Genetic and Firefly Algorithms. In: Proceedings of the International Conference on Industrial Engineering and Operations Management. Pilsen, Czech Republic, pp. 1038–1047
3. Aslan E, Simsek T, Karkacier A (2017) A Binary Integer Programming Model For Exam Scheduling Problem With Several Departments. In: 13th International Conference on Knowledge, Economoy and Management
4. Cataldo A, Ferrer J-C, Miranda J, et al (2017) An integer programming approach to curriculum-based examination timetabling. Ann Oper Res 258:369–393. https://doi.org/10.1007/s10479-016-2321-2
5. Woumans G, De Boeck L, Beliën J, Creemers S (2016) A column generation approach for solving the examination-timetabling problem. Eur J Oper Res 253:178–194. https://doi.org/10.1016/j.ejor.2016.01.046
6. Abou Kasm O, Mohandes B, Diabat A, El Khatib S (2019) Exam timetabling with allowable conflicts within a time window. Comput Ind Eng 127:263–273. https://doi.org/10.1016/j.cie.2018.11.037
7. BOUPV, Butlletí Oficial de la Universitat Politècnica de València (2022) Normativa de régimen académico y evaluación del alumnado en estudios oficiales de grado y máster universitario de la Universitat Politècnica de València

Diagnosis Model Proposal for Improvement Opportunity in Project Management: An Approach from the Perspective of Lean Waste

Marcelo Silva Pereira, Marcelo Albuquerque de Oliveira, and Fabiana David de Oliveira Gomes

Abstract Building an approach that improves the organization's process efficiency aligned with results, services, and product deliveries of ongoing projects is a growing need, especially in the post-pandemic period. Therefore, exercising the search for improvement opportunities in the processes involving the development teams, which are currently working remotely, is a challenge that requires ever-greater engagement from stakeholders. The proposal of a model that provides greater interaction between teams (remote, hybrid, or face-to-face) was the object of the study of this research. As an alternative to approaches that help the model to identify opportunities for process improvements, a study group from a technology company resorted to Lean waste practices in areas of knowledge in project management. At the first moment, the development team defines the value stream within its processes and starts to interact via the digital board to define problems that affect its final deliveries. After identifying the problem, the team tries to associate the problem (s) with lean waste and later with the impacts of the problems in the areas of project management knowledge. The development team seeks to quantify the effect of the problems and propose an action plan to reduce the impacts of the problems identified initially. As a result of this research, the model seeks to enhance the identification of opportunities for improvement by the project development teams and put an end to improving the efficiency of the organization's actions by carrying out the action plan defined by the team itself.

Keywords Lean Waste · Lean Project · Improvement Process

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1 Introduction

The search for better results led to the development of methodologies and techniques that were applied to production environments to promote, basically, cost reduction, increased efficiency, productivity gains, elimination of waste, and the satisfaction of all employees chain (productive-consumer), which, in Ohno's view [1], relates all production elements that only increase costs without adding value. Indeed, to improve performance, strategies based on the lean concept were widely used to combat waste and gained notoriety over the decades, especially from seminal works in this area, such as [2], who coined and extended the term lean manufacturing worldwide. With the application of lean solutions in various areas of knowledge, a new paradigm emerges from the identification of such losses and how to eliminate them, as activities are now carried out remotely. Despite the importance and effectiveness of the lean solutions employed, the period related to the Covid-19 epidemic allowed organizations to identify new opportunities for identifying and mapping losses due to the realization of remote activities such as those related to overproduction, waiting time, transport, processing (excess), inventory, movement, and manufacturing of defective products. Furthermore, it made it possible to identify opportunities in different social sectors affected by the impact of production activities [3–5].

The need to be efficient is an ongoing demand from organizations that have become more evident during the pandemic. In a short time, organizations needed to adapt to a new context, adopting/creating digital methods and tools that support their activities [6]. Such adequacy was directly responsible for several organizational and commercial transformations, such as the adoption of employee training platforms and safer financial transaction systems, highlighting in this context the project teams that needed to exercise resilience and develop new skills, starting to work remotely [7, 8]. The home office development teams had gains such as flexible working and saving time with commuting [9]. On the other hand, the dynamics between the teams began to suffer impacts after a certain time, causing difficulty in communication and consequently compromising the delivery of activities [10–12].

In order to articulate efficiency gains in activities and processes developed by an organization, aligned with an approach that encourages teams to analyze the internal procedures carried out in their activities, this research focused on the design of a model of diagnoses and opportunities for improvement aimed at product development processes, where the development team, as the main agent of change and the greatest beneficiary of process improvements, navigates through the activities carried out in search of results that add value to their deliveries, reducing waste in the stages of the different processes.

2 Theoretical Background

2.1 Lean Approach

[13] point out that the essence of lean thinking is based on five basic principles, which are: specify value; align the actions that create value in the best sequence – identify the value stream; carry out these activities without interruption every time someone requests them; carrying them out more and more efficiently – pull production; and perfection. Different authors point out that the key points of lean manufacturing involve certain requirements, which must be followed for the success of performance improvement actions [1, 13–16]. Being more specific, the authors refer to: Immediate total quality: which consists of going in search of "zero defects", and detection and solution of problems at their origin [17]; Minimization of waste: which consists of eliminating all activities that do not have added value and safety nets, in addition to optimizing the use of scarce resources, such as capital, people and space [18]; Continuous improvement: which consists of reducing costs, improving quality, increasing productivity, and sharing information [19]; "Pull" processes: in which the products are withdrawn by the end customer, and not pushed to the end of the production chain [20]; Flexibility: which consists of quickly producing different batches of a wide variety of products, without compromising efficiency due to smaller production volumes [21]; Relationship: Construction and maintenance of a long-term relationship with suppliers, making agreements to share risk, costs, and information [22].

2.2 Waste Management in the Lean Approach

The basis of the lean thinking concept is the elimination of waste within companies, and its application is achieved and supported by tools and methodologies that allow its implementation and maintenance, as [15] sustains.

Associated with the precepts advocated by the lean philosophy, until then more widely used in industrial processes, the concepts were extended to the supply chain, as well as to public and private services, sowing the idea of what would be called lean thinking business management philosophy, as attested by the works of different authors, with their assumptions and central characteristics [23–25], as follow: Organization based on teams involving flexible people, with diverse background, autonomy, and responsibility in their jobs [26]; Structures for solving problems that occur in the work areas, through the development of a culture of continuous improvement [27]; Lean operations, seeking to identify problems for subsequent adoption of measures that lead to their correction [28]; Leadership policies in people management (human resources) based on values, commitment, team spirit, feelings of belonging, sharing and dignity [29, 30]; Proximity and respectful relationships with suppliers [31]; Promote cross-functional development teams [32]; Management and customer relationship based on proximity and harmony [33].

Considering the proposals for tools and methodologies that aim at the continuous improvement of an organization [15, 34], summarize those that can be applied in the identification of seedlings and their elimination, emphasizing that most of the solutions were born in the industry, finding there the biggest application.

2.3 Lean Management Applied in Other Areas of Knowledge

According to [16] the expansion of lean concepts in new territories has led researchers and users to develop new methodologies and solutions that meet the needs of these sectors in the quest to eliminate waste and improve efficiency. The work developed by [14] proved the effectiveness and feasibility of applying lean tools and methodologies beyond the industrial area, by resorting to their use to combat waste in companies classified as being from the second economic sector, namely the furniture sector, butchery, bakery and small warehouses that manufacture clothes, obtaining significant results in reducing waste, improving layout, managing waste, increasing productivity, reducing costs, among other benefits.

In this context, the lean thinking and lean manufacturing approaches had developments in different segments of knowledge, among other denominations, for instance: Lean Office, aimed at improving administrative processes [35, 36]; Lean Maintenance, aimed at improving asset maintenance processes (machines, devices and equipment) [37–39]; Lean Healthcare, aimed at improving health processes and hospitals [24, 40]; Lean Construction, aimed at improving processes in civil construction activities [41–43]; Lean Education, aimed at improving educational processes [25, 44]; Lean Six Sigma, aimed at improving production processes, working to reduce process variability [45–47]; Lean Startup, aimed at creating and managing startups, product and business development, as well as reducing the product development cycle [48–50]; Lean Supply Chain, aimed at improving purchasing and logistics processes related to an organization's supply chain [33, 51, 52]; Lean Service, aimed at improving the processes of service providers, such as in sectors such as health, insurance, finance and technical assistance [17, 35, 53]; Lean Project Management, aimed at improving project management processes, such as lean construction, lean manufacturing and lean thinking in project management [54–57].

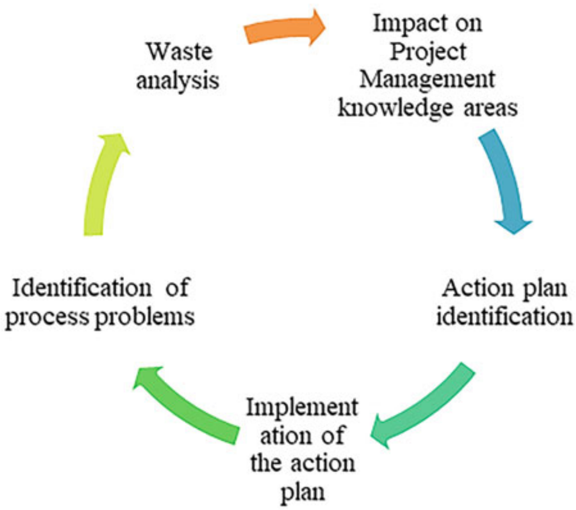
For a successful lean journey, it is not enough just to apply existing solutions without the involvement and commitment of people at all organizational levels. Without this, the results will not be permanent, but only occasional [1, 2, 15, 58].

3 Methodology

In this section, the set of techniques, procedures and approaches that will guide the related activities of this research are presented, so that the solution to the proposed problem can be found, as shown in Fig. 1. Thus, related topics are presented: nature of the research, way of approaching the problem, classification according to the objectives; classification according to procedures; research universe and sample; procedures for data collection, procedures for data analysis, and research stages.

The nature of the research can be classified as applied, as it aims to develop practical knowledge through the construction and application of a model for diagnosing opportunities for improvements in project development processes at an institute of technology. The way of approaching the problem is classified as qualitative, because through an exploratory character it seeks to understand the organizational processes and events existing in it, evaluating waste and impacts in areas of knowledge of project management. The objective of the research is classified as exploratory-descriptive, because in addition to developing the theoretical depth on the topic addressed (exploratory), it describes the object studied by establishing the relationships between the variables (descriptive), where in this research they are characterized by the waste ratio × area of knowledge in project management. The procedures that classify this research start from the bibliographical research, then the documental research and finally the action research. Bibliographic, due to the consultation of books and academic works, highlighting authors and institutions references in the subject with the objective of enriching the research. The documentary procedure was characterized by studies previously carried out by the organization and previously achieved results, in addition to reports from participants in previous initiatives. Finally, action research allows the researcher to actively engage

Fig. 1 Methodological path



with groups of people or processes studied, participating in collaboration in solving the proposed problem.

As for the universe and sample of the research, the study was carried out through a study group of organizational efficiency in project management with about 20 participants from different areas of technology projects (project management, battery development, kernel development of mobile devices, and computer vision algorithms). The procedures for collecting data in this research consider the application of the diagnostic model in each proof of concept throughout the activities of the study group. Each proof of concept identified process problems associated with waste and impacts on project management knowledge areas, indicators that needed to be improved could be defined through an action plan to be carried out over 8 months in each of the group's participants. Procedures for Data Analysis: The data from each proof of concept where the model was used, were analyzed in a cyclical and exploratory way on a weekly basis, in order to assess the proposed action plan for the problems identified along with the expected improvement results.

4 Results and Discussion

4.1 Evaluation of Internal Procedures by Project Teams

In order to articulate efficiency gains in the activities and processes developed by an organization aligned with an approach that encourages teams to analyze the internal procedures carried out in their activities, this research worked on the design of a model of diagnoses and improvement opportunities focused on processes of product development, where the development team, as the main agent of change and the greatest beneficiary of process improvements, navigates through the activities carried out below in search of results that add value to their deliveries:

(1) The development team's first exercise when using the model of diagnoses and opportunities for improvement aimed at product development processes is to define and understand the value stream of its daily activities, that is, where it starts, the journey that needs to be traversed until reaching the concept of done. (2) After identifying the value stream or the chain of activities that need to be carried out to complete the process deliverables, the team describes the problem(s) it faces during the development of the activities; (3) Once the problems are identified, they are evaluated along with a series of unwanted events that characterize waste. Waste in projects is the guide to associate problems encountered during value streams with undesirable events; (4) Once the events/waste within the value stream of a process have been identified, their impacts are linked to the project management knowledge areas, it being important to point out how the problems negatively influence the deliveries within each knowledge area; (5) It is important that problems, after being identified and associated within a knowledge area, are quantified (indicators). Whether by number of occurrences, hours or days of waiting, number of changes, unmapped failures found, among others. In the end, it is important to have a

diagnosis of the current state of the process flow and a value that one wants to reach, which allows gains in value in the processes; (6) The last item of the model describes possible actions to be taken by the development team that guide them to achieve new indicators already showing performance gains in the deliveries made. The values may be below, reaching or exceeding the expectations initially defined. However, at first, the ideal is to obtain some degree of optimization. The model shows potential in the face of the need to integrate distributed (remote) teams into a single initiative to improve and understand what needs to be done and what can be improved, in addition to allowing the integration of all in the search for added value within the processes performed.

4.2 *Case Study: Test Coverage of New Features by the Camera Test Team*

The camera test team used a model to identify opportunities for improvement within their delivery stream. As shown in Fig. 2, the team defined its value stream, starting with a test request for the camera application and ending with all the tests executed, covering all the application's functionalities. It is expected all tests to be functional, that is, ensuring that the camera application is ready to go to the end user. However, some problems were identified during the value stream of this team, as follows: **Problem 1** – *Lack of information about the new features applied to the app to start the testing cycle*; and **Problem 2** – *Have the Test Cases updated*.

Through the analysis of problem 1 by the camera test team, it was noticed that the problem generated unwanted events of waiting for information, unnecessary movement of information, over processing of information, in addition to defect/rework by the test team. It was also possible to observe that the effects of problem 1 are related to the knowledge areas of project management. Problem 1 *impacts the test team*, *the scope of the test to be carried out*, *generates risks* for the app to be delivered, *compromises the quality* of the application, exposes *communication problems* between the parties and finally compromises the test *execution time*. The effects can be visualized in Fig. 3 through the distribution of post-it in yellow by the

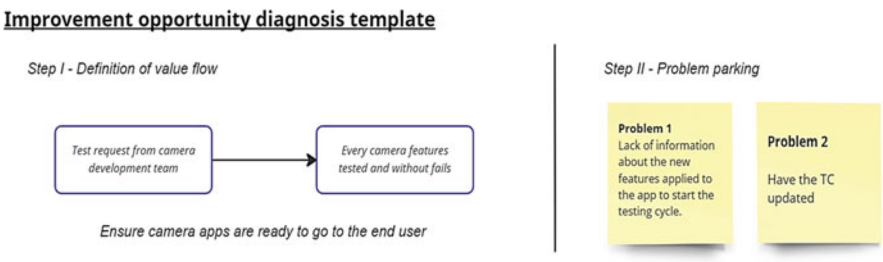


Fig. 2 Value flow definition by the camera test team

Fig. 3 Visualization of the improvement opportunities diagnostic model board for the camera team

intersection of areas of knowledge in project management and waste events. Still in Fig. 3, it is possible to visualize a contextualization of problem 1, described in more detail in the post-it notes in orange and, finally, the proposed action plan to be executed by the camera test team (described in the post-it notes in color blue). Finally, Fig. 4 shows how the camera test team reads the test coverage currently performed with the lack of information on new features integrated into the application (80% coverage of tested features – red post it) and adds that new reading/ indicator that want to achieve after applying the proposed action plan (80% coverage of tested features – green post it).

5 Conclusion

Organizations, in search of process optimization and efficiencies in their delivery of value to customers, tend more and more to look to their internal processes in search of improvements. Building an approach that was transversal to all areas of the

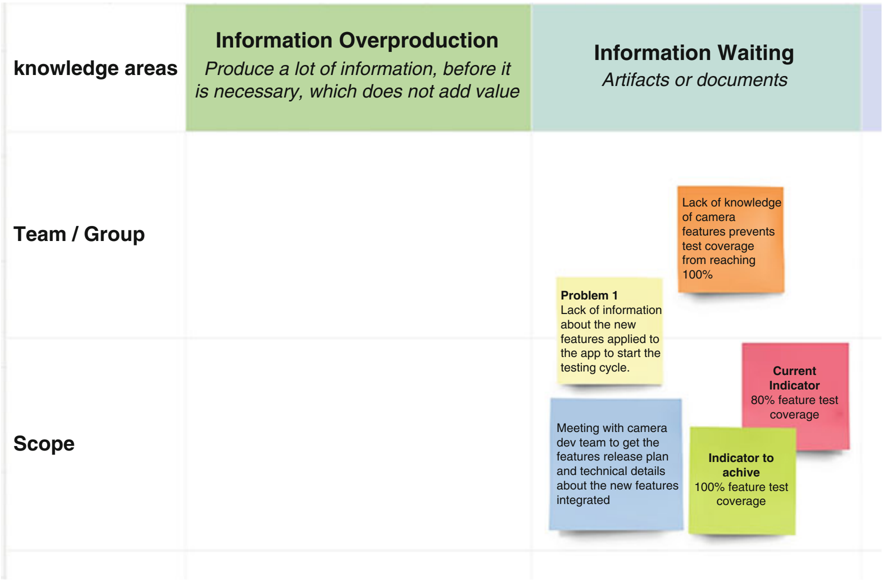


Fig. 4 Metrics view depicted in the template frame to address the camera team issue

organization (whether project areas or support areas) was a stimulus for the study group.

Articulating knowledge of the lean philosophy and its waste with the areas of project management knowledge within processes that are strongly paralyzed by the particularities of each participating area was challenging, since identifying problems (regardless of their procedural or technological nature) and designing action plans aligned with metrics to show the improvements achieved, was the main guide for the results of this study.

The proposed model provides a series of critical views on the part of those involved in the processes/projects studied, contributing to greater integration between the development teams and other project stakeholders, in addition to proposing the same direction in the search for improvement for those involved. For this reason, it fulfills the role proposed here by this research.

It is worth noting that there are opportunities to articulate other approaches within the same context of the proposed model, such as analysis of constraints aligned with the cause-and-effect analysis, but at the moment, providing development teams (regardless of the business area in which they are inserted) an approach in which together they can observe their opportunities for improvement, helps them to seek for their increasing efficiency in improving the delivery of value in their results.

References

1. Ohno T. Toyota Production System: Beyond Large-Scale Production, 1st ed. Productivity Press, New York (1988).
2. James P. Womack, Daniel T. Jones and DR. The machine that changed the world, Reprint. Free Press, New York (2007).
3. Casado-Aranda LA, Sánchez-Fernández J, Viedma-del-Jesús MI. Analysis of the scientific production of the effect of COVID-19 on the environment: A bibliometric study. Environ Res 193. https://doi.org/10.1016/j.envres.2020.110416 (2021).
4. Soto-Acosta P. COVID-19 Pandemic: Shifting Digital Transformation to a High-Speed Gear. Inf Syst Manag 37:260–266. https://doi.org/10.1080/10580530.2020.1814461 (2020).
5. Kumar A, Luthra S, Mangla SK, Kazançoğlu Y. COVID-19 impact on sustainable production and operations management. Sustain Oper Comput 1:1–7. https://doi.org/10.1016/j.susoc.2020.06.001 (2020).
6. Backes D.A.P., Arias M.I, Storopoli J.E., Ramos H. R. Os efeitos da pandemia de Covid-19 sobre as organizações: um olhar para o futuro. Rev Ibero-Americana Estratégia 19:1–10. https://doi.org/10.5585/riae.v19i4.18987 (2020).
7. Bushuyev S, Bushuiev D, Bushuieva V. Project Management During Infodemic of the Covid-19 Pandemic. Innov Technol Sci Solut Ind 0:13–21. https://doi.org/10.30837/2522-9818.2020.12.013 (2020).
8. Koch J, Schermuly CC. Managing the Crisis: How COVID-19 Demands Interact with Agile Project Management in Predicting Employee Exhaustion. Br J Manag 32:1265–1283. https://doi.org/10.1111/1467-8551.12536 (2021).
9. Joshi A, Bhaskar P, Gupta PK. Indian economy amid COVID-19 lockdown: A prespective. J Pure Appl Microbiol 14:957–961. https://doi.org/10.22207/JPAM.14.SPL1.33 (2020).
10. Aarti P. Bellara; D. Betsy McCoach. Lean on me : Teaching together from a distance. New Horizons Adult Educ Hum Resour Dev 34:17–27. https://doi.org/10.1002/nha3.20359 (2022).
11. Tortorella G, Narayanamurthy G, Godinho Filho M, et al. Pandemic's effect on the relationship between lean implementation and service performance. J Serv Theory Pract 31:203–224. https://doi.org/10.1108/JSTP-07-2020-0182 (2021).
12. Silva. DPGG de STN dos SPWG de SP dos SPJSW. Home Office : vantagens, desvantagens e desafios para empresas e funcionários. Rev Adm do UNIFATEA – RAF 16:7–273 (2018).
13. Womack, J. P.; Jones DT. Lean Thinking: Banish waste and create wealth in your corporation, Second. Free Press, New York (2003).
14. Gisele Amaral Cintra; Marcelo Albuquerque de Oliveira. Aplicação de Ferramentas Lean Manufacturing no Processo Produtivo: Estudos de Casos Múltiplos em Empresas do Segundo Setor, 1a Ed. Appris, Curitiba – PR (2021).
15. Pinto J.P. Pensamento Lean – A filosofia nas organizações vencedoras: Criar valor para todos os stakeholders, eliminando o desperdício nas organizações, 6a ed. Lidel Edições Técnicas Lta, Lisboa (2014).
16. James P. Womack and Daniel T. Jones. Lean Solutions: How Companies and Customers Can Create Value and Wealth Together, 1st ed.; F. New York (2005).
17. Jirasukprasert P, Garza-Reyes JA, Kumar V, Lim MK. A six sigma and dmaic application for the reduction of defects in a rubber gloves manufacturing process. Int J Lean Six Sigma 5:2–22. https://doi.org/10.1108/IJLSS-03-2013-0020 (2015).
18. Wyrwicka MK, Mrugalska B. Mirages of Lean Manufacturing in Practice. Procedia Eng 182: 780–785. https://doi.org/10.1016/j.proeng.2017.03.200 (2017).
19. Brito M, Ramos AL, Carneiro P, Gonçalves MA. Combining SMED methodology and ergonomics for reduction of setup in a turning production area. Procedia Manuf 13:1112–1119. https://doi.org/10.1016/j.promfg.2017.09.172 (2017).
20. Kumar CS, Panneerselvam R. Literature review of JIT-KANBAN system. Int J Adv Manuf Technol 32:393–408. https://doi.org/10.1007/s00170-005-0340-2 (2007).

21. Lopes RB, Freitas F, Sousa I. Application of lean manufacturing tools in the food and beverage industries. J Technol Manag Innov 10:120–130. https://doi.org/10.4067/s0718-27242015000300013 (2015).
22. Indrawati S, A'Azzam E, Adrianto E, et al. Lean Concept Development in Fast Food Industry Using Integration of Six Sigma and TRIZ Method. IOP Conf Ser Mater Sci Eng 722. https://doi.org/10.1088/1757-899X/722/1/012044 (2020).
23. de Almeida JPL, Galina SVR, Grande MM, Brum DG. Lean thinking: planning and implementation in the public sector. Int J Lean Six Sigma 8:390–410. https://doi.org/10.1108/IJLSS-06-2016-0027 (2017).
24. Jorma T, Tiirinki H, Bloigu R, Turkki L. LEAN thinking in Finnish healthcare. Leadersh Heal Serv 29:9–36. https://doi.org/10.1108/LHS-08-2015-0021 (2016).
25. Narayanamurthy G, Gurumurthy A, Chockalingam R. Applying lean thinking in an educational institute – an action research (2017).
26. Bortolotti T, Boscari S, Danese P. Successful lean implementation: Organizational culture and soft lean practices. Int J Prod Econ 160:182–201. https://doi.org/10.1016/j.ijpe.2014.10.013 (2015).
27. Shah D, Ratilal Patel P, Patel P. Productivity Improvement by Implementing Lean Manufacturing Tools In Manufacturing Industry Continuous improvement in SME View project Water Jet Machining View project Productivity Improvement by Implementing Lean Manufacturing Tools In Manufacturing Indu. Int Res J Eng Technol 3–7 (2018).
28. Shinde DD, Ahirrao S, Prasad R (2018) Correction to: Fishbone Diagram: Application to Identify the Root Causes of Student–Staff Problems in Technical Education (Wireless Personal Communications, 100, 2, (653-664), https://doi.org/10.1007/s11277-018-5344-y). Wirel Pers Commun 100:665. https://doi.org/10.1007/s11277-018-5502-2 (2018).
29. Fullerton R.R, Kennedy F.A, Widener S.K. Lean manufacturing and firm performance: The incremental contribution of lean management accounting practices. J Oper Manag 32:414–428. https://doi.org/10.1016/j.jom.2014.09.002 (2014).
30. Liker J, Rother M. Why Lean Programs Fail. Lean Enterp Inst 1–5 (2011).
31. Simone Ribeiro Sarges, Marcelo Albuquerque de Oliveira FR and SS. The dyad partnership-credibility and the qualification of suppliers. In: Minho University (ed) 2nd International Conference on Quality Engineering and Management_ICQEM. International Conference on Quality Engineering and Management, Guimarães, p 14 (2016).
32. Oliveira, Marcelo A.; Lima RM., Pereira MS., Vieira, Andréa, Paes L. The gamification as a tool to increase employee skills through interactives work instructions training. Procedia Comput Sci 138:630–637. https://doi.org/10.1016/j.procs.2018.10.084 (2018).
33. Shamah RAM. Measuring and building lean thinking for value creation in supply chains. Int J Lean Six Sigma 4:17–35. https://doi.org/10.1108/20401461311310490 (2013).
34. Pinto J.P. Gestão de Operações na Indústria e nos Serviços, 3a ed. Lidel Edições Técnicas Lta, Lisboa (2010).
35. Iara Tammela; Rodolfo Cardoso; Carla do Carmo Almeida. Lean Service e Lean Office: Uma Revisão Bibliográfica. In: XXXVII Encontro Nacional de Engenharia de Produção. Joinville – SC, p 17 (2017).
36. Seraphim EC, Da Silva ÍB, Agostinho OL. Lean office in health military organizations: Case study in the health center of Campinas. Gest e Prod 17:389–405. https://doi.org/10.1590/s0104-530x2010000200013 (2010).
37. Duran O, Capaldo A, Acevedo PAD. Lean maintenance applied to improve maintenance efficiency in thermoelectric power plants. Energies 10:1–21. https://doi.org/10.3390/en10101653 (2017).
38. Benjamin SJ, Marathamuthu MS. The use of 5-WHYs technique to eliminate OEE's speed loss in a manufacturing firm. J Qual Maint Eng 21:419–435. https://doi.org/10.1108/JQME-09-2013-0062 (2015).
39. Kumar Sharma R, Gopal Sharma R. Integrating six sigma culture and TPM framework to improve manufacturing performance in SMEs. Qual Reliab Eng Int 30:745–765. https://doi.org/10.1002/qre.1525 (2014).

40. Narayanamurthy G, Gurumurthy A. Is the hospital lean? A mathematical model for assessing the implementation of lean thinking in healthcare institutions. Oper Res Heal Care 18:84–98. https://doi.org/10.1016/j.orhc.2017.05.002 (2018).
41. Babalola O, Ibem EO, Ezema IC. Implementation of lean practices in the construction industry: A systematic review. Build Environ 148:34–43. https://doi.org/10.1016/j.buildenv.2018.10.051 (2019).
42. Sohi AJ, Hertogh M, Bosch-Rekveldt M, Blom R. Does Lean & Agile Project Management Help Coping with Project Complexity? Procedia – Soc Behav Sci 226:252–259. https://doi.org/10.1016/j.sbspro.2016.06.186 (2016).
43. Aziz RF, Hafez SM. Applying lean thinking in construction and performance improvement. Alexandria Eng J 52:679–695. https://doi.org/10.1016/j.aej.2013.04.008 (2013).
44. Vukadinovic S, Djapan M, Macuzic I. Education for lean & lean for education: A literature review. Int J Qual Res 11:35–50. https://doi.org/10.18421/IJQR11.01-03 (2017).
45. Gangidi P. A systematic approach to root cause analysis using 3 x 5 why' s technique. Int J Lean Six Sigma 10:295–310. https://doi.org/10.1108/IJLSS-10-2017-0114 (2019).
46. Gupta SK, Antony J, Lacher F, Douglas J. Lean Six Sigma for reducing student dropouts in higher education–an exploratory study. Total Qual Manag Bus Excell 31:178–193. https://doi.org/10.1080/14783363.2017.1422710 (2020).
47. Mahmoudsoltani F, Shahbandarzadeh H, Moghdani R. Using Pareto-based multi-objective Evolution algorithms in decision structure to transfer the hazardous materials to safety storage centre. J Clean Prod 184:893–911. https://doi.org/10.1016/j.jclepro.2018.02.235 (2018).
48. Shepherd DA, Gruber M. The Lean Startup Framework: Closing the Academic – Practitioner Divide. Entrep Theory Pract 45:967–998. https://doi.org/10.1177/1042258719899415 (2021).
49. Bocken N, Snihur Y. Lean Startup and the business model: Experimenting for novelty and impact. Long Range Plann 53:101953. https://doi.org/10.1016/j.lrp.2019.101953 (2020).
50. Harms R, Schwery M, Harms R. Lean Startup: Operationalizing Lean Startup Capability and testing its performance implications. J Small Bus Manag 00:1–24. https://doi.org/10.1080/00472778.2019.1659677 (2019).
51. Hasan S, Khan G, Hoque MR, et al. Lean practices in the Bangladeshi ready-made garments industry and global significance. Int J Logist Res Appl 0:1–19. https://doi.org/10.1080/13675567.2020.1847262 (2020).
52. Tissir S, Fezazi S El, Ayyad C. Industry 4.0 impact on Lean Manufacturing: Literature Review. In: 13th International Colloquium of Logistics and Supply Chain Management – LOGISTIQUA 2020. pp 2–4 (2020).
53. Lacerda AP, Xambre AR, Alvelos HM. Applying Value Stream Mapping to eliminate waste: A case study of an original equipment manufacturer for the automotive industry. Int J Prod Res 54: 1708–1720. https://doi.org/10.1080/00207543.2015.1055349 (2016).
54. Dinelli TDB, Oliveira MA De, Vieira RK, Melo ES De. Comparative Study of Methodologies for Schedule Management in an Environment of Multiple Simultaneous Projects. Eur J Bus Manag Res 6:146–150. https://doi.org/10.24018/ejbmr.2021.6.3.886 (2021).
55. Mesa HA, Molenaar KR, Alarcón LF. Comparative analysis between integrated project delivery and lean project delivery. Int J Proj Manag 37:395–409. https://doi.org/10.1016/j.ijproman.2019.01.012 (2019).
56. Vittorio Cesarotti; Silvia Gubinelli; Vito Introna. The evolution of Project Management PM: How Agile, Lean and Six Sigma are changing PM. J Mod Proj Manag 7:28. https://doi.org/10.19255/JMPM02108 (2019).
57. Brian J. Galli. Can Project Management Help Improve Lean Six Sigma ? IEEE Eng Manag Rev 46:55–64. https://doi.org/10.1109/EMR.2018.2810146 (2018).
58. Chiarini A, Baccarani C, Mascherpa V. Lean production, Toyota Production System and Kaizen philosophy: A conceptual analysis from the perspective of Zen Buddhism. TQM J 30: 425–438. https://doi.org/10.1108/TQM-12-2017-0178 (2018).

Design of a Corporate Training Academy: The Case Study of a Pharmaceutical Company

Pedro Alexandre Marques, Lara Ramos, and Bruna Mota

Abstract Aside from being the only resource that cannot be copied because its skills are unique and impossible to replicate, human capital also serves as a facilitator to ensure product quality and compliance. Given the importance of this asset, organizations realize the importance of training. Investing in people's knowledge and skills through continuous learning are key in driving enterprises do adapt to markets' challenges with the aimed quality and effectiveness. This paper proposes a good practices model for the design and establishment of a corporate's academy of a pharmaceutical company. This model, which purpose is to support continuous training in a labor context, was developed attending to a carefully literature review. The framework provided by the model was tested according to the following stages: (1) identification of competencies; (2) course and curriculum architecture; (3) choice of trainers, transmission, and evaluation methods; (4) construction of competence matrices. By implementing the methodology comprising these steps, the size and complexity of the existing training system of pharmaceutical company was reduced. Among other achievements, a learning path of essential training courses to qualify the operational personnel could be defined, contributing to reduce the required time to become autonomous in their job functions. Additionally, a monitoring plan was proposed and validated for the confirmation of the results expected with the full implementation of the academy.

Keywords Learning · Pharmaceutical industry · Professional training

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1 Introduction

In any industry, the success of companies depends on the knowledge and skills of their personnel [12]. Thus, to deal with increasing competitiveness in the markets, together with increasing customer demand, solutions to better manage these resources as well as their knowledge become essential for organizations [2]. Particularly, in the pharmaceutical industry, where medical devices that directly impact human life are produced, both requirements and quality assurance are equally important. In this sense, the creation of corporate academies is becoming an effective strategy to ensure that employees have the required competencies to perform their jobs effectively and meet the specific needs of the company. This approach allows employees to learn how they should operate under the requirements and regulations for developing their work. Similarly, training can be customized and specifically targeted to a certain job.

This paper describes a case study of a Portuguese company from the pharmaceutical industry. The case illustrates the roadmap to design and launch a training academy capable of providing its employees with the necessary knowledge and skills to effectively perform their job, as required by Good Manufacturing Practices (GMP).

2 Literature Review

2.1 The Importance of Human Capital

According to Dimov [9], human capital refers to the sum of knowledge and skills arising from education and experience that can be used to benefit of firms. This advantage is associated with the creation of value that people can bring to companies through their ability to transform and acquire knowledge [2]. In this sense, human capital is the only resource that cannot be copied. So, with successive technological advances, dependence on this type of asset has been increasing over the time [4]. This reality can become even more critical in patent-producing companies that are more vulnerable and dependent on the development of knowledge [1, 11, 20, 23]. Nevertheless, human's knowledge by its own do does not serve as sustenance for organizations. In this sense, seeking to cultivate and disseminate this knowledge is also a decisive factor, since it is what allows companies to adapt to the evolutionary changes in markets [2]. Thus, organizations often realize that the need to invest in training as well as its continuous improvement over time to enhance the capabilities if individuals.

2.2 Training Management

It is also critical that companies do understand how training should be developed to meet their needs. A good strategy for that purpose may be to understand the standards related to training in the field of quality management. In the specific case of the relevant international management system standards, ISO 10015:2019 provides guidelines to manage for the training processes by considering five sequential stages: (1) identification of training needs; (2) planning and construction of a training program (3) training implementation; (4) evaluation of results; and (5) continuous improvement [12]. In this way, and with these guidelines in mind, the mentioned standard guides companies to design, implement, and sustain an effective training system regarding all its components [7]. Complementary to the mentioned standard, both ISO 30401:2018 and ISO 10018:2012, which respectively refer to knowledge management requirements and guidelines for engaging people, are also relevant in this context.

2.3 Learning Tools

To assist and guide training activities, there are a set of tools available. As is the case of the competencies' matrix, which identifies, specifies, and visually displays a set of key information about the existing levels of competencies among the members of a team to perform a job, task, or process [17]. Furthermore, it can be useful for the identification of skills' gaps and training needs, as well as for improving the allocation of personnel to tasks [17, 26].

On the other hand, learning management systems (LMS) stand out regarding the implementation and delivery of training sessions. Since these systems provide a set of important statistics that serve to improve and personalize educational experience, they also work as a content repository of courses' materials, which enables a better connection between trainees and trainers [6, 19]. Once it is assured that the programmatic contents are coherent with the stated learning objectives and that the LMS platform is simple to use, then the whole potentialities that such tool can provide can be achieved, allowing the desired knowledge transmission [25].

2.4 Evaluation of the Learning Process

Several methods can be used to evaluate the results of from the training activities. The most well-known was conceived by Kirkpatrick [16], who defines this evaluation into four levels: (1) evaluation of the trainees' reactions and feedback to the training; (2) evaluation of knowledge retention; (3) Evaluation of behaviors; (4) evaluation of the contribution of training activities to the improvement of the company's performance. In addition to this method, Tamkin et al. [24] suggest alternative evaluation methods that can be divided into two groups: those that focus on the evaluation objective and those that provide alternative evaluation measures. Other authors also mention additional evaluation methods, as is the case of Hammond and Snyderb [8], and Carless [5].

2.5 *Quality: Role in the Pharmaceutical Industry*

In an industry in which manufactured products' quality have a significant impact on human health, the ability for effectively managing the competencies of their personnel is critical for all pharmaceutical enterprises. Therefore, the role of quality assurance is very important. According to the World Health Organization [27], Quality Assurance refers to the set of actions that certify that the quality of pharmaceutical products constantly complies with the applicable standards. To ensure that this quality is maintained, one option may include following good practices (GxP) that, through their principles, can guide companies to always produce the same quality standards. In order to prove that adherence to these standards consequently results in improvements, some studies have been conducted. As is the article by Eich and Friedli [10] which concluded, that in general, companies that invest in operational excellence, specifically in quality management systems, are more likely to show favorable results in inspections. Furthermore, the study by Narhi et al. [21] refer that the handling and transportation of medical substances are impacting factors on the quality and safety of medicines. This indirectly reflects the importance of following GDPs integrated into a quality management system, which prevents the quality and efficacy of products from being compromised. Given these studies, it is concluded that standards should be valued because, combined with the correct training provided to workers, they enable the delivery, regardless of the reality experienced, of consistent products in terms of quality (Elsafty and Osman 2021).

3 Case Study

The case study was conducted in a Portuguese pharmaceutical company that stands out in the market for its chemical and drug product development, which unfolds in three main manufacturing stages: chemical synthesis, particle engineering, and drug formulation. The company have manufacturing sites in Portugal, Ireland and the United States of America. Since GMP requires that personnel must be competent in the work they perform, this is of course one of the audit criteria that is regularly verified during second- and third-party audits. In this sense, and especially in the pharma industry, all activities that impact the qualification of the workers are extremely relevant and need to be properly recorded.

3.1 Current Situation

The pharmaceutical organization has a training management system in place. The qualification of the personnel is a process that comprises two parts: (1) the realization of general training, designated as onboarding that occurs every month, which aims to address all the general but fundamental information that any employee needs to know or be aware of to work for the company, regardless of his/her job function; (2) specific training that on the other hand, depends on the person's role and job description. For employees to be qualified in these specific training, departmental heads must choose from a set of existing courses, those that they consider relevant for employees to do their job. Therefore, this phase of the training system works for all employees in a decentralized way. After these courses are attended by the employees, a theoretical test, which evaluates the retention of knowledge, is held. Employees whose technical positions is related to manufacturing operations will also attend a school of operators, that occurs every 2 months for 5 weeks, where are addressed the most fundamental basic productive operational concepts. For these cases, in addition to the ordinary evaluation method, there is also a behavioral evaluation that occurs 3 months after the person started working in the operational area. Thus, obtaining the qualification for a manufacturing operator will depend on subsequent evaluation and approval by managers.

The process previously explained occurs on average once a month whenever a new employee joins the organization. In the case of employees who are already in the company, the acquisition of qualifications depends on the training needs that arise during his/her career. This means that there is no clear training path for these personnel.

The pharmaceutical company has in place an existing learning management system (LMS), where evaluations and knowledge assessments are recorded, tutorials are stored, and other data necessary for qualifications' tracking are placed.

3.2 Diagnosis of Problems

The allocation and creation of the courses by departmental heads inhibited the standardization of the training practices between the various manufacturing sites of the organization. Furthermore, quantitative data gathered from LMS revealed that a total set of 4400 courses exist, which creates obvious constraints to the daily management of the training stream. By performing a set of overlapping analysis, the project team also realized duplications in the courses' contents, hence suggesting that an excessive number of courses might exist. Table 1 summarizes a collection of problems that arise from the current training management system. Attending to this, the company decided to start a strategic project with the aim of redesigning the whole training management system, including its processes, courses' contents, and LMS.

Table 1 Cause and impacts of the diagnosed problem

Cause	Problem	Impact
LMS out-of-date	Old and hard-to-use LMS	Less dynamic training / Negative learning experience / Complexity of working and extracting data from LMS
Easy access to create courses arbitrarily	Existence of numerous and often redundant courses	Unnecessary consumption of time and facilities
Use of theoretical tests to assess practical skills	Unsuitable evaluation system	Lack of assurance that employees are properly skilled
Lack of pre-defined standardized training plans throughout career development	Lack of knowledge about people's qualifications and their respective evolutionary processes / Lack of clarity in career evolution	Inappropriate employee allocation management / Career stagnation
Dependence on the allocation of courses to direct managers	Decentralization in the creation/allocation of courses	Many redundant courses exist / Errors in curriculum allocation
Limit access restrictions to existing LMS	Manual qualification of personnel may occur	Impact on the reliability of the performance indicators collected
Courses without competencies allocated	Existence of courses without qualifications allocated	Discrediting those courses / Demotivation
Skilled trainers are often allocated in teaching basic training	Over-skilled trainers for foundational courses	Time spent on activities that do not add value
Significant differences between training plans among manufacturing sites	Lack of standardized approach to training across sites	Demotivation of workers / Lack of standardized training practices
Condensation of training in the first years of work	The gap between the time of training and the need to apply knowledge	Waste of time in redoing training or asking another employee to teach
Numerous courses specific to a product, equipment, or building	Poor adaptability of operators between manufacturing areas	Increased adaptation time / Difficulty in implementing employee turnover among areas

4 Proposed Good Practices Model

To respond to the problems previously described a new model was developed attending to a set of best practices identified in the literature review. However, it is important to note that during the literature review stage no specific reference mentioning how a corporate training academy can be built was found. In this sense, the new proposed model was developed by combining a set of relevant scientific contributions and organized around the logic provided by the PDCA cycle. The methodological steps adopted for the design, development and launch of the academy were aligned with that 4-stage cycle. The proposed model comprises the following stages: planning, construction, implementation, evaluation, and monitoring.

4.1 1st Phase – Planning: Planning the Academy

In this phase it is important to align the project planning with the objectives and needs of the company, as referred in the 4.2 clause contained in the ISO 10015 [12] standard. This clause underlines the importance of understanding the organizational context through the identification of training needs and other initiatives to increase the ability to run competence management and people development processes in an enterprise. After this, research conducted by Kuruba [17] highlights the importance of setting business organizational objectives in a clear way so that, based on them, it is possible to define specific action plans to meet the training needs previously identified. Afterwards, it was also important to define an applicability scope for these action plans. This was done in line with the guidelines provided by the clause 4.3 of ISO 30401 [15] for knowledge management systems (KMS). This clause underlines the importance of defining the scope of the KMS to better set the learning priorities as part of the business continuity strategy. To meet this phase's goals and attending to the mentioned literature, the following best practices (BP) are herein proposed:

BP1. Identify organizational training requirements based on the current organizational context.
BP2. Define action objectives based on the identified training needs, while keeping the vision and mission of the organization in mind.
BP3. Define the scope of applicability of the objectives considering the priority knowledge domains in business continuity.

4.2 2nd Phase – Do / Execute: Building and Developing the Academy

The ideas presented by Kuruba [17] are easily adaptable to this phase, as they refer to a sequence of steps that should guide the process of developing a competency matrix, which is tool intended to be included in the proposed model. The following steps proposed by the author were considered for this phase:

- Identify roles and describe them – regards the definition and communication of the organizational structure, its job functions, and their associated responsibilities and authorities.
- Identify the necessary competencies – concerns the identification, definition, and specification of the competencies for the personnel to perform their job

effectively. It also involves the definition of proficiency levels for each key competency.
- Allocating competence levels to job functions – it is related to the assignment, for each job role, of the degree of competency that exists and/or is required.

In addition to the previous steps, the following points derived from clauses 5.2 and 5.3 of ISO 10015 [12] were included in the methodology's second phase:

- Detailing the training program – it is related to the definition of the specific ideas and objectives for the training.
- Select the training method – it involves the selection of the most convenient training method for each training activity.
- Select the trainer – it concerns the identification and choice of the trainer with the appropriate profile and set of skills.
- Select the evaluation method – it refers to the suitability of the type of evaluation capable of validating the achievement of the learning objectives established in the training program.

Kirkpatrick [16] suggest an additional method to assess training activities, that consists in evaluate the training in the following levels: reaction, knowledge, and behavior.

Furthermore, all the stakeholders impacted by the project were identified and the most relevant involved from this planning stage. This was done in line with the guidelines provided by the clause 4.2 of ISO 10018 [13]. This clause suggests that strategies are defined to ensure the commitment of those involved in the project. So, considering all these contributions, the following best practices are identified:

BP4. Identify all roles and associated responsibilities.
BP5. Determine, define, and specify the competencies required for the development of the organizational operations.
BP6. Assign proficiency levels to the competencies identified.
BP7. Identify the required level of proficiency for each job function.
BP8. Create courses, define their obligation and their respective contents aligned with the required competences.
BP9. Adapt the transmission mode to the type of training to be adopted.
BP10. Choose the trainer according to their qualifications and skills.
BP11. Select the best knowledge assessment method according to the type the training and its goal.
BP12. Involve the project stakeholders to ensure their commitment.

4.3 3rd Phase – Check: Assessment

The contributions of Kirkpatrick [16] and ISO 10015 [12] were considered for this phase. The former proposes a method for evaluating the results in terms of training effectiveness, while the later highlights in its clause 5.6 the importance of assessing the impact of the training activity. This is a specific moment of evaluation that differs from the one mentioned for 2nd phase, since it promotes the understanding of how training contributed to create value for the business, through the performance improvement. The resulting good practice for this phase is following:

B15. Evaluate the contribution of training activities in the long and short term through using proper key performance indicators.

4.4 4th Phase – Act: Monitoring and Continuous Improvement

To set this phase's best practices, requirements under the clause 5.7 of the ISO 10015 [12] standard were considered. It suggests that opportunities for improvement should be sought on a continuous basis:

BP16. Continuously strive to improve training activities by actively responding meeting to the needs identified.

5 Model Validation

To validate the proposed model, semi-structured interviews were conducted with company training specialists. For that aim, three selected interviewees (whose functions performed are senior learning and development specialist, trainer in productive areas and trainer in operational excellence) were asked the same set of questions:

Q1. What do you think about the model proposed? Is it useful considering the company's needs?
Q2. Do the good practices established cover everything that the design, development, and implementation of the academy involve? If not, what would you include in the model?
Q3. Would you eliminate any good practices that you believe are unnecessary?

Given the answers obtained from the interviews, it was possible to conclude that the proposed model is suitable to be employed during the planning, construction, and implementation stages of the academy. However, to ensure that the model is aligned with the company's needs, it was suggested to include: (1) A good practice to foster stakeholder engagement during the development stage of the academy; (2) the clauses of the ISOs mentioned in the template to clarification in case of doubt.

These suggested adaptations were incorporated, from the outset, in the model to be tested.

6 Model Validation

6.1 1st Phase – Planning: Planning the Academy

BP3 According to the company's decision, the good practices model will focus on the Operations Academy, whose organizational areas directly impact the products' value streams. In parallel, it is in these areas that most of the trainers are nearing retirement age and most of the courses and training time are spent. So, to meet GMP requirements, put in place an effective knowledge management processes, and to enable business continuity strategies, this development and launch of this academy was a priority. To design and implement this academy, the company allocated a multidisciplinary team.

6.2 2nd Phase – Do / Execute: Building and Developing the Academy

BP4 This phase involved a conjoint work between the Human Resources (HR) department and the area managers to identify the different job functions and their descriptions (including responsibilities) for each one.

BP5 In line with the fifth best practice, the project team proceeded with the determination of the required competencies that qualified personnel, depending on their role and is functions, should have to perform their job tasks effectively. For this aim, the project team identified the set of competencies for each job role using the categorization framework proposed by Kuruba [17] to classify them into competencies specific to the business unit (operations) and competencies that are inherent to each job function or role.

- Business unit skills identification – These sorts of competencies were identified by conducting a set of workshops with the area managers, being then organized around affinities using the KJ methodology, also known as affinity diagram, which is a quality planning and management tool. To avoid considering redundant competencies, the in-scope/out-of-scope tool was adopted.
- Identification of specific competencies for each job function – Considering all the areas covered by the Operations Academy, the project team was faced with a wide set of organizational functions with sometimes very different required competencies. Due its relevance, the manufacturing area responsible for producing active pharmaceutical ingredients (API), was chosen in the scope of this research. In this department the competencies required are, in their majority, common to other productive areas. The job function "operator" was chosen because it represents more than 50% of the personnel to be covered by the Operations Academy and is also the function with the greatest need for training. For the identification of the specific competencies for this function, it was necessary not only to monitor

production processes and associated production sheets but also obtain the assistance and approval of employees and department heads.

BP6 Adapting the levels proposed by Kuruba [17], the project team established the following five levels of proficiency: Level 0 denotes the absence of the necessary skill or competency. Level 1 requires basic skills, which translates to the need for supervision during work. Level 2 is assigned to an employee who can work autonomously. Level 3 is achieved when an employee masters a certain competency, demonstrating ability to perform a task in any circumstance. Finally, at level 4, the employee not only is an expert but is also able to train.

BP7 The level of proficiency may vary, depending on the employee experience and background. The criteria for assigning proficiency levels were however based on the team leaders' judgement.

BP8 To facilitate the creation of courses for the Operations Academy, the guidelines described below were followed by the project team. The courses defined were allocated to the following three classes of courses:

- Fundamental training – E-learning courses with the aim of providing general knowledge regarding a subject, topic or area.
- Operational training – Theoretical and simulated practice types of training that provides comprising process-related courses for a specific job family.
- Task training – On-the-job training courses intended to provide specific skills to perform a specific task in an effective manner focusing on providing knowledge and skills regarding a specific point of the operational sequence required to produce a product.

In terms of training content, fundamental courses will address only theoretical content, operational courses will address theoretical-practical content, and task-oriented courses will only address practical content. The courses identified can be of a mandatory, required or optional nature. Mandatory courses are those courses where legal or regulatory requirements are involved. Required courses are those that must be taken at the company's internal request. Optional courses are those that may or may not be taken at the employee's will. The courses were defined and distributed according to the three classes previously described.

BP9 Training formats for each course were defined to suit the following set of variables: its learning objectives, the size of the target audience, the desired degree of interaction with the trainee. In this sense, for instance, "Fundamentals of Operations" is an e learning course since it aims to cover a wide set of newcomers from the different locations of the company. On the other hand, for Operational and Task courses, a mix of three training types were defined: (1) face-to-face classroom training to provide live foundational knowledge; (2) simulated practice course for a mixed theoretical-practice training; (3) on-the-job training.

BP10 In order to select the most suitable instructor for a specific course from a pool of internal qualified trainers, as suggested in the tenth best practice, the pharmaceutical company established the following procedure:

- Step 1: Identification of employees that match with the of ideal profile set for a trainer: be an expert on the subject (proficiency level 3 or 4) to be taught, have excellent communication skills, and be enthusiastic about training.
- Step 2: If the requirements of the ideal profile are identified by a team leader, the employee qualification will be composed of an interview followed by specific training, both behavioral training and a train the trainer session for any specific course to ensure standardized practices among trainers.

BP11 Based on the model proposed by Kirkpatrick [16], the following knowledge evaluation methods were defined: (1) Training reaction questionnaires for final knowledge assessment in theoretical courses; (2) Quizzes or multiple-choice tests for e-learning courses; (3) On-the-job observations to assess skills and proficiency levels when performing a task. The assessment methods and the proficiency levels are therefore correlated.

BP12 In order to promote executive managers and other key internal stakeholders, as stated by clause 4.2 of ISO 10018:2012, workshops and regular meetings were often held. To monitor stakeholders' perception about the project outcomes and the usefulness of those meeting and workshops, the NPS (Net Promoter Score) metric was adopted, while a ROTI (Return On Time Invested) matrix was filled at the end of each workshop. The ROTI matrix allows the measurement of the degree of return that an employee has compared to the time and effort invested [18], while the NPS value is useful to measures the degree of commitment of those involved in the project through a questionnaire [3].

BP13 To guide the implementation phase of the academy, the use of competence matrices to identify the existing training gaps and to manage the allocation of personnel to shifts and production lines in scheduling and production planning activities are of key importance. In this project, and attending to the reality of the pharmaceutical industry, it was decided that the competence matrix would only include task-related competences.

BP14 To be able to meet all required qualifications from a GMP perspective, a standard curriculum for each job function was created.

6.3 3rd Phase – Check: Assessment

BP15 As suggested in ISO 10015:2019, the evaluation of the training effectiveness activities should be carried out at this stage. To that purpose, the following sequence of steps was adopted:

- Identification of key performance indicators (KPIs): considering the principles for KPIs definition from ISO 22400:2014 [14], together with and the levels of measurement proposed by the ISO 10015:2019 to infer the impact of training activities on people development, a set of KPIs were proposed.
- Validation of KPIs: to validate the suggested indicators, interviews were conducted with members of the project team and managers. One could conclude that the KPIs were representative of the intended improvements, hence susceptible of being adopted in the future.
- Monitoring plan: due to time constraints related with the full academy implementation, the calculation of the proposed indicators was not possible to perform; however, to help measure these metrics in the future, a monitoring plan was established. It is suggested that the company use these indicators before and after the implementation of the academy. In addition, it is suggested that these indicators are assessed whenever a new training plan is allocated to a particular employee or group of employees.

6.4 4th Phase – Act: Monitoring and Continuous Improvement

BP16 As suggested by clause 5.7 of ISO 10015:2019, a monitoring plan of the proposed indicators was developed due to time constraints related with the full academy implementation, the calculation of the proposed indicators was not possible to perform; however, to help measure these metrics in the future, a monitoring plan was established. It is suggested that the company use these indicators before and after the implementation of the academy. In addition, it is suggested that these indicators are assessed whenever a new training plan is allocated to a particular employee or group of employees.

7 Results

This section of the paper aims to assess how the proposed model can contribute to simplifying the functioning of the training system. That assessment is organized around in the following categories: (i) Trainee's learning path; (ii) Training management system; (iii) Trainee motivation.

7.1 Impact on the Trainee's Learning Path

Because all training courses directly derived from the competences, redundant topics and training sessions could be avoided, thus leading to a reduction in the number of courses and required hours for theoretical course. According to estimates made, it is expected that the number of courses for manufacturing operator function can be reduced by about 80%, just by eliminating duplications and redundancies in the courses' offer, as well as in simplifying the training curricula. The number of hours spent by an associate manufacturing operator in theoretical course could be reduced from an average of 137 hours to just 55 hours without comprising any relevant content for this job function.

7.2 Impact on the Training Management System

According to Wang et al. [26] a competence matrix facilitates the process of scaling human resources to job tasks. In this regard, it is predicted an enhancement in the effectiveness of the activities related the personnel resource planning, including the scheduling of manufacturing operators. The matrix displays in a visual mode the proficiency levels a worker have for each competence that is necessary to perform a job.

Another positive impact of the model is enabling curricula standardization. It is intended that all responsibilities and job descriptions for each job function are clearly defined and communicated across all sites. With this in mind, a training plan can be automatically assigned by the LMS, thuss eliminating the dependency on departmental heads to perform that task. Consequently, it is expected that the time managers spend in developing a managing the training plan of their personnel can be reduced.

7.3 Impact on the Trainee Motivation

The company considered to be relevant the implementation of a LMS training platform to support training management activities. When compared with the existing one, the new LMS will allow a wide set of new functionalities, including the introduction of training content in video format and a more robust and accurate management of professional qualifications. It will allow restricted access to manual qualifications and to creation of new courses. This will improve the learning experience of the employees, contributing to their motivation.

Another important impact is the clarification of the curricula and learning path per job function, which promotes the creation of a continuous learning culture within the company. Due to the fact that training is provided throughout an employee career, personnel tend to be more committed, skilled, and empowered.

8 Conclusions

The pharmaceutical company to which the case study refers is part of a highly regulated business sector, where it is necessary to comply with a set of requirements including those related with the training and qualification of its employees. The literature review revealed a lack of available research studies concerning the design and development of a corporate training academy. To fill this gap, this paper proposed a new model containing a set of good practices, which also derived from a careful literature review.

The good practices were organized around a sequence that is aligned with the PDCA cycle, which is the foundational approach of both improvement and innovation cycles. The model was presented, employed, and validated. To that purpose, a set of interviews with experts from the company's Learning & Development area was conducted. The model was first tested in the API or drug substance manufacturing area.

The results of the case study, particularly in the mentioned area, show a significant reduction in the number of courses and hours required for training. In this way, one can conclude that the proposed model suits the business needs regarding training. Preliminary results also allowed the predict the following benefits: (1) Elimination of redundant theoretical courses and more proportion of time allocated to on-the-job training courses; (2) Decrease in the amount of unnecessary time spent on creating and managing training plans by the area managers; (3) Reduce the necessary time spent in planning and scheduling activities; (4) Increase the personnel motivation and their empowerment. Specific key performance indicators were suggested to measure and monitor whether the expected performance.

9 Suggestions for Future Work

After the implementation of the academy, it would be interesting to create and test a method model that allows measuring the degree of commitment of employees to the new training system. To that purpose, the percentages of attendance and training completion could be gathered, monitored, and analyzed using the functionalities of the new LMS. Additionally, it would be relevant to measure how the transformation of some courses from a traditional classroom format to e-learning will impact the knowledge management processes and their performance, including on the employee's turnover rate. Moreover, with would be useful to study how a significant greater proportion greater proportion of the on-the-job training can reduce the time to proficiency of a manufacturing operator. In parallel, it would be beneficial for the to conduct a survey to estimate determine the proportion percentage of employees who left the company after being trained and achieved the minimum level of proficiency to work autonomously in tasks. This would be necessary to determine if the new training system has a greater capability to retain employees in the company. This would also allow the assessment of the organizational risk of knowledge loss exit mentioned by Olander et al. [22].

References

1. Alpkan, L., Bulut, C., Gunday, G., Ulusoy, G., Kilic, K.: Organizational support for intrapreneurship and its interaction with human capital to enhance innovative performance. Management Decision 48(5), 732–755 (2010).
2. Armstrong, M.: Armstrong's handbook of human resource management. 13th edn. Kogan Page, London, UK (2014).
3. Baehre, S., O'Dwyer, M., O'Malley, L., Lee, N.: The use of Net Promoter Score (NPS) to predict sales growth: insights from an empirical investigation. Journal of the Academy of Marketing Science 50, 67–84 (2022).
4. Bontis, N.: Assessing knowledge assets: a review of the models used to measure intellectual capital. International Journal of Management Reviews 3(1), 41–61 (2001).
5. Carless, D.: Exploring learning-oriented assessment processes. Higher Education 69, 963–976 (2015).
6. Cavus, N., Uzunboylu, H., Ibrahim, D. Assessing the success rate of students using a learning management system together with a collaborative tool in web-based teaching of programming languages. Journal Educational Computing Research 36(3), 301–321 (2007).
7. Chang, W.-L., Chen, S.-T.: The performance of Taiwan's training quality excellence system. Total Quality Management & Business Excellence 24(5–6),561–576 (2013).
8. Darling-Hammond, L., Snyderb, J.: Authentic assessment of teaching in context. Teaching and Teacher Education 16(5–6), 523–545 (2000).
9. Dimov, D.: Towards a qualitative understanding of human capital in entrepreneurship research. International Journal of Entrepreneurial Behaviour and Research 23(2), 210–227 (2017).
10. Eich, S., Friedli, T.: Analysis of the effects of operational excellence implementation on inspection outcomes in the pharmaceutical industry: An empirical study. Brazilian Journal of Operations and Production Management 18(3), 1–5 (2021).
11. Huang, H.C., Lai, M.C., Lin, T.H.: Aligning intangible assets to innovation in biopharmaceutical industry. Expert Systems with Applications, 38(4), 3827–3834 (2011).
12. ISO – International Organization for Standardization: ISO 10015 | Quality management – Guidelines for competence management and people development, ISO Standard, Geneve, Switzerland (2019).
13. ISO – International Organization for Standardization: ISO 10018 | Quality management – Guidelines on people involvement and competence, ISO Standard, Geneve, Switzerland (2012)
14. ISO – International Organization for Standardization: ISO 22400-1 | Automation systems and integration – Key performance indicators (KPIs) for manufacturing operations management – Part 1: Overview, concepts, and terminology, ISO Standard, Geneve, Switzerland (2014).
15. ISO – International Organization for Standardization: ISO 30401 | Knowledge management systems – Requirements, ISO Standard, Geneve, Switzerland (2018).
16. Kirkpatrick, D.L.: Evaluating Training Programmes, Berrett-Koehler, San Francisco, CA, USA (1994).
17. Kuruba, M.: Role Competence Matrix, Springer, Singapore (2019).
18. Loeffler, M.: Improving Agile Retrospectives: Helping Teams Become More Efficient. Addison-Wesley Professional, Boston, MA, USA (2018).
19. Lwande, C., Muchemi, L., Oboko, R.: Identifying learning styles and cognitive traits in a learning management system. Heliyon, 7(8), e07701 (2021).

20. Mehralian, G., Rasekh, H.R., Akhavan, P., Ghatari, A.R.: Prioritization of intellectual capital indicators in knowledge-based industries: Evidence from pharmaceutical industry. International Journal of Information Management, 33(1), 209–216 (2013).
21. Narhi, L. O., Chou, D. K., Christian, Twinkle R., Gibson, S., Jagannathan, B., Jiskoot, W., Jordan, S., Sreedhara, A., Waxman, L., Das, T.K.: Stress Factors in Primary Packaging, Transportation and Handling of Protein Drug Products and Their Impact on Product Quality. Journal of Pharmaceutical Sciences (2022).
22. Olander, H., Hurmelinna-Laukkanen, P., & Heilmann, P.: Human resources – strength and weakness in protection of intellectual capital. Journal of Intellectual Capital, 16(4), 742–762 (2015).
23. Schneider, U., Friedli, T., Basu, P., Werani, J.: Operational Excellence in Practice – the Application of a Takt-Time Analysis in Pharmaceutical Manufacturing. Journal of Pharmaceutical Innovation 10(2), 99–108 (2015).
24. Tamkin, P., Yarnall, J., & Kerrin, M.: Kirkpatrick and Beyond: A review of models of training evaluation. Institute for Employment Studies, London, UK (2002).
25. Thepwongsa, I., Sripa, P., Muthukumar, R., Jenwitheesuk, K., Virasiri, S., Nonjui, P.: The effects of a newly established online learning management system: the perspectives of Thai medical students in a public medical school. Heliyon, 7(10), e08182 (2021).
26. Wang, X., Ferreira, F.A., Chang, C.: Multi-objective competency-based approach to project scheduling and staff assignment: Case study of an internal audit project. Socio-Economic Planning Sciences 81(C) (2022).
27. World Health Organization (2007). *Quality assurance of pharmaceuticals: A compendium of guidelines and relatedmaterials*, Volume 2, 2nd updated edition, WHO Press, Geneva, Switzerland.

Socioenvironmental Effectiveness of IoT: Structure and Elements of a Proposal Assessment Tool

Adriane Cavalieri, João Reis, and Marlene Amorim

Abstract The purpose of this research is to identify and describe the structure of an original assessment tool to support the evaluation of the socioenvironmental effectiveness of IoT technologies in manufacturing companies. The research methodology follows the systematic literature review applying Prisma process. The theoretical contributions are based on scientific-academic demands for empirical studies on IoT technologies towards sustainability and circular economy principles, which impacts the research on digital transformation oriented to environmental and social approaches. The contribution to management practices is an assessment tool, which provides support to the company's decision-making process regarding the use of IoT technologies oriented towards a socioenvironmental sustainability. The limitation of this research is the fact that the assessment tool is literature-based, without empirical evidence; it is relevant to get the contributions and suggestions of experts for feedback and new insights. Another limitation is the assessment tool has not yet been tested for its validity and reliability. On the other hand, these are an

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opportunity for future research, improving the assessment tool by applying the Delphi process and the mentioned tests. It is worth in future research, to extend this subject to the service sector. The authors believe that the assessment tool will push manufacturing company leaders' views on IoT technologies toward social and environmental sustainability, and circular economy principles, rather than merely associated with the organization's financial performance.

Keywords Internet of Things · Socioenvironmental effectiveness · Assessment tool

1 Introduction

The research focus on manufacturing since it regards as a major impact on the ecosystem and on working conditions from the point of view of environmental and social sustainability [1]. Besides, the approach that develops manufacturing industries towards sustainability or Triple Bottom Line (TBL) [2] is known as sustainable manufacturing [3].

Accordingly, there is a lack of a comprehensive understanding of Industry 4.0 technologies and sustainable manufacturing in relation to an empirical point of view [4–6]. The recognizing the sustainability priorities and the potential of the technologies, that there are still very specific and diversified experiences, open the way to the need for structured management tools that help managers/decision-makers plan the adoption of IoT. The purpose of this study is to offer a "building block" in this context.

In this regard, the central question is: What are the structure and the elements of the proposed assessment tool to guide the companies using IoT technologies to be oriented to socioenvironmental sustainability?

2 Concepts

The definition of "Sustainable Manufacturing" for this study follows the US Department of Commerce, mentioned by the Organization for Economic Cooperation and Development (OECD) Sustainable Manufacturing Toolkit, which considers "The creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" [7] (p. 4).

To some extent many of the prevalent business practices still emphasize the approach of achieving environmental sustainability by minimizing environmental impact while increasing economic gains. The focus remains on a linear approach to economy, for which the product life cycle is open (extraction, manufacturing, use, and disposal). In this context there is no use of waste in the production process itself.

Instead, the circular economy perspective emphasizes the restoration of technical cycles and the regeneration of biological cycles, without leaving aside the principles of sustainability [8]. The "Loop" or "Rs" approach translates circular economy principles into practical applications, closing the loop of the materials, components, products, and waste as inputs to produce other products [9].

IoT technologies are an enabler of sustainable practices in manufacturing contexts. IoT holds the potential to push towards sustainability while fueling the relationship between economic, environmental and social performances (TBL [2]) [5]. Some researchers claim that IoT technologies can improve the efficiency of the manufacturing process considering the "6R" model ("reduce," "reuse," "recycle," "recover," "redesign," and "remanufacture") to conserve natural resources [10, 11], on the other hand, the "10R" approach fits into a smart environment, as explained by Bag et al. [12].

The concept of IoT effectiveness at this work regards the degree of IoT alignment with socioenvironmental sustainability, following the phases of the project management life cycle [13, 14] to its operation in company. In this sense, the IoT technologies are considered effective once the actions or requirements oriented towards the socioenvironmental approach are fully developed and carried out by the company and/or its supply chain in a systematic and standardized way.

3 Research Methodology

The development of the proposed assessment tool was based on the Jabareen's [15] methodology and the systematic literature review using the PRISMA process [16], assisted by Refs. [17–21].

The PRISMA process [16] considered the Garetti and Taisch [1] suggestion regards the keywords "'Sustainable Manufacturing' OR 'Sustainable Production' OR 'Sustainable Operations'" adding the term "Internet of Things" to select the publications from the Web of Science (WoS) and Elsevier's Scopus databases. This research was conducted on 14 April 2022 [5]. The PRISMA process is shown at Fig. 1. The papers selected from PRISMA should contribute to the qualitative synthesis of the research. The 6 (six) papers selected are listed at Table 1.

After the six selected papers were mapped from PRISMA process, the Jabareen's [15] methodology supported the categorization, syntheses and resynthesizes of these papers. The categorization represents an extensive reading of the selected resource to identify and name the contents according to their main attributes, assumptions and roles. Therefore, they are organized and grouped via similarity of their concepts. The synthesis and resynthesis are an iterative process of identifying and naming the contents, combining and grouping them in relation to their concepts.

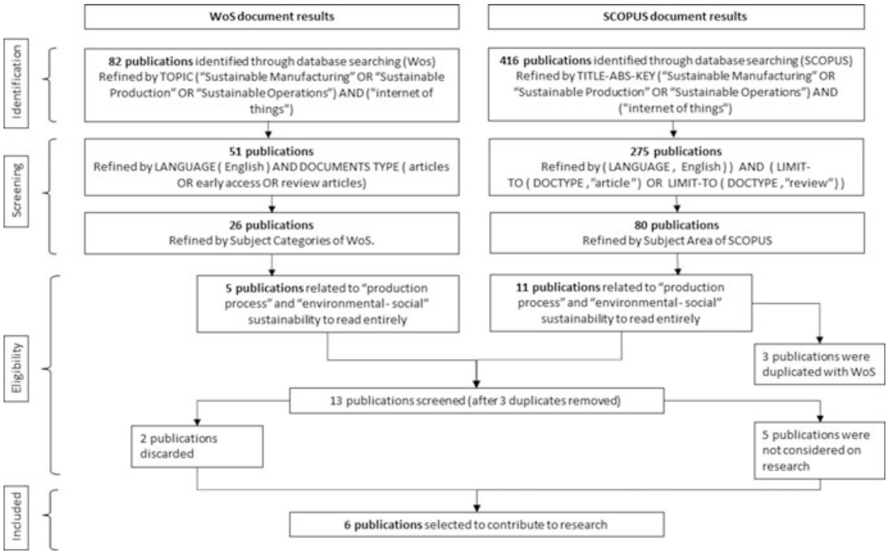

Fig. 1 PRISMA process

4 Result

The authors follows the Jabareen's methodology to develop the assessment tool employing the structure [18, 19]: (1) the dimension, which represents the theme to be evaluated (principal objective); (2) the construct, representing the subjects to be evaluated, related to that dimensions (secondary objective); (3) the statements, which are the different requirements (variables) organized and grouped in accordance to the constructs, that influence the indicators; (4) the qualitative indicators, in other words, the non-numerical factors which express the opinions of the respondents about the requirements presented at the statements of a specified construct, giving a sense of the direction in relation to the phenomenon towards a specific goal.

The dimensions of the assessment tool are the IoT technologies *per si* (IoT technology), and the IoT in relation to the environmental (Environmental dimension) and social (Social dimension) context.

The assessment of IoT *per si* diagnosis the expectation of the IoT as strategic and/or operational in company, the challenges and barriers to its implementation and use, which concerns the investigation of the potential of IoT to contribute to sustainability and circularity.

In addition, the IoT *per si* assesses the IoT characteristics (IoT technological capability, integration, process management and data flows), which objective is to understand the extent to which IoT is planned, developed, tested, deployed and being used by the company [14] in its manufacturing operations and in its supply chain to identify their strengths and weaknesses to sustainability and circularity.

Table 1 Papers selected to qualitative synthesis

Author	Title	Study Objective
Abubakr, M.; Abbas, A.T.; Tomaz, I.; Soliman, M.S.; Luqman, M.; Hegab, H [10]	Sustainable and Smart Manufacturing: An Integrated Approach	Integrating sustainable manufacturing and smart manufacturing; and discussing the current and future challenges that are faced by the manufacturing sector.
Feroz, A.K.; Zo, H.; Chiravuri, [22]	Digital Transformation and Environmental Sustainability: A Review and Research Agenda	Development of a framework that drives the digital transformation in the environmental sustainability domain in four key areas: pollution control, waste management, sustainable production, and urban sustainability.
Li, K.; Zhou, T.; Liu, B. [23]	Internet-Based Intelligent and Sustainable Manufacturing: Developments and Challenges	Exploring the current manufacturing concepts, technologies, framework features, application effects, resource optimization, and future challenges in the paradigms of emerging information and communication technologies such as Internet, cyber-physical system, Internet of Things, cloud computing, and big data.
Pasi, B.N.; Mahajan, S.K.; Rane, S.B [11]	The Current Sustainability Scenario of Company 4.0 Enabling Technologies in Indian Manufacturing Industries	Exploring the understanding of the Industry 4.0 (I4.0) concept among Indian manufacturing industries; determining the motivating factors for I4.0 implementation; identifying the enabling technologies; exploring the impact of these technologies on sustainability pillars; determining how Indian manufacturing industries interpret the concept of I4.0; and developing a road map for I4.0 implementation and sustainability.
Sartal, A.; Bellas, R.; Mejías, A.M.; García-Collado, A. [24]	The Sustainable Manufacturing Concept, Evolution and Opportunities within Company 4.0: A Literature Review	Addressing sustainable manufacturing opportunities within Industry 4.0 and explanation of these concepts. Exploring the impacts on production systems, management, the economy, the environment and society in a broader sense.
Waibel, M.W.; Steenkamp, L.P.; Moloko, N.; Oosthuizen, G.A. [25]	Investigating the Effects of Smart Production Systems on Sustainability Elements	Investigation of the technical, economic, social and environmental elements of possible smart production systems and the barriers and challenges to smart production.

The assessment tool evaluates the IoT connections with environmental and social contexts to investigate its contribution to the sustainability and circularity of materials, components, products and waste, or the regeneration of elements of nature; and the enhancement of human factors in the world of work. The focus is the evaluation of the company socioenvironmental engagement, the assessment procedures of the company and the indicators applied. Moreover, the tool evaluates the company's practices of the IoT with respect to (1) resources, products and waste, in order to identify its contribution to environmental sustainability and circular economy; (2) its relationship with employees to contribute to social sustainability; and (3) the company partners in order to identify its contribution to social and environmental sustainability in supply chain.

The statements and related items are grouped into constructs according to their attributes, what is shown as an example at Table 2.

The dimensions, constructs and their meanings are listed at Table 3. There are seven constructs for IoT technology dimension as: IoT expectations, IoT technology capacity, IoT technologies integration, IoT-based process management, IoT data, IoT challenges and IoT barriers; four constructs for environmental dimension as: company engagement, performance measurement methodology, performance indicators implementation and environmental sustainability and circular economy practices; and four constructs for social dimension as: company engagement, performance measurement methodology, performance indicators implementation and social sustainability practices.

The qualitative indicators reveal the phenomenon identified by the opinions of the respondents regarding the requirements presented at the statements. The constructs, the qualitative indicators and requirements are described at the Table 4.

The purpose of the assessment tool is supporting the evaluation of the social and environmental effectiveness of the IoT in manufacturing companies and its supply chain. Notably, it is intended to investigate the degree of alignment of IoT planning, implementation, and operations to the environmental and social contexts, and to what extent the results obtained from this alignment serve as a basis for achieving the environmental and social goals.

The assessment tool is designed to be applied from the perspective of the opinion of the leaders and employees respondents [18, 19] of the company investigated, as directors, production managers, project managers, supply chain managers, human resource managers, sustainability managers, shop floor employees, who work on processes using IoT in production and/or supply chain. As an example, regards the assessment of the expectation of the IoT, challenges and barriers to its implementation and use, the respondent registers his/her opinion about the statement by a Likert scale [21] with the extremes as "strongly disagree" to "strongly agree" [19].

Table 2 Statement examples

	Statement	Statement items
IoT technology construct		
IoT technologies integration	The intelligent network connections employing IoT technologies are established between different subsystems within . . .	A) . . . the company, including sensors, actuators control, management area and manufacturing (vertical integration) [10]. B) . . . different companies in the supply chain to share and exchange information (horizontal integration) [10].
Environmental approach construct		
Environmental sustainability and circular economy practices	The IoT supports the information and communication technologies, such as platforms and applications, which are employed within the 'intelligent shop floor' helping to reduce the . . .	A). . . energy consumption [24]. B). . . solid waste [24]. C). . . use of packaging [24]. D). . . by-products [24]. E). . . use of raw materials [23]. F). . . water consumption [23]. G). . . water waste [23].
Social approach construct		
Company engagement	As digital technologies develop dynamically, the training keeps employees up to date [11].	–

5 Discussion

The proposed assessment tool endorses the demand for survey research. There is greater attention to academic research on human thoughts, perceiving the importance of them as a source of knowledge concerning the phenomenon to be investigated, what generate the growth of the survey-based research [26]. On the other hand, with the advent of on-line survey platforms, the quality of survey studies has declined [27], consequently, the citation impact is declining either [26].

The survey research is criticized regards its development, usability, and analysis phases, because some issues warned its validity, including [26]: (1) Development: unprofessionally constructed questions; (2) Usability: sample bias (people surveyed are not representative of the population of interest), non-response bias (people completing the survey are not representative of the people receiving it) and response bias (people giving the survey inaccurate answers); (3) Analysis: unprofessionally analyzed questions, inadequate reporting.

In contrast, survey research specialist claims that "These problems might be overlooked even by experienced reviewers in fields where surveys have been rare. Thus, editors may consider ensuring that at least one specialist reviewer is always selected for surveys, may promote survey guidelines (. . .) on the website for authors

Table 3 Dimension, constructs and meanings

Constructs	IoT technology dimension	Constructs	Environmental dimension	Social dimension
IoT expectations	Assess the orientation of leaders and managers towards the use of IoT at manufacturing operations and the supply chain.	Company engagement	Assess the company's commitment to integrate environmental sustainability and/or circular economy principles with digital transformation at the manufacturing and supply chain operations.	Assess the company's commitment to integrate social sustainability with digital transformation at the manufacturing and supply chain operations.
IoT technology capacity	Assess the company's potential innovation resulting from the application of IoT technologies in its manufacturing operations and supply chain.	Performance measurement methodology	Assess the company's procedures to evaluate the negative/positive effects on the environment due to its manufacturing operations and its supply chain using IoT technologies.	Assess the company's procedures to evaluate the negative/positive effects on the human factor due to its manufacturing operations and its supply chain using IoT technologies.
IoT technologies integration	Assess company intelligence by IoT connectivity within the manufacturing operations and supply chain, with respect to identifying, selecting, analyzing, and managing relevant information of potential events or problems with real-time responses.	Performance indicators implementation	Assess how and what data/information the company captures from its processes and outcomes of local and/or external contexts in relation to the negative/positive effects at the environment due to its manufacturing operations and its supply chain using IoT technologies	Assess how and what data/information the company captures from its processes and outcomes of local and/or external contexts in relation to the negative/positive effects on the human factor due to its manufacturing operations and its supply chain using IoT technologies.
IoT-based process management	Assess the company management based on the use of IoT in manufacturing operations and supply chain.	Environmental sustainability and circular economy practices	Assess the results of integrating digital technology (IoT technologies) with environmental sustainability goals and/or circular economic principles to mitigate and/or eliminate negative effects and leverage positive effects on the environment due to manufacturing and the supply chain operations.	–

IoT data	Assess the company data flow related to IoT technology at the manufacturing operations and the supply chain to support decision makers.	Social sustainability practices	–	Assess the results of integrating digital technology (IoT technologies) and social sustainability goals to mitigate and/or eliminate negative effects and leverage positive effects on the human factor due to manufacturing and the supply chain operations.
IoT challenges	Assess the company's problems in operating IoT.			
IoT barriers	Assess the organizational, technological, governmental, and ecosystem obstacles that the company faces to implement IoT.			

Table 4 Constructs, qualitative indicators and requirements

IoT technology	Author (year)	Qualitative indicator	Requirements	IoT technology	Author (year)	Qualitative indicator	Requirements
IoT expectations	Feroz et al. (2021)	Leadership's view of IoT	IoT focus (valuable to the digitalized world; agent of improvement; agent of transformation).	IoT-based process management	Li et al. (2020)	IoT contribution to process management (supply chain)	Information sharing within the supply chain; collaboration within the supply chain; business decision-making by analyzing big data within the supply chain; information in real time from every node in the supply chain; sharing information to facilitate collaboration between people and things.
IoT technology capacity	Abubakr et al. (2020) Li et al. (2020) Pasi et al. (2021)	Technological sophistication definition	Data analysis; data mining; massive data storage; massive data retrieving; massive data processing; massive data analysis; data analytics applications; machine learning applications; artificial intelligence applications.			IoT contribution to process management (production operations)	Monitoring and controlling production process by collecting data; business decision-making by analyzing big data within the production process; sharing information to facilitate collaboration between people and things; interconnection of physical and virtual space (distributed devices embedded with computing,

							identification, communication, and sensing capabilities).
		Data management definition	Large amount of data through the cloud; real-time management; useful information to production decision-making.	IoT data	Li et al. (2020)	Data route definition (internal)	Warehousing management; production management; entire company operation.
		Interrelationship among the company intelligent constituent elements	Interrelationship among intelligent products; interrelationship among intelligent facilities; interrelationship among physical entities; interrelationship among networking components.			Data route definition (external)	Customer relationship management; supply chain; entire product lifecycle.
		Manufacturing network definition	Vertical integration (internal business departments); horizontal integration (between company and supply chain).	IoT challenges	Li et al. (2020)	Data access and utilization of "smart objects"	Identification and sensing of "smart objects"; data collecting for the identification of "smart objects".
IoT technologies integration	Abubakr et al. (2020) Pasi et al. (2021) Sartal et al. (2020)	Connections among the company intelligent network within the company	Production and other company departments; production and distributors; production and customers; different subsystems integration within the company (vertical integration).			Transference and data analysis results	Management of "smart objects"; transference of data by the network technology.

(continued)

Table 4 (continued)

IoT technology	Author (year)	Qualitative indicator	Requirements	IoT technology	Author (year)	Qualitative indicator	Requirements
		Connections among the company intelligent network within the company's supply chain	Different subsystems integration within different companies in the supply chain (horizontal integration).	IoT barriers	Pasi et al. (2021)	Organizational barriers	Senior management support system; top management system; perceptions for digital revolution; risky investment; digital strategy; data-based service system; fluctuation in production size.
		Shop floor interconnection definition	Interconnection of industrial processes by data analytics, machine learning, and artificial intelligence; monitoring wirelessly; controlling wirelessly.			Technological barriers	Technology cost; I4.0 standards; data security system; internet technology infrastructure and service centers; parts to be produced.
		Networked processes access and use	Machines negotiation and interaction to reconfigure the production; data collection; data exchange; data analysis.			Government and ecosystem maturity barriers	Government policies; supports from government; manufacturing company maturity; technology ecosystem; consultants and trainers in the field.
		Compatibility of the digital system	New smart system compatibility with old one.				

Environmental approach	Author (year)	Qualitative indicator	Requirements	Environmental approach	Author (year)	Qualitative indicator	Requirements
Company engagement	Abubakr et al. (2020) Feroz et al. (2021) Sartal et al. (2020)	Development of environmental sustainability strategy	Environmental situation prediction; environmental strategic goals definition; environmental strategic goals implementation; environmental goals measurement definitions.	Performance indicators implementation	Li et al. (2020) Sartal et al. (2020) Waibel et al. (2017)	Circular economy Assessment metrics within the company	Materials, parts, products reused; materials, parts, products sharing.
		Definition of sustainable manufacturing practices within company and its supply chain	Environmental awareness dissemination to the company's supply chain and customers.			Performance metrics for additional environmental liability	Energy and resource consumption of data centers; material consumption for electrical devices (require intensive extraction and processing efforts).

(continued)

Table 4 (continued)

Environmental approach	Author (year)	Qualitative indicator	Requirements	Environmental approach	Author (year)	Qualitative indicator	Requirements
		Development of environmental sustainability and digital transformation integration strategy	Integrated smart and environmental sustainability goals implementation; strategic decision process implementation based on digitalized technologies and environmental sustainability practices; new digitalized business practices pushed by eco-friendly customer needs.	Environmental sustainability and circular economy practices	Li et al. (2020) Sartal et al. (2020) Waibel et al. (2017)	Practices carried out in the linear economy	Raw material purchasing by demand; recycling.
		Development of new business model	Innovative digitalized business models to (e.g.) reduce carbon emissions and minimize solid waste.			Design for 10R within the company (intelligent use of the product and/ or the production process)	Eliminating harmful waste residue to the environment; reducing scrap on shop floor; reduce the entry of virgin resources; reduces CO2 emanations; new ways of coping

							with waste; product design oriented to product maintenance; product design oriented to recycling (end-to-end integration); product design oriented to product life cycle.
Performance measurement methodology	Abubakr et al. (2020) Sartal et al. (2020	Development of environmental sustainability assessment methodology	Criteria development to mitigate and/or eliminate negative effects of smart manufacturing on the environment; performance indicators development of the interconnected production process focusing on the environment; monitoring the real-time (by sensors) effects of the production process on the environment.			Design for 10R within the company's supply chain (intelligent use of the product and/ or the production process)	Share the raw materials; eliminating waste across entire value chain; reduce losses generated throughout the entire chain.

(continued)

Table 4 (continued)

Environmental approach	Author (year)	Qualitative indicator	Requirements	Environmental approach	Author (year)	Qualitative indicator	Requirements
		Guidelines for the environmental sustainability performance	Plans of sustainability performance metrics integrating smart manufacturing and environmental assessment; environmental sustainability assessment metrics agreed among employees; standard environmental sustainability assessment metrics			Design for 10R within the company's supply chain (increasing the useful time of the product or parts)	Reuse the raw materials; reuse the waste; share the waste; reutilization of materials in a remanufacturing process; enhancing sustainable consumption.
		Definition of tools and methods for "environmental sustainability and smart manufacturing" performance within the company shop floor	Reliable tools integrating environmental assessment and smart manufacturing; platforms and applications employed within the 'intelligent shop floor' to register production management information with a			Design for 10R within the company employing platforms and applications (intelligent use of the product and/ or the production process)	Energy consumption reduction; solid waste reduction; package use reduction; by-products reduction; raw materials use reduction; water consumption reduction; water waste reduction.

			focus on environmental sustainability.				
		Definition of tools and methods for "environmental sustainability and smart manufacturing" performance within the company's supply chain	Platforms and applications integrating production area with distributors to register distribution management information with a focus on environmental sustainability; platforms and applications integrating production area with customers to register post-sale management information with a focus on environmental sustainability.			Monitoring information of Environmental Components of Sustainability	Sensors provide real-time air quality monitoring information; better energy management through dynamic interconnection among energy providers – company – market demand; smart devices increase visibility and awareness of energy consumption.
		Development of data-driven smart algorithms for design "environmental	"Smart" algorithms to design sustainable manufacturing, sustainable supply			Monitoring information of Environmental and Economical	Intelligent processes simultaneously favor increased production rate,

(continued)

Table 4 (continued)

Environmental approach	Author (year)	Qualitative indicator	Requirements	Environmental approach	Author (year)	Qualitative indicator	Requirements
		sustainability and smart manufacturing”	chain, sustainable product end of life, and life cycle assessment.			Components of Sustainability	effective utilization of resources, reduction of carbon dioxide (CO2) emissions and waste reduction; clean manufacturing processes reduce the cost and the negative impact on the ecosystem.
Performance indicators implementation	Li et al. (2020) Sartal et al. (2020) Waibel et al. (2017)	Environmental sustainability assessment metrics within the company	Consumption of sources that are environmentally friendly, abundant, and locally available; raw materials consumption; energy consumption; water consumption; water waste; solid waste; by-products; packaging use; air pollution.				

Social approach	Author (year)	Qualitative indicator	Requirements	Social approach	Author (year)	Qualitative indicator	Requirements
Company engagement	Abubakr et al. (2020) Pasi et al. (2021) Sartal et al. (2020)	Politics for bilateral communication	Systems integration promote communication between different levels of the company, between manufacturing plants.	Performance indicators implementation	Abubakr et al. (2020) Sartal et al. (2020)	Worker adaptation	Continuously adaptation to the new restrictions imposed on job options.
		Development of training program for digital technologies	Training at the early stage of Industry 4.0 implementation; training keeps employees up to date.			Job sustainability	Capability of understanding the set information from diverse sources; capability of using the set of information from diverse sources; new skills; new profiles.
		Politics for a safer workplace	Digital technology solutions to career sustainability, to decrease workplace accidents, to increase employees' morale, to make work easier.			Self-learning	Capability of upgrade himself/herself abilities to perform new tasks.
		Politics for job retention	Retaining creative people; retaining people with strong analytical skill.			Continuous learning	Motivation for continuing education.

(continued)

Table 4 (continued)

Social approach	Author (year)	Qualitative indicator	Requirements	Social approach	Author (year)	Qualitative indicator	Requirements
Performance measurement methodology	An insight from references Abubakr et al. (2020) Sartal et al. (2020)	Development of social sustainability assessment methodology	Criteria development to mitigate and/or eliminate negative effects of smart manufacturing on human factor; performance indicators development of the interconnected production process focusing on the human factor.	Social sustainability practices	Abubakr et al. (2020) Pasi et al. (2021) Sartal et al. (2020)	Cognitive and analytical human skills	Manual work is reduced in favor of cognitive and analytical skills.
		Guidelines for the social sustainability performance	Plans of sustainability performance metrics integrating smart manufacturing and human factor assessment; standard human factor sustainability assessment metrics.			New skills and new profiles	Automation engineering; control system configuration; artificial intelligence; software engineering; machines communication and negotiation open the way and increase the demand for new jobs.
		Definition of tools and methods for "social sustainability and smart	Reliable tools integrating human factor assessment and			Concerns regarding unemployment	Machines communicate and make minor decisions without human

		manufacturing" performance	smart manufacturing.				intervention; shrinking the human workforce, thus lowering job opportunities; resistance against adopting Industry 4.0 initiatives; lose job due to insufficiency knowledge on digital technologies; being afraid of losing jobs; rejecting new instructions.
						New kind of working conditions	Better and safer working conditions; improving equipment for operator safety; better maintenance solutions; real-time hazard warnings; safety process, privacy, and ethical issues.
						Valorization of the human work	Machines work hand in hand with humans observing them and learning from them, complementing

(continued)

Table 4 (continued)

Social approach	Author (year)	Qualitative indicator	Requirements	Social approach	Author (year)	Qualitative indicator	Requirements
							humans, not replacing them; better division of work between humans and intelligent machines; analysis, cooperation and creativity continue to be carried out by human workers.
						Collaborative networks	Supply chain knowledge and experiences exchanging.
						Environmental, Economic, and Social Components of Sustainability (Triple Bottom Line – TBL)	Intelligent processes simultaneously favor operating costs reduction, profitability improvement, shop floor safety, and reduced company's impact on the environment.

(. . .) or may publish best-practice articles on the topic" [26](p. 10). Fairclough and Thelwall [26] mentions the study of Malhotra and Grover published on 1998, who calls for rigor in relation to survey research in the field of production management and operations similar to those carried out in the field of health [28].

The structure development of the assessment tool is rigorous to avoid one of the criticisms mentioned earlier as 'unprofessionally constructed questions'. On the other hand, the assessment tool is based on literature without empirical evidence. The tool has not yet been taken to the experts for evaluation [29], nor has been statistically tested [21]. From this perspective, it is relevant to get experts' contributions and their new insights, for example from consensus methods, and to test the validity and reliability of the assessment tool. The consensus and the validity processes should be studied and developed at a future work.

6 Conclusions

The assessment of IoT effectiveness is oriented to the 17 Sustainable Development Goals [30], and the circular economy principles [8].

The assessment tool evaluates the company orientation to innovation, the contribution to minimize waste, improve resource efficiency, minimize consumption of the resources, ensure access to affordable and renewable energy; the well-being of employees and the associated community, decent work, inclusive and equitable quality education and learning opportunities for employees, and supply chain partnerships to the establishment of the social and environmental goals.

Concerning the circular economy principles, the assessment tool assesses the opportunity for realizing the closed loop by intelligent use of the product and production process (reducing the use of raw materials; intensive use of the product); increasing the lifetime of the product or parts (product reuse, maintenance, product improvement, creating new products from parts or old products, reusing the product for a different purpose); and recycling, a practice even performed in the linear economy.

The authors believe that the assessment tool will push manufacturing company leaders' views on IoT technologies toward social and environmental sustainability, and circular economy principles, rather than merely associated with the organization's financial performance.

6.1 Managerial and Theory Contributions

The theory contributions rely on the scientific–academic demands empirical studies on IoT technologies towards sustainability and the circular economy approach, impacting the research on digital transformation supporting the environmental and social goals.

The contribution to management practices is that the assessment tool should be an input to the company's decision-making process regarding the use of IoT technologies oriented towards a social and environmental approach. The company leaders can use it together with other stakeholders as an assistance to understand the how, why and consequences, which will allow timely, planned, permanent and innovative actions to maximize strengths, minimize or eliminate the diagnosed weaknesses, and monitor future changes. The possibility of negotiating projects, ideas and strategies will emerge, favoring the debate of the industrial context towards sustainability, not only economically, but also related to social and environmental sustainability in the environment in which the company operates.

The research contribution is more than an assessment tool. In fact, it is almost closer to an "assessment methodology", i.e. it has the assessment instrument, but it also has some indications about who is addressed and how to apply, and some indications of how to analyze the results.

6.2 Research Limitations and Suggestions for Future Research

The limitation of this research is that the assessment tool is not tested concerning its validity and reliability. On the other hand, this is an opportunity to researchers improve the assessment tool based on the Ball [27] and Malhotra and Grover [28] studies in relation to, respectively: (1) the principles presented to conduct survey research covering the design of an online survey, validity and reliability, sample/sampling, the data collection and analysis, and the reporting survey data; and (2) the normative perspective on 'good survey research practices'.

Besides, the Delphi process should be applied at the future research to validate the assessment tool among experts' opinions, who give feedback, new insights and comments by consensus, gathering general agreement on topics that are ambiguous or controversial [29]. The other process such as usability and analysis should be studied and developed considering the Ball [27] and Malhotra and Grover [28] studies.

This research kept the focus on manufacturing. It is worth in future research extending this subject to the service sector to identify and understand from the scientific literature review, if there is applicability and, if so, the sector which is more developed and which is more deficient in the relationship between IoT and socioenvironmental sustainability.

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References

1. Garetti, M., Taisch, M.: Sustainable manufacturing: trends and research challenges. Prod. Plan. Control. 23, 83–104 (2012). https://doi.org/10.1080/09537287.2011.591619.
2. Hallinger, P.: Analyzing the intellectual structure of the Knowledge base on managing for sustainability, 1982–2019: A meta-analysis. Sustain. Dev. 28, 1493–1506 (2020). https://doi.org/10.1002/sd.2071.
3. Malek, J., Desai, T.N.: A systematic literature review to map literature focus of sustainable manufacturing. J. Clean. Prod. 256, 120345 (2020). https://doi.org/10.1016/j.jclepro.2020.120345.
4. Laskurain-Iturbe, I., Arana-Landín, G., Landeta-Manzano, B., Uriarte-Gallastegi, N.: Exploring the influence of industry 4.0 technologies on the circular economy. J. Clean. Prod. 321, 128944 (2021). https://doi.org/10.1016/j.jclepro.2021.128944.
5. Cavalieri, A., Reis, J., Amorim, M.: A Conceptual Model Proposal to Assess the Effectiveness of IoT in Sustainability Orientation in Manufacturing Industry: An Environmental and Social Focus. Appl. Sci. 12, 5661 (2022). https://doi.org/10.3390/app12115661.
6. Tambare, P., Meshram, C., Lee, C.-C., Ramteke, R.J., Imoize, A.L.: Performance Measurement System and Quality Management in Data-Driven Industry 4.0: A Review. Sensors. 22, 224 (2022).
7. OECD: The OECD Sustainable Manufacturing Toolkit. (2011).
8. Ellen MacArthur Foundation: Delivering the circular economy: A toolkit for policymakers. Ellen MacArthur Foundation (2015).
9. Cavalieri, A., Amorim, M., Reis, J.: Eco-Innovation and Digital Transformation Relationship: Circular Economy as a Focal Point. In: Tavares Thomé, A.M., Barbastefano, R.G., Scavarda, L. F., Gonçalves dos Reis, J.C., and Amorim, M.P.C. (eds.) Industrial Engineering and Operations Management. pp. 49–64. Springer International Publishing, Cham (2021). https://doi.org/10.1007/978-3-030-78570-3_4.
10. Abubakr, M., Abbas, A.T., Tomaz, I., Soliman, M.S., Luqman, M., Hegab, H.: Sustainable and Smart Manufacturing: An Integrated Approach. Sustainability. 12, 2280 (2020). https://doi.org/10.3390/su12062280.
11. Pasi, B.N., Mahajan, S.K., Rane, S.B.: The current sustainability scenario of Industry 4.0 enabling technologies in Indian manufacturing industries. Int. J. Product. Perform. Manag. 70, 1017–1048 (2021). https://doi.org/10.1108/IJPPM-04-2020-0196.

12. Bag, S., Gupta, S., Kumar, S.: Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development. Int. J. Prod. Econ. 231, 107844 (2021). https://doi.org/10.1016/j.ijpe.2020.107844.
13. Dinsmore, P., Cavalieri, A.: Como se tornar um profissional em gerenciamento de projetos. São Paulo: Qualitymark. (2010).
14. PMI ed: The standard for project management and a guide to the project management body of knowledge (PMBOK guide). Project Management Institute, Inc, Newtown Square, Pennsylvania (2021).
15. Jabareen, Y.: Building a Conceptual Framework: Philosophy, Definitions, and Procedure. Int. J. Qual. Methods. 8, 49–62 (2009). https://doi.org/10.1177/160940690900800406.
16. Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., for the PRISMA Group: Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ. 339, b2535–b2535 (2009). https://doi.org/10.1136/bmj.b2535.
17. Macedo-Soares, T.D.L. de: An Integrative Model for Strategic Analysis: Focussing Firms in Brazil. In: INFORMS-KORMS Conference Proceedings. pp. 460–467. Seoul (2000).
18. Cavalieri B., A.M.C.: Avaliação do desempenho da universidade no Brasil: um instrumento de auto-avaliação focando no ensino e na gestão., https://www.crie.ufrj.br/assets/Centro-de-estudos/Tese-Doutorado-Adriane-Cavalieri.pdf, (2001).
19. Cavalieri, A., Macedo-Soares, T.D. v. A. de, Thiollent, M.: Avaliando o Desempenho da Universidade. Loyola/PUC-Rio (2004).
20. Sá (Org.), P., Costa (Org.), A.P., Moreira (Org.), A.: Reflexões em torno de Metodologias de Investigação: recolha de dados. (2021). https://doi.org/10.34624/KA02-FQ42.
21. Sullivan, G.M., Artino Jr, A.R.: Analyzing and interpreting data from Likert-type scales. J. Grad. Med. Educ. 5, 541–542 (2013).
22. Feroz, A.K., Zo, H., Chiravuri, A.: Digital Transformation and Environmental Sustainability: A Review and Research Agenda. Sustainability. 13, 1530 (2021). https://doi.org/10.3390/su13031530.
23. Li, K., Zhou, T., Liu, B.: Internet-based intelligent and sustainable manufacturing: developments and challenges. Int. J. Adv. Manuf. Technol. 108, 1767–1791 (2020). https://doi.org/10.1007/s00170-020-05445-0.
24. Sartal, A., Bellas, R., Mejías, A.M., García-Collado, A.: The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review. Adv. Mech. Eng. 12, 168781402092523 (2020). https://doi.org/10.1177/1687814020925232.
25. Waibel, M.W., Steenkamp, L.P., Moloko, N., Oosthuizen, G.A.: Investigating the Effects of Smart Production Systems on Sustainability Elements. Procedia Manuf. 8, 731–737 (2017). https://doi.org/10.1016/j.promfg.2017.02.094.
26. Fairclough, R., Thelwall, M.: Questionnaires mentioned in academic research 1996–2019: Rapid increase but declining citation impact. Learn. Publ. leap. 1417 (2021). https://doi.org/10.1002/leap.1417.
27. Ball, H.L.: Conducting Online Surveys. J. Hum. Lact. 35, 5 (2019). https://doi.org/10.1177/0890334419848734.
28. Malhotra, M.K., Grover, V.: An assessment of survey research in POM: from constructs to theory. J. Oper. Manag. 16, 407–425 (1998). https://doi.org/10.1016/S0272-6963(98)00021-7.
29. Waggoner, J., Carline, J.D., Durning, S.J.: Is there a consensus on consensus methodology? Descriptions and recommendations for future consensus research. Acad. Med. 91, 663–668 (2016).
30. United Nations General Assembly: Transforming our world: the 2030 Agenda for Sustainable Development. U. N. N. Y. NY USA. (2015).

Monte Carlo Simulation Applied for the Identification of Arrival and Departure Constraints at the São Paulo International Airport, Brazil

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Abstract This paper presents a study that aims to identify operational bottlenecks at the São Paulo International Airport in Brazil. For this purpose, a Monte Carlo simulation model was developed, which uses random numbers to represent possible entries of a system. In this case, these entries are the numbers of arrivals and departures at each hour of the day. The Monte Carlo model is part of the group of static and discrete simulation models, that is, it is not able to show evolution over time and works with countable events, as is the case of the operations analyzed in this work. Given that São Paulo International Airport is the second largest in Latin America in number of flights – landings and takeoffs – and the inflexible nature of large physical structures to accommodate capacity changes in short periods, long-term planning is necessary in order to predict operational bottlenecks. The present study identified, from projections of the number of flights between October 2022 and March 2023, that there is the possibility of bottlenecks for both arrivals and departures if the operational capacity of the airport remains the same.

Keywords Monte Carlo · Simulation · Airport · Arrivals and departures

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1 Introduction

Decision-making models are important tools developed to assist decision makers in reaching a conclusion on which path is the best to solving a particular problem within the assessed scenario. Between 2003 and 2019, the number of articles with the keyword "decision making" increased almost seven-fold [1]. Several models can be used according to the scenario, the business and the decision needed to be made [2, 3]. The current study presents the application of a simulation method for reasons that will be clarified in the following paragraphs.

Events and systems simulation techniques have been applied for decades in order to understand their behaviors and even the relationship between their elements. With the popularization of computers and the exponential increase in processing capacity, new possibilities emerged, since complex scenarios that depend on several simulations to generate reliable results began to be executed in minutes [4].

One of the most commonly used simulation models is the Monte Carlo Model, which works with random numbers to represent system variables. This model fits into the group of static modeling and discrete events, that is, events that can be counted [5]. This is the case in the present study, since the number of arrivals and departures are discrete variables (increments of 1).

São Paulo International Airport (https://www.gru.com.br/pt/institucional/sobre-gru-airport) receives tens of thousands of daily flights; however, the number of runways and operational capacity are, a priori, static. On the other hand, demand can fluctuate considerably and, inevitably, the airport will reach its operational limit. Since it is impossible to do real tests with airplanes and runways to determine in which operations bottlenecks are identified, simulation tools are used for different scenarios.

This work used information available on the São Paulo International Airport website, such as projections of arrivals and departures, and operational capacity in order to identify, through the application of the Monte Carlo Model with Microsoft Excel, possible bottlenecks. These have been identified for both arrivals and departures.

2 Simulation

Simulation is one of the most widely used techniques among all of those available under the Operational Research umbrella. In the stricter sense, simulation means computational simulation, since it depends on the use of computers for its application [3].

According to [4], simulation models can be classified into two large groups: discrete and continuous. For the scenario under analysis in this work will be used a discrete simulation model, since flights are countable events and occur in increments of 1. By means of comparison, examples of continuous events are the distribution of electricity and oil production, whose volume is "uncountable".

2.1 Monte Carlo Simulation

According to [6, 7], Monte Carlo simulation uses a sample of possible results of a system to calculate the probability of occurrence of each of them and, later, uses random numbers to simulate such results.

Due to the relative ease of application, the model has been used in the resolution of problems that cover several areas, such as improvement of logistic modals for emergency response [8], definition of hazardous materials dump sites [9] and even boarding places for taxis around airports in order to reduce queues [10].

In the present work, the variables to be simulated are the number of arrivals and departures per hour of the day. Possible results for these variables were obtained through the projection made available by the airport itself on its website.

2.2 Monte Carlo Simulation Applied to Airport Operations Management

In this section a more in-depth analysis of the application of Monte Carlo simulation to airport operations and identification of operational constraints will be conducted.

According to [11], simulation has an important role when it comes to airport planning and improvement, and the work of [12] also highlights the relevance of the technique when assessing capacity constraints and developing mitigation strategies given its replicability and possibility to work with different scenarios.

As can be seen in Table 1 in the Appendix (from [13] through [21]), Monte Carlo simulation method has been applied to similar scenarios – or exactly the same scenario – as the one presented in this study. Studies dating from 1998 through 2022 corroborate the accuracy and relevance of the method and support the hypothesis of the present research that Monte Carlo simulation is indeed an applicable tool when trying to identify possible operational bottlenecks [22, 23].

3 Case Study

According to its own website (https://www.gru.com.br/pt/institucional/sobre-gru-airport/historico), São Paulo International Airport was founded in 1985 and is today the second largest airport in Latin America, with a total of 188,573 flights in 2021 (total number of landings and takeoffs, between domestic and international flights). However, this number was strongly impacted by the COVID-19 pandemic, which restricted the movement of people worldwide.

In 2014 the airport had a movement of 306,050 flights, a value 62% higher than that presented in 2021. The number of flights in July in the last 3 years – 2020 to 2022 – is presented in Table 2 and shows the great variation observed in the period.

Table 2 Number of flights in July 2020–2022

Year	Number of flights	Growth
2020	7227	
2021	17,331	140%
2022	22,091	27%

	A	B	C	D	E	F	G	H	I	J
4	Date	12:00:00 AM	1:00:00 AM	2:00:00 AM	3:00:00 AM	4:00:00 AM	5:00:00 AM	6:00:00 AM	7:00:00 AM	8:00:00 AM
5	2022-10-30	9	2	3	3	4	17	31	21	27
6	2022-10-31	13	3	4	6	5	26	31	30	28
7	2022-11-01	16	9	6	4	5	26	31	30	28
8	2022-11-02	16	8	7	6	7	23	31	30	29
9	2022-11-03	17	8	5	7	5	24	31	29	29
10	2022-11-04	16	8	7	6	5	26	31	30	30
11	2022-11-05	16	9	6	8	5	26	30	31	27
12	2022-11-06	10	2	4	3	4	17	31	24	26
13	2022-11-07	13	3	4	6	6	26	31	30	28
14	2022-11-08	16	9	6	4	5	26	31	30	28
15	2022-11-09	16	8	7	6	7	23	31	30	29
16	2022-11-10	17	8	5	7	5	24	31	29	29
17	2022-11-11	16	8	7	6	5	26	31	30	30

Fig. 1 Projection of arrivals per hour per day

The number of flights in July 2022 is close to the historical maximum in the same period in 2014 (27,176 flights), so due to the increase in the number of flights in recent years, it is important to identify possible operational bottlenecks that may arise in the coming periods. The following section presents the application of the Monte Carlo simulation model, used for this purpose.

3.1 *Application of Monte Carlo Simulation*

The São Paulo International Airport website, presented in the previous section, has a page with operational information and projections for future periods. For the application of the Monte Carlo model, the projection for arrivals and departures was used between October 2022 and March 2023.

Figure 1 shows the number of arrivals for a few days of the period under analysis. The same process was repeated for the number of departures.

From this projection, the quantities of flights per hour of the day were identified and the cumulative probability for each number of flights in the defined period was calculated.

Table 3 shows the projected flight quantities for the interval between 00:00 and 00:59 within the analyzed period and the cumulative percentage.

Using the cumulative percentage for all hours of the day and the Excel function that generates random numbers between 0 and 1 (=rand()), 150.000 replications were generated. From them, the average value of arrivals was obtained for each hour of the day.

Table 3 Arrivals between the hours of 00:00 and 00:59

Number of arrivals	Occurrences	% of total	Cumulative %
9	1	0.7%	0.7%
10	20	13.6%	14.3%
11	0	0%	14.3%
12	0	0%	14.3%
13	21	14.3%	28.6%
14	0	0%	28.6%
15	1	0.7%	29.3%
16	83	56.5%	85.7%
17	21	14.3%	100%
Total	147	100%	

	A	B	C	D	E	F
150205						
150206	Square root (n) n=150000	387.298				
150207	Confidence level	95%				
150208	Z α/2	1.96				
150209						
150210	Standard deviation	2.307	2.709	1.286	1.485	1.231
150211	Error	0.012	0.014	0.007	0.008	0.006
150212						
150213		12:00:00 AM	1:00:00 AM	2:00:00 AM	3:00:00 AM	4:00:00 AM
150214	Lower limit	14.988	6.986	4.993	5.992	5.994
150215	Average number of arrivals per hour	15	7	5	6	6
150216	Upper limit	15.012	7.014	5.007	6.008	6.006

Fig. 2 Average simulated number of arrivals per hour

By using a 95% confidence level and the number of replications mentioned above, it was possible to calculate the error associated with the mean, which in the case of arrivals was less than 0.02 flight at all hours.

Figure 2 contains a sample of the average values of arrivals per hour obtained by the simulation, as well as measurement error and lower and upper limits.

The same process was replicated for the departure operation and the numbers associated with the simulation are presented in Figs. 3 and 4, and in Table 4.

3.2 *Results*

The application of the Monte Carlo simulation model for the proposed scenario generated values of arrivals and departures per hour with a very low associated error, that is, the certainty of the values is high, according to the parameters used.

Comparing the values generated by the simulation and the numbers found on the São Paulo International Airport website for hourly flight capacity, a total of 5 periods in which the arrival capacity is not sufficient and 6 periods for departures can be identified, according to Figs. 5 and 6.

	A	B	C	D	E	F	G	H	I	J	K
4	Date	12:00:00 AM	1:00:00 AM	2:00:00 AM	3:00:00 AM	4:00:00 AM	5:00:00 AM	6:00:00 AM	7:00:00 AM	8:00:00 AM	9:00:00 AM
5	2022-10-30	3	7		3	2	3	25	25	30	29
6	2022-10-31	5	8		4	3	11	24	28	30	32
7	2022-11-01	5	8	4	7	8	13	26	28	30	31
8	2022-11-02	3	7	5	7	11	13	26	28	29	32
9	2022-11-03	4	9	5	7	8	12	25	29	29	31
10	2022-11-04	5	7	5	7	9	13	26	28	28	32
11	2022-11-05	3	10	5	7	9	12	27	27	31	29
12	2022-11-06	3	8		3	3	7	24	25	30	29
13	2022-11-07	6	9		4	3	11	24	28	30	32
14	2022-11-08	5	8	4	7	8	13	26	28	30	31
15	2022-11-09	3	7	5	7	11	13	26	28	29	32
16	2022-11-10	4	9	5	7	8	12	25	29	29	31
17	2022-11-11	5	7	5	7	9	13	26	28	28	32

Fig. 3 Projection of departures per hour per day

	A	B	C	D	E	F
150209						
150210	Square root (n) n=150000	387.2983346				
150211	Confidence level	95%				
150212	Z α/2	1.96				
150213						
150214	Standard deviation	1.089848957	0.9977648	0.400301	1.60273	2.9232831
150215	Error	0.005515397	0.0050494	0.0020258	0.0081109	0.0147939
150216						
150217		12:00:00 AM	1:00:00 AM	2:00:00 AM	3:00:00 AM	4:00:00 AM
150218	Lower limit	3.994	7.995	4.998	5.992	6.985
150219	Average number of departures per hour	4	8	5	6	7
150220	Upper limit	4.006	8.005	5.002	6.008	7.015

Fig. 4 Average simulated number of departures per hour

Table 4 Departures between the hours of 00:00 and 00:59

Number of departures	Occurrences	% of total	Cumulative %
3	63	42.8%	42.8%
4	21	14.3%	57.1%
5	46	31.3%	88.4%
6	17	11.6%	100.0%
Total	147	100%	

4 Conclusion

In order to identify possible operational bottlenecks in relation to the ability to accommodate more flights – arrivals and departures – at São Paulo International Airport, this work used projections provided by the airport itself to develop a Monte Carlo simulation model.

Morning	12:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00
Hourly arrival capacity	23	18	18	20	20	20	28	28	28	28	28	28
Hourly arrival demand – simulated	15	7	5	6	6	24	31	29	28	23	16	19
Hourly departure capacity	24	18	18	21	21	21	29	29	29	29	29	29
Hourly departure demand - simulated	4	8	5	6	7	12	26	28	30	30	28	10

Fig. 5 Simulated flight demand per hour of day and constraints – Morning period

Afternoon	12:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00
Hourly arrival capacity	28	28	28	28	28	28	28	28	28	28	28	28
Hourly arrival demand – simulated	16	27	23	17	20	23	28	31	30	26	20	14
Hourly departure capacity	29	29	29	29	29	29	29	29	29	29	29	29
Hourly departure demand - simulated	25	16	18	30	19	23	19	20	26	31	33	34

Fig. 6 Simulated flight demand per hour of day and constraints – Afternoon period

Due to the computational ease of generating numerous replications – in the case of this study, 150,000 for both arrivals and departures – in a few seconds, the level of error attributed to the calculations is very low, which means that the simulation results are reliable. Thus, periods of the day were identified in which there are chances of bottlenecks in both operations. Namely:

Arrivals:

From 05:00 to 07:59 in the morning and from 07:00 to 08:59 at night – total of 13 possible flights over the current capacity

Departures:

From 08:00 to 09:59 in the morning, from 03:00 to 03:59 in the afternoon and from 09:00 to 11:59 pm – total of 14 possible flights over the current capacity

It is important to note that, as mentioned in the previous section, the Monte Carlo Simulation model is static and, in the case of an airport operation – due to its magnitude, importance and costs associated with the changes – it is recommended to apply dynamic simulation models, which provide results as close to reality as possible. However, the results found by the present study can be used as initial parameters.

Appendix

Table 1 Literature review

References	Publication	Summary	Results
[13]	1998	Monte Carlo simulation was applied to determine if airplanes needing maintenance could be towed during peak hours without conflicting with landing airplanes.	Contrary to the initial hypothesis, the research shows that for the specific scenario, it is possible to tow aircrafts at peak hours without disrupting the airport operations.
[14]	1999	The authors used Monte Carlo simulation in order to understand airport capacities and constraints under the new definitions proposed by the European Aviation Council.	3 scenarios with different approaches are proposed and scenario 3 is shown to be the least restrictive.
[15]	2002	In this thesis, the author aims to evaluate runway layouts at Philadelphia International Airport by using simulation.	Although the author decides to use a different simulation method, it is explicit, through a literature review, that Monte Carlo simulation is sophisticated method to achieve the proposed goal.
[16]	2006	This study presents the application of the Monte Carlo method in assessing delay times of arrival and departure operations.	The results of the simulation show that the capacity of the airport can increase dramatically.
[17]	2015	The authors used Monte Carlo simulation to assess the viability of five different enhancement projects at an airport in London.	The authors state that one of the simulated projects would be able to increase peak hours movements by 21%, however, they also note that such projects also need an environmental evaluation before being approved.
[18]	2015	The Monte Carlo method was used to simulate the runway capacity of a Chinese airport.	The authors considered the application of Monte Carlo simulation successful since it was possible to identify improvement opportunities and the simulations only took about 1 minute to run.
[19]	2018	In this research, the author utilizes different techniques to assess the impacts of the implementation of safety procedures at high density traffic airports. Monte Carlo simulation was used to analyze delays and operational capacity.	The authors found that the airports presented a 32% reduction in maximum capacity, however, with scheduling optimization the operational constraints become insignificant.

(continued)

Table 1 (continued)

References	Publication	Summary	Results
[20]	2018	Monte Carlo simulation was used to confirm the feasibility of transitioning from a single-hub to multiple-hub infrastructure as the studied airport has already reached full capacity.	After assessing a few different scenarios, the author concludes that even with improvements to the current airport, it would face minimal delays, whereas no delays would be experienced if a new hub was built.
[21]	2022	With a database containing information on the operations of 239 airports in China, this study applies Monta Carlo simulation to three different scenarios to predict capacity constraints within a 10-year period.	After a thorough analysis, the authors could identify that the great majority of the airports studied do not experience overload, however, ten of them, international airports, stand out as having serious capacity constraints.

References

1. Costa, Igor Pinheiro de Araujo; Costa, Arthur Pinheiro de Araujo; Sanseverino, Adriana Manzolillo; Gomes, Carlos Francisco Simoes; Santos, Marcos dos. Bibliometric studies on multi-criteria decision analysis (MSDA) methods applied in military problems. Pesquisa Operacional (2022) 42: e249414 p.1–26
2. Almeida, Isaque David Pereira de; Costa, Igor Pinheiro de Araujo; Costa, Arthur Pinheiro de Araujo; Corriça, José Victor de Pina; Moreira, Miguel Ângelo Lellis; Gomes, Carlos Francisco Simoes; Santos, Marcos dos. A multicriteria decision-making approach to classify military bases for Brazilian Navy. Procedia Computer Science 199 (2022) 79–86
3. Costa, Igor Pinheiro de Araujo; Basílio, Marcio Pereira; Maêda, Sérgio Mitihiro do Nascimento, Rodrigues, Marcus Vinícius Gonçalves; Moreira, Miguel Ângelo Lellis; Gomes, Carlos Francisco Simoes; Santos, Marcos dos. Algorithm Selection for Machine Learning classification: An application of the MELCHIOR Multicriteria method. (2021) Modern Management based on Big Data II and Intelligent Systems III
4. Winston, Wayne L. Operations Research: Applications and Algorithms. 4th ed. California: Brooks/Cole, 2004
5. Hillier, F. S.; Lieberman, G. J. Introduction to Operations Research. 11th ed. New York: Mc-Graw Hill, 2021
6. Raychaudhuri, Samik. Introduction to Monte Carlo simulation. 2008 Winter Simulation Conference, 2008, pp. 91–100
7. Benton, D. James. Monte Carlo Simulation: The Art of Random Process Characterization. 1 ed. Independetly published, 2018
8. Banomyong, Ruth; Sopadang, Apichat. Using Monte Carlo simulation to refine emergency logistics response model. International Journal of Physical Distribution & Logistics Management, Vol. 40 Iss 8/9 pp. 709–721, 2010
9. Rabbani, M.; Heidari, R.; Yazdanparast, R. A Stochastic Multi-Period Industrial Hazardous Waste Location-Routing Problem: Integrating NSGA-II and Monte Carlo Simulation, European Journal of Operational Research (2018)

10. Wang, Xiu-Li; Wen, Qiang; Zhang, Zhao-Jun; Ren, And Mu. The Optimal Queuing Strategy for Airport Taxis. IEEE Access, vol. 8, pp. 208232–208239, 2020
11. Rakas, Jasenka; Mumayiz, Saleh. Airport-Airspace simulations for capacity evaluation. Transpostation Research Circular, n. E-C035, 2001, ISSN 0097-8515
12. Gelhausen, Marc C.; Berster, Peter; Wilken, Dieter. Airport capacity constraints and strategies for mitigation: A global perspective. 1 ed. California: Academic Press/Elsevier, 2020
13. Pitfield, D. E.; Brooke, A. S.; Jerrard, E. A. A Monte Carlo simulation of potentially conflicting ground movements at a newe international airport. Journal of Air Transport Management 4 (1998) 3–9
14. Pitfield, D. E.; Jerrard, E. A. Monte Carlo comes to rome a note on the estimation of unconstrained runway capacity at Rome Fiumucino International Airport. Journal of Air Transport Management 5 (1999) 185–192
15. Subramanian, Prakash. A simulation study to investigate runway capacity using TAAM. Thesis: Master of Business Administration in Aviation, Embry-Riddle Aeronautical University, 2002
16. Consiglio, Maria; Sturdy, James. Monte Carlo analysis of airport throughput and traffic delays using self separation procedures. ICAS 2006 – 25th Congress of the International Council of the Aeronautical Sciences
17. Irvine, Daniel; Budd, Lucy C.S.; Pitfield, David E. A Monte Carlo approach to estimating the effects of selected airport capacity options in London. Journal of Air Transport Management 42 (2015) 1–9
18. Wang, Fei; Zhao, LiGang. Capacity evaluation method for parallel runway based on Monte Carlo simulation. The 30th Chinese Control and Decision Conference, 2018
19. Perez-Castan, J.A.; Comendador, F. Gomez; Rodriguez-Sanz, A.; Montes, R. Barragan; Valdes, R. Arnaldo; Sanz, L. Perez. Impact of continuous climb operations on airport capacity. Transportation Research Part C: Emerging Technologies, vol. 96, November 2018, pp. 231–250
20. Karaman, Abdullah. Simulating air transportation networks under capacity constraints transforming into a multi-hub infrastructure. Kybernetes, Vol. 47 Issue: 6, pp.1122–1137, https://doi.org/10.1108/K-01-2017-0022
21. Hu, Rong; Feng, Huilin; Witlox, Frank; Zhang, Juefeng; Connor, Kevin O. Airport capacity constraints and air traffic demand in China. Journal of Air Transport Management 103 (2022) 102251
22. Zhang, H., Wu, W., Zhang, S., Witlox, F., 2020. Simulation analysis on flight delay propagation under different network configurations. IEEE 103236–103244. https://doi.org/10.1109/ACCESS.2020.2999098
23. Knabe, F., Schultz, M., 2016. A new way to indicate airport airside performance from an economic perspective. Transport. Res. Procedia 14, 3771–3780. https://doi.org/10.1016/j.trpro.2016.05.462

Binary Programming for Allocation of Players in Soccer Competitions by a Canadian Sports Event Management Company

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Abstract The resource allocation problem becomes more complex as resources and activities are added to the scenario as the possibility of combinations grows exponentially, since by adding only one resource or activity, the number of variables increases as a function of the product of available resources per activity. With that complexity factor in mind, this work develops a Binary Programming model with the objective of allowing a Canadian sports event management company to optimize the allocation of individually enrolled players in 14 different soccer competitions. The problem considers constraints such as players' availability on different days of the week, teams mix, minimum and maximum number of players per team, player skill level and different competitions on the same day. The aim of the model was to maximize the number of competitions each player will participate in, and although not all competitions had enough players allocated to them, the result was satisfactory as all players were allocated to at least one competition.

Keywords Binary programming · Resource allocation · Soccer · Competition

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1 Introduction

Studies involving the application of Operational Research (OR) to sports began at almost the same time the discipline was officially created, historically accepted as the period of World War II. Examples of application range from problems such as scheduling competitions that respect minimum rest intervals for athletes [1], strategies involving decisions of when to attack or defend against certain teams; to selection of players that minimizes hiring costs while optimizing the chances of the hiring team being champion [2].

Several decision-making methods that involve subjective assessment and dependent on the decision-maker experience have been developed [3, 4], however, this work involves the development of a Binary Programming model aiming to maximize the number of games played by 31 players who signed up individually – i.e. they are not part of a team – to a program that offers 14 different soccer competitions.

The problem was identified by a Canadian sports event management company when it needed to allocate players to different competitions knowing that each player has restrictions on the days of the week they can participate in, skill level, size, and team mix. The company has to ensure that all registered players participate in at least one competition and that no player is allocated to two or more competitions that take place on the same day.

The model presented in this work was structured using Microsoft Excel and solved with the help of Solver developed by the company Frontline Solvers (www.solver.com), which is similar to the native option of MS Excel, but is able to support all variables and constraints of the present problem. The results of the application of the model were satisfactory, since, although not all competitions have the minimum number of players allocated to them, all players will participate in at least one competition.

2 Mathematical Programming

As stated in [5], a Binary Programming problem resembles a Linear Programming problem (in which the objective function and constraints are linear equations), with the difference that all decision variables should accept only the values 0 or 1. This binary characteristic of variables can be interpreted as “yes-no”, “open-do not open” or “choose-do not choose” decisions. The latter example represents the decision problem addressed in this work, which intends to allocate, or not, certain players to specific competitions.

As defined in [6], the following system of equations is an example of a general binary programming model:

$$Max\ or\ \min Z = f(x1, x2, \ldots, xn) = c1x1 + c2x2 + \ldots + cnxn$$

Subject to:

$$\begin{gathered}
a11x1 + a12x2 + \ldots + a1nxn\ \{\leq, =, \geq\}\ b1 \\
a21x1 + a22x2 + \ldots + a2nxn\ \{\leq, =, \geq\}\ b2 \\
\ldots \\
am1x1 + am2x2 + \ldots + amnxn\ \{\leq, =, \geq\}\ bm \\
x1, x2, \ldots, xn \geq 0 \\
x1, x2, \ldots, xn\ binary
\end{gathered}$$

2.1 Operations Research in Sports

Although the application of mathematical tools for decision-making were already used long before World War II in various sectors of society (in fact there are precursor works of Operations Research (OR) dating back to the fifteenth century, according to [7]), that period is considered to be the era of the official emergence of OR. Great focus was given to the discipline at that time in order to optimize the allocation of scarce resources to soldiers and also assist in logistics decisions [8].

With the end of the war and the successful application of OR tools, professionals and universities began to focus their efforts both in applying the models already known as well as developing new models for solving civil problems, such as optimization of production mix, asset choices with greater profitability and even optimal location of facilities [8–10].

[8] explains that one topic under OR that has been massively studied in the past 60 years is the resource allocation problem, concerned with the optimal allocation of resources to specific activities in order to maximize productivity or minimize cost. The same authors also argues that the allocation problem can be seen in a variety of application areas, such as sales force allocation and portfolio selection.

As in other sectors that have limited resources and rely on well-founded strategic decisions to ensure economic viability, several organizations in the sports sector started to use optimization tools [11]. From firms involved in defining the best dates of football matches [12], the best strategic formation for a football team [13], sports marketing teams that need to optimize resource allocation for different advertising vehicles [14], strategy for changing tires in car racing [15], and even the best locations within a hockey rink for a player to score a goal [16].

The present work intends to apply a Binary Programming model for the allocation of players to different soccer competitions according to restrictions defined by the players themselves and others being characteristics of the competitions. This same modeling is widely used with several different objectives, such as allocating salespeople in different regions to maximize profit, identifying the ideal location to open a distribution centre so the logistics costs are minimized, among others [5].

2.2 Binary Programming and the Allocation Problem in Sports

Although apparently trivial, the allocation problem can become unmanageable without the use of an optimization model given the number of possible combinations between variables grows exponentially as those increase by one unit – such problems are called combinatorial optimization problems [17].

It is common to find allocation and scheduling studies involving sports in the literature, however most are concerned with scheduling of games at specific venues [18] and allocating games and players in ways to minimize tournament costs [19], rest duration differences between games [1], and group-strength fairness [20].

In this study, the authors are concerned with the formation of as many teams as possible by allocating players to different competitions with the objective of maximizing the number of competitions played by each player throughout the week.

3 Case Study

This section presents a case study referring to a Canadian sports event management company whose identified problem is intended to be solved with the application of a Binary Programming model.

In Canada, from mid-October until mid-March, low temperatures and snow make it difficult, when not impossible, to play sports outdoors, therefore many indoor multi-sports facilities are available to offer citizens the opportunity to play different sports during that period.

Although the number of facilities increase every year, it is challenging to accommodate everyone's individual needs and preferences, which lead a few municipal-level organizations to setup specific competitions at certain indoor facilities in order to make it possible for most people to attend as many games/sports as they please. Participants can enroll in those competitions either as part of a team or individually (the latter meaning that the company is responsible for allocating each person to as many competitions as possible according to his/her availability and competitions' constraints).

In this study, a company needs to allocate 31 individually enrolled players – including 19 men and 12 women – in 14 soccer competitions. Such competitions take place on different days (sometimes with more than one competition per day), are divided into 2 skill levels, co-ed (males and females in the same team) or 1-sex team, and number of players per team (Tables 1, 2 and 3). Tables 4 and 5 – in the Appendix – show the different characteristics of each competition, while Tables 1 and 2 identify the competitions in which each player can participate with the "Player x Competition" cell highlighted in blue and marked with an "x", e.g., Man 1 can play all competitions, while Woman 1 can participate only in competitions 3 and 8.

Table 1 Men's availability

	Competition													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Man 1														
Man 2														
Man 3														
Man 4														
Man 5														
Man 6														
Man 7														
Man 8														
Man 9														
Man 10														
Man 11														
Man 12														
Man 13														
Man 14														
Man 15														
Man 16														
Man 17														
Man 18														
Man 19														

Table 2 Women's availability

	Competition													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Woman 1														
Woman 2														
Woman 3														
Woman 4														
Woman 5														
Woman 6														
Woman 7														
Woman 8														
Woman 9														
Woman 10														
Woman 11														
Woman 12														

Table 3 Model result

	Competition										
	1	2	3	4	5	6	7	8	13	14	Competitions per week
Man 1	0	1	1	1	0	1	0	0	0	0	4
Man 2	1	1	1	1	0		1	0	0		5
Man 3		0	0	1	0			1		1	3
Man 4	0	0				1	0		1	1	3
Man 5	0	1	0		1		1	1	1		5
Man 6						1					1
Man 7			1					0			1
Man 8	0								1		1
Man 9	0			1	0				1		2
Man 10		0	0	1	0			1		1	3
Man 11	1	0	0	0	1	1	0	1	0	1	5
Man 12				1							1
Man 13	1	1	1		1		1	0	0		5
Man 14						1					1
Man 15	0	0	0	0	1	1	0	1	1	1	5
Man 16	0	0	1	0	1	0	1	0	0	0	3
Man 17	1		0	0	1	0	1	0	0		3
Man 18	1								0		1
Man 19		1				0	1			0	2
Woman 1			1					0			1
Woman 2	1	1	1		1		1	0	0		5
Woman 3	1	1	0	1	0	1	0	1	0	0	5
Woman 4	0								1		1
Woman 5	1			1	0						2
Woman 6	0		0	0	0	0	1	1	1		3
Woman 7										1	1
Woman 8		0				0	1			1	2
Woman 9	0	1	1		1		1	0	1		5
Woman 10						1	0				1
Woman 11			1	1					1	1	4
Woman 12			0	0	0			1			1

3.1 Computational Implementation

For the construction of this problem, each player i (i = 1, . . ., 31), provided his/her availability to play competition j (j = 1, . . ., 14). As the model must choose whether player i participates in competition j, variable xij must be 1 or 0 – binary variable – where 1 indicates that player i participates in competition j, and 0 if it does not participate in that competition. In the case of a player i, who cannot play competition j, the variable xij will not be included in the model.

The objective function of the problem seeks the maximization of the number of players participating in competitions, therefore:

$$\text{Maximize Z} = \sum xij \tag{1}$$

Subject to:

$$\mathrm{xij} = 0, \mathrm{i} = 20, \ldots, 31 \text{ and } \mathrm{j} = 10, 11 \tag{2}$$

$$\mathrm{xi1} + \mathrm{xi13} \leq 1, \mathrm{i} = 1, \ldots, 31 \tag{3}$$

$$\mathrm{xi2} + \mathrm{xi10} + \mathrm{xi14} \leq 1, \mathrm{i} = 1, \ldots, 31 \tag{4}$$

$$\mathrm{xi3} + \mathrm{xi8} \leq 1, \mathrm{i} = 1, \ldots, 31 \tag{5}$$

$$\mathrm{xi4} + \mathrm{xi5} + \mathrm{xi11} + \mathrm{xi12} \leq 1, \mathrm{i} = 1, \ldots, 31 \tag{6}$$

$$\mathrm{xi6} + \mathrm{xi7} + \mathrm{xi9} \leq 1, \mathrm{i} = 1, \ldots, 31 \tag{7}$$

$$\sum xij \geq 3, \mathrm{i} = 1, \ldots, 19 \text{ and } \mathrm{j} = 1, 2, 3, 8, 9, 13, 14 \tag{8}$$

$$\sum xij \leq 5, \mathrm{i} = 1, \ldots, 19 \text{ and } \mathrm{j} = 1, 2, 3, 8, 9, 13, 14 \tag{9}$$

$$\sum xij \geq 5, \mathrm{i} = 1, \ldots, 19 \text{ and } \mathrm{j} = 4, 5, 6, 7, 12 \tag{10}$$

$$\sum xij \leq 6, \mathrm{i} = 1, \ldots, 19 \text{ and } \mathrm{j} = 4, 5, 6, 7, 12 \tag{11}$$

$$\sum xij \geq 5, \mathrm{i} = 1, \ldots, 19 \text{ and } \mathrm{j} = 10, 11 \tag{12}$$

$$\sum xij \geq 2, \mathrm{i} = 20, \ldots, 31 \text{ and } \mathrm{j} = 1, \ldots, 14 \tag{13}$$

$$\sum xij \leq 4, \mathrm{i} = 20, \ldots, 31 \text{ and } \mathrm{j} = 1, \ldots, 14 \tag{14}$$

$$\sum xij \geq 5, \mathrm{i} = 1, \ldots, 31 \text{ and } \mathrm{j} = 1, 2, 3, 8, 9, 10, 11, 13, 14 \tag{15}$$

$$\sum xij \geq 7, \mathrm{i} = 1, \ldots, 31 \text{ and } \mathrm{j} = 4, 5, 6, 7, 12 \tag{16}$$

$$\text{xij is binary for all i and j} \tag{17}$$

$$i = 1, \ldots, 31 \text{ and } j = 1, \ldots, 14 \tag{18}$$

The problem's constraints are identified below:

1. The company's goal is to get all enrolled players to participate in at least one competition (Eq. 1 above)
2. No woman can participate in competitions 10 and 11, as they are exclusive to men, so they are highlighted in gray in Fig. 1 (Eq. 2 above)
3. Players cannot be allocated in more than one competition on the same day (Eqs. 3, 4, 5, 6 and 7 above)
4. In competitions with teams of 5 players, at least 3 and maximum 5 must be men (Eqs. 8 and 9 above)
5. In competitions with teams of 7 players, at least 5 and maximum 6 must be men (Eqs. 10 and 11 above)
6. Competitions 10 and 11 must have at least 5 men allocated to each o them (Eq. 12 above)
7. Co-ed competitions must have a minimum of 2 and a maximum of 4 women per team (Eqs. 13 and 14 above)
8. A competition only takes place if there are at least 5 or 7 players per team, according to the characteristic of the competition (Eqs. 15 and 16 above)
9. Every variable xij is binary, i.e., its value must be either 0 or 1 (Eq. 17 above)

Figure 1 – in the Appendix – shows the structure of the problem created in MS Excel, which has a total of 202 variables, 139 of which are associated with male players and 63 with female players, and 193 constraints.

3.2 Results

The Binary Programming model presented in the previous section, with all its constraints, does not have a possible solution, since the following cannot be respected:

- Allocate at least 3 men in Competition 9
- Allocate at least 5 men in Competitions 10 and 11
- Allocate at least 5 men in Competition 12

Thus, the authors chose to relax such constraints, that is, to exclude them from the model, and rerun it, which allowed the resolution of the problem and an optimal result for the new scenario was found. However, due to the relaxation of the previous constraints, the solution found cannot allocate enough players to Competitions 9, 10, 11 and 12. All other competitions had enough players allocated to them and the goal of allocating each player to at least one competition has been met (all players will participate in at least 1 competition and a maximum of 5 competitions). In addition, all other constraints have been respected.

Table 3 shows the competitions each player had availability to play highlighted in blue, similar to Tables 1 and 2, and also which competition each of them will be actually playing – 1 – and which they will not – 0 – as determined by the binary programming model. The table also shows, in the rightest column, the number of competitions per week each player was assigned to. Note that competitions 9, 10, 11 and 12 have been removed.

4 Conclusion

The use of an optimization model for the studied scenario can be considered successful, given the main objective was achieved in a timely manner. Due to the constraints associated with the competitions' rules, the prosed model could not find a solution that allocated enough players to all competitions, but the main goal – allocating every player to at least 1 competition – was achieved.

If the company in question had chosen to find the optimal solution manually, it should have worked with a number of possibilities in the order of 2^n, where n is the number of variables, therefore in the order of $2^{202} = 6.43 \times 10^{60}$ possibilities (without taking the constraints into account). In addition, there are companies responsible for defining calendars and allocating resources for major events and professional leagues, where variables can reach tens of thousands, making the problem impossible to solve without the application of an optimization model, such as that presented in this paper.

Although not in the scope of this work, therefore not a variable included in the optimization model, profit increase can be considered a secondary benefit of the application of the proposed model insofar as all players pay an enrollment fee to participate in the competitions, thus, the more players allocated, the higher the profit.

It should be noted that the model presented in this study is a proposal of an initial model, with the possibility of further studies to implement improvements according to operational needs. The methodology proposed in this paper can, however, be applied to the most diverse problems of the public, private or military sectors.

Appendix - Problem Structure in MS EXcel and Competitions by Team Size

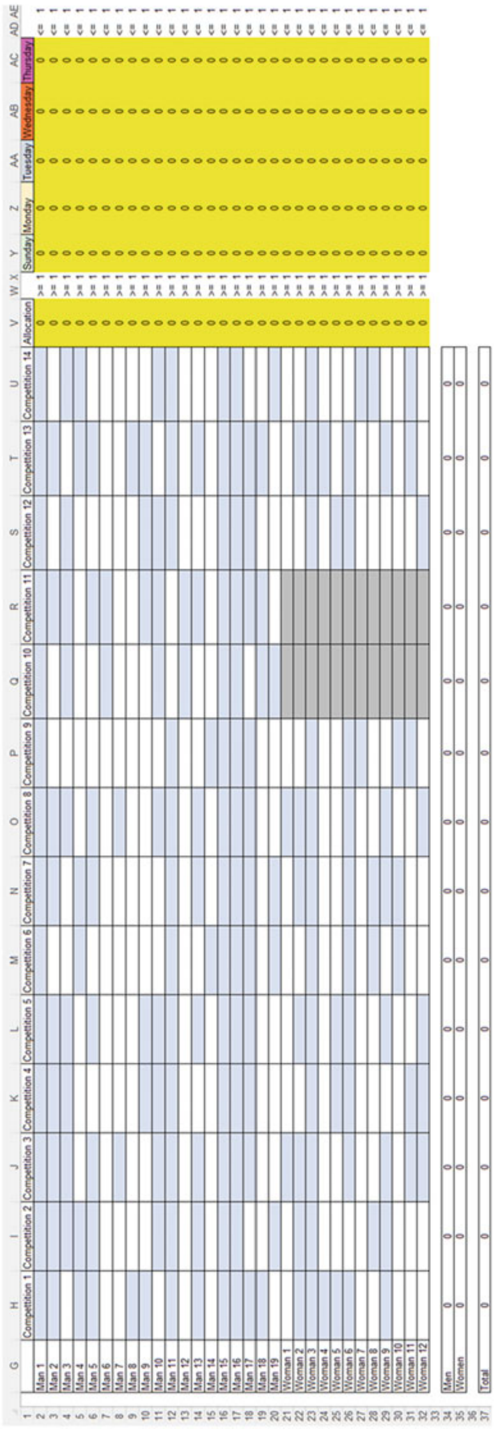

Fig. 1 Problem structured in MS Excel

Table 4 Competitions – 5-player teams

	Competition								
	1	2	3	8	9	10	11	13	14
Players	5v5	5v5	5v5	5v5	5v5	5v5	5v5	5v5	5v5
Weekday	Sunday	Monday	Tuesday	Tuesday	Thursday	Monday	Wednesday	Sunday	Monday
Skill	Recreative	Recreative	Recreative	Recreative	Competitive	Competitive	Recreative	Recreative	Competitive
Mix	Co-ed	Co-ed	Co-ed	Co-ed	Co-ed	Men's	Men's	Co-ed	Co-ed

Table 5 Competitions – 7-player teams

	Competition				
	4	5	6	7	12
Players	7v7	7v7	7v7	7v7	7v7
Weekday	Wednesday	Wednesday	Thursday	Thursday	Wednesday
Skill	Competitive	Recreative	Competitive	Recreative	Competitive
Mix	Co-ed	Co-ed	Co-ed	Co-ed	Co-ed

References

1. Tuffaha, Tasbih; Çavdaroglu, Burak; Atan, Tankut. Timetabling Round Robin Tournaments with the Consideration of Rest Durations. Proceedings of the 13th International Conference on the Practice and Theory of Automated Timetabling – PATAT 2021: Volume II
2. Salles, Segio Augusto Faria; Hora, Henrique Rego Monteiro da; Erthal, Milton; Santos, Ana Carla Souza Gomes dos. Operations Research Contributions for Football Teams Formation: A Systematic Review. Brazilian Operations Research Society, Pesquisa Operacional (2019) 39(2): 277–293
3. Santos, Nicole; Rocha Junior, Claudio de Souza; Moreira, Miguel Ângelo Lellis; Santos, Marcos dos; Gomes, Carlos Francisco Simões; Costa, Igor Pinheiro de Araújo. Strategy Analysis for Project portfolio evaluation in a technology consulting company by the hybrid method THOR. Procedia Computer Science 199 (2022) 134–141
4. Maêda, Sérgio Mitihiro do Nasciment; Basílio, Marcio Pereira; Costa, Igor Pinheiro de Araújo; Moreira, Miguel Ângelo Lellis; Santos, Marcos dos; Gomes, Carlos Francisco Simões. The SAPEVO-M-NC Method. Modern Management based on Big Data II and Machine Learning and Intelligent Systems III, 2021
5. Winston, Wayne L. Operations Research: Applications and Algorithms. 4 ed. California: Brooks/Cole, 2004
6. Favero, Luiz Paulo; Belfiori, Patricia. Data Science for Business and Decision Making. 1 ed. Cambridge: Academic Press, 2019
7. Bouyssou, Denis. Review of "An annotated timeline of Operations Research, An informal history" by Saul I. Gass and Arjang A. Assad, Kluwer, 2005. European Journal of Operational Research 174(1):671–674, October 2006
8. Hillier, F. S.; Lieberman, G. J. Introduction to Operations Research. 11 ed. New York: Mc-Graw Hill, 2021
9. Katsikis, Vasilios N.; Mourtas, Spyridon D. Binary Beetle Antennae Search Algorithm for Tangency Portfolio Diversification, Journal of Modeling and Optimization 2021;13(1):44–50
10. Katoh, N. (2001). Combinatorial Optimization Algorithms in Resource Allocation Problems. In: Floudas, C.A., Pardalos, P.M. (eds) Encyclopedia of Optimization. Springer, Boston, MA. https://doi.org/10.1007/0-306-48332-7_56
11. Mottley, Charles M. The Application of Operations-Research Methods to Athletic Games, Journal of the Operations Research Society of America, Vol. 2, No. 3 (Aug., 1954), pp. 335–338
12. Goçgun, Yasin; Bakır, Niyazi Onur. Optimal matchday schedule for Turkish professional soccer league using nonlinear binary integer programming, An International Journal of Optimization and Control: Theories & Applications, Vol.12, No.2, pp.113–127 (2022)
13. Budak, Gercek; Kara, Imdat; Iç, Yusuf Tansel; Kasimbeyli, Refail. New mathematical models for team formation of sports clubs before the match. Cent Eur J Oper Res 27, 93–109 (2019)

14. Bamford, David R.; Hannibal, Claire; Kauppi, Katri; Dehe, Benjamin. Going the distance: Sport operations management in the public and third sectors, Public Service Operations Management: A research handbook, 1 ed. New York: Routledge, 2015
15. Maharwal, Akshat; Sanghavi, Akshit; Jaipuria, Anoushka; Kapoor, Arpan; Bhardwaj, Bhagya. Application of Operations Research in Gaming and Sports, International Journal of Scientific & Engineering Research Volume 10, Issue 10, October-2019
16. Becker, Devan G.; Woolford, Douglas G.; Dean, Charmaine B. Algorithmically deconstructing shot locations as a method for shot quality in hockey, J. Quant. Anal. Sports 2021; 17(2): 107–115
17. Rasmussen, Rasmus V.; Trick, Michael A. Round robin scheduling – a survey. European Journal of Operational Research, volume 188, Issue 3, 2008, https://doi.org/10.1016/j.ejor.2007.05.046
18. Croce, F. Della; Tadei, R.; Asioli, P. S. Scheduling a round robin tennis tournament under courts and players availability constraints. Annals of Operations Research 92 (1999) 349–361. DOI: https://doi.org/10.1023/A:1018999101596
19. Kendall, Graham; Knust, Sigrid; Ribeiro, Celso C.; Urrutia, Sebastian. Scheduling in sports: Na annotated bibliography. Computers & Operations Research, volume 37, Issue 1, 2010, https://doi.org/10.1016/j.cor.2009.05.013
20. Dirk Briskorn; Sigrid Knust. Constructing fair sports league schedules with regard to strength groups, Discrete Applied Mathematics, volume 158, Issue 2, 2010, https://doi.org/10.1016/j.dam.2009.08.006

Analysis of Dentists Allocation in Health Care Centers: A Case of Qatar

Reem Hassan A. A. Alabdulmalik and Shaligram Pokharel

Abstract The paper proposes an analytical model to assess the current allocations of dentists based on patient visits in a number of clinics. The model is formulated as a linear programming resource allocation model to maximize the number of dentists to be allocated for clinics inside the healthcare centers. The model is applied to a case of primary healthcare centers' dental clinics across Qatar. The analysis shows that the current trend of patient visits in different healthcare centers is causing long queues for appointment dates and long waiting times inside the health centers. Therefore, based on the current and project visits, the analysis shows how reallocation with the current number of dentists and reallocation with an increased number of dentists and an increased number of patient visits can increase the efficiency of the dental clinics. The paper reports some scenarios for consideration by the decision-makers.

Keywords Healthcare · Resource allocation · Modeling · Scenario analysis

1 Introduction

A responsive healthcare system should be able to reduce waiting times as it is one of the critical factors to assess the access and ease of healthcare in a country [1]. When primary healthcare facilities are available, they become the first point for investigation and referral of a patient. Therefore, the allocation of resources in such facilities becomes important. Therefore, long waiting time becomes a concern of healthcare providers.

Longer times for waiting can result in overcrowding of the centers, frustration of the patients and the staff attending the centers, and uneven utilization of resources. Although an easy solution could be to increase the number of service providers, that may be costly and may not resolve the long-term allocation problems of uneven distribution of resources among the healthcare centers. As there are walk-in patients

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and appointment-based (allocated) patients, there could be no shows of allocated patients would result in underutilization of the resources, and this might happen due to the longer waiting time, once the patient arrives in the health center.

Keeping up with patient demand while maintaining high treatment standards has been a persistent problem for the healthcare sector. Patient conditions deteriorate, patient dissatisfaction rises, and the organization's image will tarnish when healthcare facilities are plagued by long waiting times, a lack of timely appointments, and a high level of no-show patients. Over the past year, patients have consistently ranked the issue of waiting time as one of their top concerns, especially at the Dental and Ophthalmology Clinics in Qatar's Primary Healthcare Centers. Long patient waiting times, a lack of available appointment times, and the need to keep healthcare providers on the clock longer are just some of the challenges the clinics face. Therefore, the two main objectives being discussed in this paper are: (i) the development of a resource allocation model suitable for healthcare centers and (ii) analyze the data from the dental clinics for better allocation/scheduling of dentists. It is to note that although scheduling/allocation of dentists also means the allocation of resources (equipment/accessories and staff), separate allocation of these resources is not considered here, as the number or the quantity of these resources to be attached to a dentist is fixed.

2 Review of Literature

Resource allocation problem provide decision-making challenges as multiple factors such as skills set, time period, and resource constraints have to be considered. However, when only one type of resource is considered, the skill sets can be of less problem than the numbers of patients to be served. Human resources allocation in healthcare centers is also considered challenging by Bouajaja and Dridi [2]. Scheduling imposes challenges on the availability of resources for a specific period [3] and this is compounded by the need to address unplanned appointments by the clinics.

Researchers have used different models to analyze resource allocations. For example, Makena [4] use data mining and time-stamped observations in a simulation model to evaluate the effectiveness of the outpatient clinic. The authors measured clinic efficiency by considering three appointment lengths (time). The authors mention that if supporting staff is used, the patient wait times and inefficiency in resource allocations of the main medical service provider can be reduced. Another simulation model is used by Lin et al. [5] to examine the difficulties faced by outpatient clinics in regulating staff overtime, patient wait times, and crowded waiting areas by using a two-stage simulation model. The analysis done for an ophthalmology clinic of a public hospital shows that enhancing resource flexibility at bottleneck processes can help in scheduling and may require no additional resources.

Resources allocations in different disciplines may be useful for healthcare applications as well. Shohaimay et al. [6] used the optimization model for allocating instructors in a teaching institution. The authors conducted a case study for one semester to allocate 141 teaching hours among nine instructors to obtain optimal allocations. Such optima. allocation of faculty is also considered by Das et al. [7].

Optimal allocation model for healthcare is studied by Kamran et al. [8] by considering manpower and equipment for emergency services in a medical center. The authors formulated multiple objectives and solved them with a goal-programming approach. Metsakoivu [9] proposed an integer programming model to develop a policy for advanced scheduling and capacity allocation to minimize patient wait times, and the underutilized available resources. Silva and Nunes [10] formulated a pair of integer linear programming models to reduce workload disparity while increasing workload parity.

3 Model Development

A linear programming model is proposed to get the required number of dentists allocated to each healthcare center-dental clinic to serve the patients. A similar type of model has been developed for teachers' resource allocation by Shohaimay et al. [6]. However, the model was modified to fit the needs of this project report. The indices used for the model are given below:

i = Healthcare center (e.g., ARP, OBK, . . ., WAJ).
j = Dental clinic1..J inside a healthcare center.
di = Number of dentists to be allocated in healthcare center i.
dHi = Minimum number of dentists required in a healthcare center.
bi = Weight associated with the importance of doctors in clinic i.
Cj = Number of dental clinics in each healthcare center.

The objective function of the model is to minimize the required number of dentists to be allocated at the healthcare centers' dental clinics for the patient loads.

$$\text{Min Z} = \sum_{i=1}^{28} d_i b_i \tag{1}$$

subject to

$$\text{di} \geq \text{dHi} \tag{2}$$

$$\text{di} \geq \text{Cj} \tag{3}$$

$$\sum \boldsymbol{d_i} = 212 \tag{4}$$

$$\text{di} \geq 0, \text{integer} \tag{5}$$

To calculate the minimum number of required dentists per healthcare center, the number of patients per dentist is calculated first as:

$$\text{Number of patients per dentist} = \frac{total\ number\ of\ patients\ visists}{total\ number\ of\ dentists\ available} \quad (6)$$

Then, the minimum number of required dentists is calculated by dividing the total number of patient visits by the number of patients per dentist. The formula used is as below:

$$\text{Min required dentists/healthcare center} = \frac{total\ number\ of\ patients\ visists\ (HC)}{number\ of\ patients\ per\ dentist} \quad (7)$$

4 Data Collection and Analysis

Patient visit, resources available, and resource allocation data for the analysis was obtained from the Primary Health Care Center (PHCC). The data (Table 1) shows that although a good amount of required dental staff is deputed in the organization, the average percentage of dental clinic utilization is only 51%, which may be due to an improper assignment of dentists in the PHCC dental clinics. The data shows the name of the healthcare centers, the total number of appointment visits and walk-in visits, the number of dental clinics (rooms) in each health center, the initial allocation of dentists, and their distribution among the morning and evening shifts. The name of the health centers has been disguised in the table.

For the application of the model, as a constraint, at least one dentist per healthcare center should be allocated and all health centers are to be considered equally important (bi = 1). It requires that the total number of dentists allocated across all 28 healthcare centers must not exceed the number of available dentists. The total number of dentists across all the health centers has been set to 212, which is the current number of available dentists. The solution for the analysis is obtained through Microsoft Excel Solver. Equations (6) an (7) are evaluated as per the following.

$$\text{Number of patients per dentist} = \frac{total\ number\ of\ patients\ visists}{total\ number\ of\ dentists\ available}$$

$$= \frac{592565}{212} = 2795$$

For example, the minimum number of required dentists to be allocated in RAK is:

Table 1 PHCC-dental clinic data from January 2022 to December 2022

Healthcare center	Patients			# of dental clinics in the healthcare center	Dentist allocations		
	Appointment	Walk-in	Total visits		Current PHCC allocation	AM	PM
LBB	24,887	15,569	**40,456**	10	19	10	9
MUA	25,286	16,651	**41,937**	10	16	8	8
ABS	17,273	17,594	**34,867**	5	10	5	5
RAK	13,825	14,694	**28,519**	10	17	10	7
UMS	20,626	13,346	**33,972**	6	13	7	6
THM	17,776	13,122	**30,898**	8	13	7	6
MES	16,266	9841	**26,107**	5	11	6	5
WAJ	15,869	11,067	**26,936**	10	10	5	5
WAB	15,110	10,365	**25,475**	8	10	5	5
ABN	16,704	15,273	**31,977**	5	10	5	5
OBK	18,524	10,717	**29,241**	5	9	5	4
QUN	13,347	7759	**22,106**	8	9	5	4
RYN	16,474	15,271	**31,745**	4	8	4	4
WAK	18,577	11,078	**29,655**	4	8	4	4
ARP	13,685	8479	**22,164**	4	7	4	3
WBC	14,199	11,718	**25,917**	3	6	3	3
GHR	14,338	11,473	**25,811**	3	6	3	3
MKH	10,253	8038	**18,291**	3	6	3	3
DYN	7323	6285	**13,608**	3	6	3	3
SHN	7403	5998	**13,401**	2	5	3	2
KHR	8611	6719	**15,330**	4	4	2	2
UMG	5148	3912	**9060**	2	4	2	2
RUW	2631	2594	**5225**	6	3	2	1
SWK	3022	1705	**4727**	1	2	1	1
KAR	902	1178	**2080**	1	1	1	0
JUM	504	665	**1169**	1	1	1	0
GHW	448	495	**943**	1	1	1	0
KBN	449	499	**948**	1	1	1	0

$$\text{Number of dentists} = \frac{total\ number\ of\ patients\ visists\ (HC)}{number\ of\ patients/dentist} = \frac{28519}{2795}$$

$$\approx 10\ dentists$$

Table 2 Resource allocation results from linear programming model

Healthcare center	# of clinics in the healthcare center	Current PHCC Allocation	Total dentists allocated with the model (base case)	Differences
MUA	10	16	**15**	−1
LBB	10	19	**14**	−5
ABS	5	10	**12**	2
UMS	6	13	**12**	−1
RAK	10	17	**12**	−5
RYN	4	8	**11**	3
THM	8	13	**11**	−2
ABN	3	6	**11**	5
WAK	4	8	**10**	2
OBK	5	9	**10**	1
WAJ	10	10	**10**	0
MES	5	11	**9**	−2
WBC	3	6	**9**	3
GHR	3	6	**9**	3
WAB	8	10	**9**	−1
QUN	8	9	**8**	−1
ARP	4	7	**7**	0
MKH	3	6	**6**	0
RUW	6	3	**6**	3
KHR	4	4	**5**	1
DYN	3	6	**4**	−2
SHN	2	5	**4**	−1
UMG	2	4	**3**	−1
SWK	1	2	**1**	−1
KAR	1	1	**1**	0
JUM	1	1	**1**	0
GHW	1	1	**1**	0
KBN	1	1	**1**	0
Grand total	131	212	**212**	0

4.1 Results of the Analysis

The result of data analysis is shown in Table 2. The data shows that WAK, WBC, GHR, ABS, ABN, and RYN healthcare centers need to have more dentists to be allocated than the available clinics/rooms in the health center. This is because these health centers have more patients than those with more clinics. A classic example is RYN, which has only 4 clinics, but the model has allocated 11 dentists there compared to QUN health center with 8 clinics (double the number of clinics), with 8 dentists allocated only. This is due to patients' visits to the respective health center. RYN has 31,745 patient visits compared to QUN, which has 22,106 visits from

Table 3 Linear programming-scenario analysis results

Healthcare center	Current PHCC allocation	Base case optimal allocation	Scenario	
			Allocation of dentists per clinic	Changes compared to the optimal solution
MUA	16	**15**	16	1
LBB	19	**14**	15	1
ABS	10	**12**	13	1
UMS	13	**12**	13	1
RAK	17	**12**	16	4
RYN	8	**11**	12	1
THM	13	**11**	12	1
ABN	6	**11**	12	1
WAK	8	**10**	11	1
OBK	9	**10**	11	1
WAJ	10	**10**	10	0
MES	11	**9**	10	1
WBC	6	**9**	10	1
GHR	6	**9**	10	1
WAB	10	**9**	10	1
QUN	9	**8**	8	0
ARP	7	**7**	8	1
MKH	6	**6**	7	1
RUW	3	**6**	6	0
KHR	4	**5**	6	1
DYN	6	**4**	5	1
SHN	5	**4**	5	1
UMG	4	**3**	3	0
SWK	2	**1**	1	0
KAR	1	**1**	1	0
JUM	1	**1**	1	0
GHW	1	**1**	1	0
KBN	1	**1**	1	0

January 2021 to December 2022. That is close to 10,000 more patients in RYN than in QUN. The result shows that reallocation of dentists would be required if the current number of doctors is fixed. The result also mentions that some of the PHCCs would require an added number of clinics to accommodate the number of patients scheduled in that clinic.

A scenario is developed here to see what happens if the total number of dentists are increased by 10% to cater the needs of the increased patient visits. The analysis with 22 more dentists is shown in Table 3, which shows that allocation would help to remove the deficit of dentists in all clinics, although some of the clinics are over-allocated.

Taking KBN as an example, the optimal allocation is 1, and the scenario 1 allocation was also 1. However, for ABN, Scenario 1 showed a surplus of 1 compared with the optimal solution. The solution also shows that some of the healthcare centers may need to have additional clinics to cater to the needs of the patients. For example, MKH and RYN would require an extra number of clinics and other resources to attend to the patients.

5 Conclusions and Limitations

Proper resource allocation, the appointment system, and effectiveness and ease of access for the patients are important for delivering a good healthcare service system. This report focused on dental appointments in PHCC in Qatar. The data shows that, in PHCC-Dental Clinics, some dentists are overwhelmed by the number of patients they have to see daily, while others remain idle most of the time, thus showing an imbalance of resource allocations.

This project proposes an integer linear programming (LP) model to assess resource allocation based on the number of patients and clinics available. It is noted that allocating healthcare resources is a critical issue that needs further research. When demand exceeds supply, allocation becomes a significant issue. A decision must now be made on distributing healthcare resources in light of increased demand and rising expenses associated with providing healthcare.

The linear programming model formulated in this project considered only two factors; the number of patient visits and the number of dental clinics in the healthcare centers. It thus does not consider other factors such as cost, clinic utilization, shifts, no-show, or referred patients. Also, the distribution of the dentists across each dental clinic is not considered, as this would involve large data sets making the problem NP-hard.

References

1. Valentine, N., Silva, A. D., Kawabata, K., & Darby, K.: Health system responsiveness: concepts, domains, and operationalization. Geneva: World Health Organization (2003).
2. Bouajaja, S., Dridi, N.: A survey on human resource allocation problem and its applications. Operational Research, 17(2), 339–369 (2017).
3. Ala, A. & Chen, F.: Appointment scheduling problem in complexity systems of the healthcare services: A comprehensive review. Journal of Healthcare Engineering, 1–16. https://doi.org/10.1155/2022/5819813 (2022).
4. Makena, R.: Simulation analysis of outpatient appointment scheduling of Minneapolis VA Dental Clinic. Retrieved from the University of Minnesota Digital Conservancy, https://hdl.handle.net/11299/191257 (2015).
5. Lin, C. K. Y., Ling, T. W. C., Yeung, W. K.: Resource allocation and outpatient appointment scheduling using simulation optimization. Journal of Healthcare Engineering, 1–19. https://doi.org/10.1155/2017/9034737 (2017).

6. Shohaimay, F., Dasman, A., Suparlan, A.: Teaching Load Allocation using Linear Programming: A Case Study in Mathematics Department (2016).
7. Das, S., Verma, S., Gupta, M.: Human resource allocation model using linear programming. International Journal on Emerging Technologies, 8(1), 361–367 (2017).
8. Kamran, M. A., Karimi, B., Bakhtiari, H., & Masoumzadeh, S. (2016). A resource allocation model in a healthcare emergency center using goal programming. Journal of Engineering Research, 4(4), 81–97 (2016).
9. Metsakoivu, K.: A capacity allocation method for appointment scheduling in public healthcare. Aalto University School of Science Master's Programme in Mathematics and Operations Research. Espoo: Alto University Press (2021).
10. Silva, D. F., Nunes, D. P.: Applying an Integer Linear Programming Model to an appointment scheduling problem. Eduardo Silva Medeiros. Ponta Delgata. https://repositorio.uac.pt/bitstream/10400.3/6305/1/DissertMestradoEduardoSilvaMeeiros2022.pdf (2021).

Digital Technologies and Lean 4.0: Integration, Benefits, and Areas of Research

Giovanna Bueno Marcondes, Arthur Henrique Gomes Rossi, and Joseane Pontes

Abstract Lean manufacturing or lean philosophy has been widely used in the production system since the beginning of the twentieth century. With the advent of digitalization, however, the update for the evolution of the tools that make up lean becomes latent. After all, how do Lean Manufacturing tools work and evolve within the concept of Industry 4.0, and how do they behave in conjunction with digital technologies? With this, the aim of this paper is to identify (1) the integration of digital technologies in Lean 4.0 tools, (2) the benefits of this integration, and (3) its main areas of research. To achieve this objective, a literature review was carried out using the PRISMA methodology, followed by a bibliometric analysis aided by the VOSVIEWER software and a content analysis QSR-NVIVO version 10. As a result, the total portfolio of 44 articles was analyzed, where links between 12 digital technologies in 12 Lean tools were mapped, which suggests that digital technologies improve the performance of lean tools, besides other benefits found. Moreover, this article shows the main research areas and research fields pointed out in this article portfolio, contributing to the emergence of future studies on the subject.

Keywords Lean 4.0 · Industry · 4.0 · Digital technologies

1 Introduction

The manufacturing industries are being progressively inserted in the context of digitalization systems so that they can increase their competitiveness and reduce their costs. As the market becomes increasingly demanding and competitive, there is a need to adapt new technologies in the factory environment to meet the growing demand for customization and flexibility. This disruption comes in the form of new technologies and concepts to be implemented, such as the well-known Industry 4.0. [1]. Its relationship has been studied by several authors in conjunction with Lean

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thinking, which is already known and used by organizations from all production levels. Industry 4.0 is made up of a range of new technologies and concepts. There are numerous manufacturing technologies, and it is discussed in the academic field which of them can be considered as the pillars of smart factories. More and more publications discuss this topic, but there is a need to analyze these different approaches to understand what changes exist in this volatile scenario of concept development.

According to the National Industry Confederation, the percentage of smart factories could reach 21.8% in Brazil within a decade. This percentage is currently at 1.6%, which shows a rapid expansion of the concept in factory environments. This rapid expansion is primarily due to the COVID-19 pandemic, which has played an important role in all countries. In Europe, this growth reached more than 60%, according to a study carried out by the European Investment Bank (EIB) Investment Survey (EIBIS) and conducted between the periods from April to July 2021. Such data are similar around the globe. Each country has its growth percentage, but all of them are heading towards smart factories. It can be seen in the literature that a concept related to the performance improvement of Industry 4.0 is the lean concept. The Lean methodology was proposed by Taiichi Ohno [2], responsible for creating the Toyota Production System. Ohno was an engineer at Toyota Motor Corporation who was given the complicated mission of increasing the company's productivity in the midst of the second world war [3, 4]. This system gave rise to Lean Thinking, which currently proposes 7 wastes, namely: Transport, Inventory, Motion, Waiting, Overproduction, Over-processing, and Defects [5].

Some authors cite Skills as an eighth type of waste, and still others cite even a ninth waste, which would be digital waste, the latter being a waste inherent to Industry 4.0 [6]. In short, Lean manufacturing seeks to reduce factory waste, optimize productive resources, and increase profitability, for this reason, this concept is an important approach when it comes to the advent of a new manufacturing era. Lean manufacturing includes some tools, such as Heijunka, Jidoka, Just in Time (JIT), Kaizen, Kanban, Poka-Yoke, Total Productive Maintenance (TPM), Value Stream Map (VSM), PDCA (Plan, Do, Check, Act), 5S, Heijuka, Andon and Single Minute Exchange of Die (SMED) [5, 7–9]. Lean can be combined with other methodologies such as Six Sigma, which seeks to reduce defects as much as possible, in order to bring better results than separately. Some interesting results were found regarding the LSS and will be commented on in the paper. With the various social spheres, such as industries and hospital organizations, seeking this technological insertion, the need for further studies on the subject arises. There are still few studies that discuss how the adequacy of Lean tools with Industry 4.0 technologies would happen.

Having this in mind, the aim of this paper is to identify (1) the integration of digital technologies in Lean 4.0 tools, (2) the benefits of this integration and also (3) its main areas of research. To achieve this objective, a bibliographic review will be carried out using the PRISMA methodology, followed by a bibliometric analysis using the VOSVIEWER software to identify the main authors, the main keywords and the number of publications per year. Furthermore, content analysis will be performed with the help of the QSR-NVIVO version 10 software.

This paper is organized in the following format: Section 2 presents the methodology used, reporting the steps for searching and analyzing the article portfolio by means of a Systematic Literature Review and Bibliometric and Content Analysis. Section 3 presents the results and Discussions, subdivided into sections presenting the bibliometric analysis and content analysis: Digital technologies embedded in lean 4.0 tools and Benefits of integrating digital and lean technologies and their areas of research. Finally, Sect. 4 presents the final considerations about this study.

2 Methodology

Seeking to map the portfolio needed to carry out the research on the topic of interaction between Lean tools and Industry 4.0 technologies, a systematic literature review was carried out based on the PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [10]. Through this methodology, it is possible to identify and select studies that are congruent with the topic analyzed through a systematic search in pre-selected databases following some criteria of relevance.

First, it was necessary to identify the keywords about the topic and define the search criteria in the selected databases (Scopus and Web of Science). The search terms were defined according to the different synonyms of the concept of digital waste observed in the literature, and their variations were included in the searches using the Boolean operator “OR”. The search terms were used in English in order to involve a wider range of studies without a defined search period. With that, the axis “(“Lean” OR “Lean 4.0” OR “Digital Lean”) AND (“Digital Technologies” OR “Tools” OR “Technologies”) AND (“Industry 4.0” OR “fourth industrial revolution” OR “smart manufacturing” OR “Industry 5.0”)” was obtained.

Subsequently, a review of the studies found from the information flow of the PRISMA methodology was carried out, in the present research subdivided into 4 phases, namely: (i) Identification: search in selected databases according to the research axes and/or search terms defined from the research protocol; (ii) Selection: filtering of articles following the criteria for reading the title and reading the abstract proposed by the methodology, in order to verify the alignment of the article proposal with the topic in question, (iii) Eligibility: full reading of previously selected articles for the design of the final research portfolio or, if incompatibility with the topic is verified, the article is excluded and (iv) Inclusion: phase of inclusion of other studies by qualitative analysis to compose the final research portfolio.

All stages of the systematic literature review were supported by the Mendeley software, which is characterized as a computational tool for managing references. With the help of the software, 39 duplicates were identified, which were automatically discarded from the analysis. Figure 1 represents all the steps needed for the development of the methodology applied to the articles obtained, from its initial

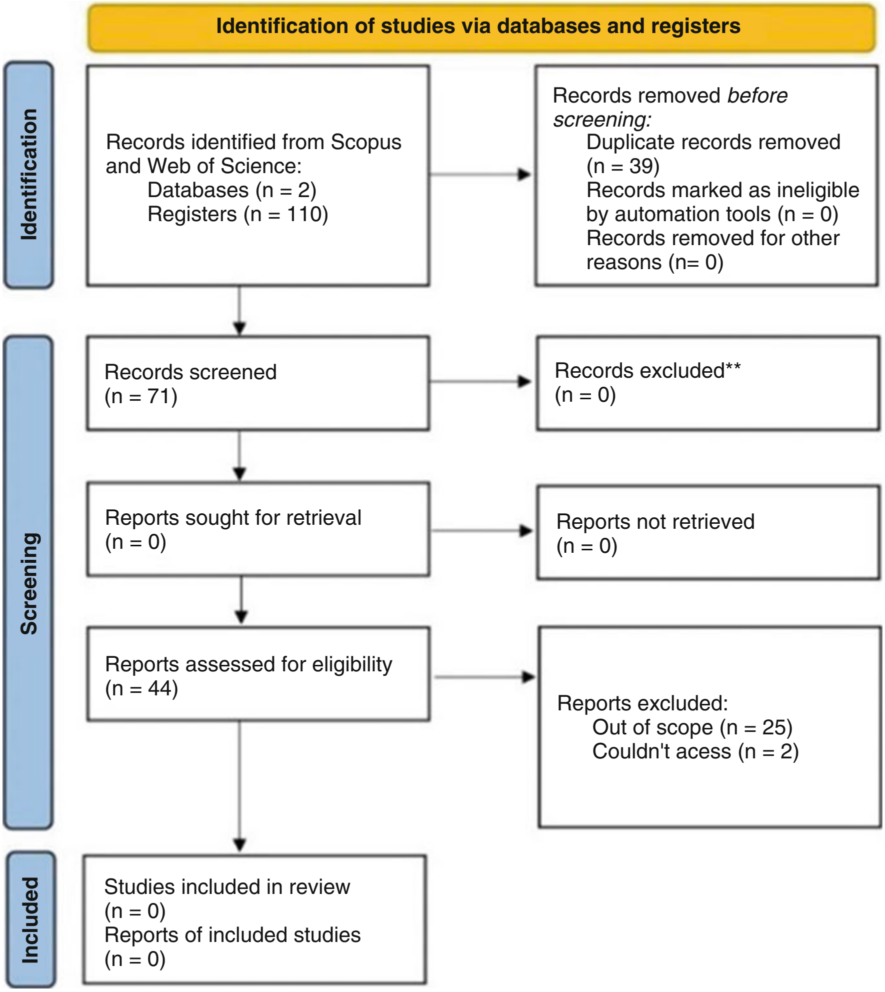

Fig. 1 Development of PRISMA methodology steps

search in the databases to the selection of the final portfolio. Once all the steps described in the methodology were carried out, a final portfolio was obtained consisting of 11 articles, which were submitted to further analysis, thus being able to contribute to the objective of the research on the study of the topic.

Through the selection of articles, a series of bibliometric analyzes were carried out. In order to observe the state of the art of the theme, these analyzes were carried out with the help of the VOSVIEWER software. We then sought to identify the following factors: (i) distribution of publications over the years; (ii) keywords used in the articles and (iii) main authors related to the topic. The answers obtained are detailed in Sect. 4. Considering the content analysis, in addition to the bibliometric analysis, the QRS-NVIVO software was used. With it, it is possible to identify several themes related to the phenomenon studied, with this it is possible to obtain a greater basement of the topic addressed. Manual nodes were generated with NVIVO version 10 so that the main technologies of Industry 4.0, the main Lean tools, and the connection between them could be obtained.

3 Results and Discussion

A total of 44 articles were selected for further analysis. The Mendeley software was used at this stage to assist in this stage of the systematic literature review process. A CSV file (comma-separated-values) of the portfolio was generated so that the analysis of publications per year could be performed using Excel. For the analysis of the authors who publish the most on the topic and the most recurrent keywords in the articles, the VOSVIEWER software was used with the .ris file of the portfolio. It is a software tool for building and visualizing bibliometric networks. It allows the creation of networks of citation, co-citation, or co-authorship relationships.

3.1 Bibliometric Analysis

The data were rearranged and filtered to obtain a graph of the number of publications per year. Between 2016 and 2019 there were few publications involving the theme, around zero to four publications per year. From 2020 there was an explosion of publications, tripling or quadrupling the number of publications from previous years. This fact is possible due to the advent of the COVID-19 virus and the consequent pandemic that followed it. With the pandemic, the theme has re-emerged with force, as organizations need to adapt to the new post-pandemic environment and the prevention of similar situations, to avoid a new stoppage of production lines. Despite this, the theme is not restricted to this benefit but presents numerous others that will be discussed subsequently. Using VOSVIEWER, the occurrences of each author were analyzed. It is discernible that the most cited author [11] (7 documents) and [12] (3 documents) [11]. is also one of the strongest links in the portfolio, being cited 24 times by other authors. It also has a higher number of authorships and co-authorships compared to other works, mainly studying the behavior of Industry 4.0 and Lean manufacturing. It was also possible to extract the recurring keywords among the selected articles. The keywords with the highest number of occurrences were “Industry 4.0”(40 occurrences), “Lean Manufacturing” (13 occurrences), “Lean Production” (10 occurrences), “Lean Automation” (6 occurrences), “Lean Management” and “Smart Manufacturing”. It is possible to verify that they are in agreement with the researched theme and that the portfolio adheres to the proposed objective. The keyword industry 5.0 is not part of the word cloud because none of the 44 articles in the portfolio has the topic industry 5.0 in its content. This shows that there are no articles about lean 5.0 and there is an opportunity to relate the lean theme with the 5.0 industry.

3.2 Content Analysis: Industry 4.0 and Lean in the Digital Age

Next, the results of the content analysis based on the 44 articles with the help of the NVIVO version 10 software will be presented.

Industry 4.0 influences all fields of the company, such as resource management and the production line, through continuous automation of different manufacturing processes. It will require a more complex level of employee training and skills. More specialists will be needed to evolve their skills within the manufacturing spaces that have advanced processes [6].

According to [13], the term "Industry 4.0" is characterized by industries where digital technologies (or smart technologies) facilitate greater levels of mass customization of processes, products, and services, enabling industries to reach higher levels of performance. Figure 2 was generated from works by [4, 5, 7, 11, 13–23]. It exemplifies the main tools inserted in the context of industry 4.0, with a brief summary of their function. Being the technologies: Additive Manufacturing (AM), Cloud Computing (CC), Autonomous Robots (AGV's), Artificial Intelligence (AI), TAGS, Big Data (BD), Cyber Physical Systems (CPS), Cybersecurity (CS), Internet of things (IOT), Virtual Reality (VR) e Augmented Reality (AR). According to [14], when technologies are implemented, many benefits such as maximum resource usage and efficiency, access to real-time data when making strategic decisions, efficient maintenance, new product development, customization of products to meet the customer demand and competitive advantage over competitors can be achieved.

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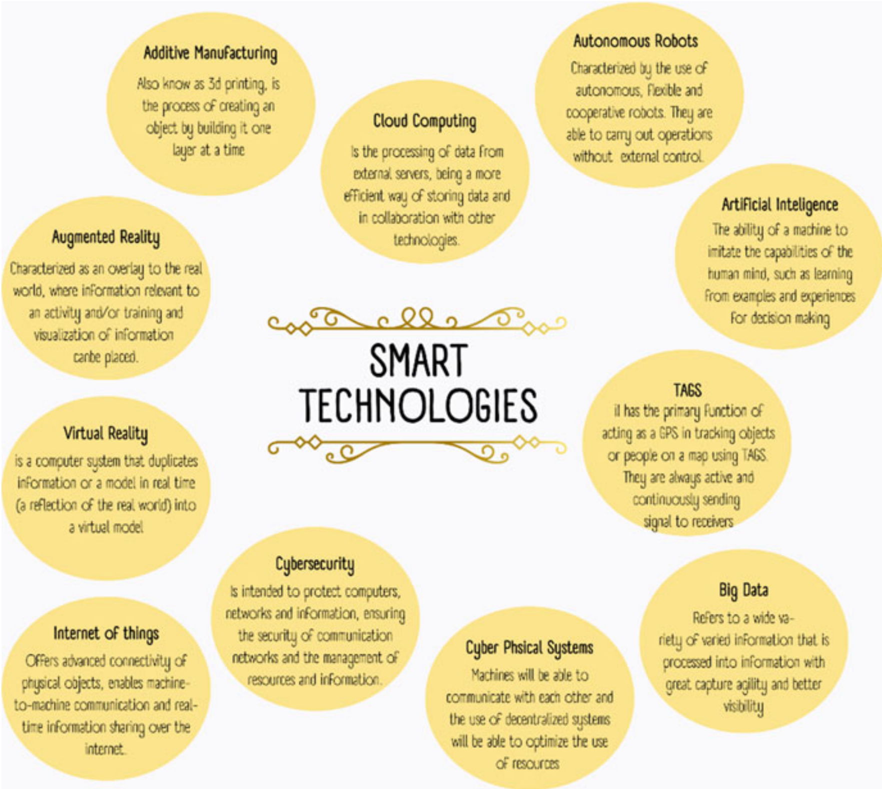

Fig. 2 Industry 4.0 technologies

After presenting the technologies arising from Industry 4.0, it is important to mention Lean 4.0, where there are several tools capable of merging with the mentioned technologies [4]. cites some tools that are suitable for Lean 4.0, and whose relationship was studied together with technologies. They are: Just in Time 4.0, Kanban 4.0, Poka-Yoke 4.0, Value Stream Map 4.0, Kaizen 4.0, and Total Productive Maintenance 4.0. These tools will be studied, complementing other studies that assume other tools such as Heijunka, Jidoka, PDCA (Plan, Do, Check, Act), 5S, Heijuka, Andon, and Single Minute Exchange of Die (SMED).

3.2.1 Integration of Digital Technologies into Lean Tools

Figure 3 presents the main links between the proposed technologies and the Lean 4.0 tools. From the literature, it was found that some technologies proved to be very important for lean tools to become intelligent.

With the figure, it is noticeable that the technology that most support the integration of Lean tools in Industry 4.0 is Big Data (BD), followed by Sensors

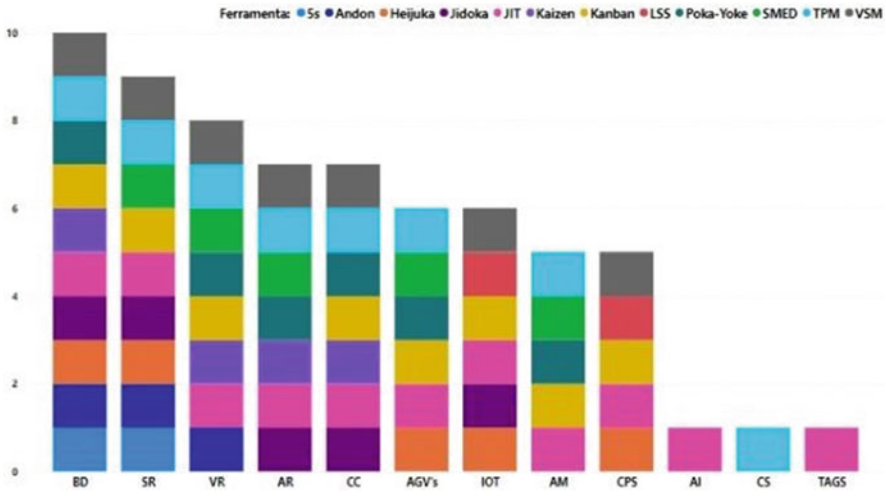

Fig. 3 Industry 4.0 technologies

(SR) and Virtual Reality (VR). The tools that least support this integration are Artificial Intelligence (AI), Cybersecurity (CS), and TAGS. This may be due to the lack of development of works that study these specific integrations or factors that can make this integration difficult [16, 24]. conclude that most Lean tools will benefit from new technologies, and that some may be facilitators or even prerequisites for Industry 4.0. Despite this, technological systems are rigid and difficult to change or adapt for continuous improvement, which can characterize a problem in adapting tools due to these contradictory aspects.

The works of [4, 5] discuss this integration. Despite this, it was possible to carry out further investigation on the subject, presenting a systematic literature review, a bibliometric analysis, and a qualitative analysis as novelties, in order to contemplate works developed after them. Another interesting approach obtained with the qualitative analysis was the inclusion of some Lean Six Sigma (LSS) tools addressed by certain authors. Some benefits of integrating technologies with Lean tools will be discussed below.

3.2.2 Benefits of Integration of Digital Technologies into Lean Tools and Its Main Research Areas

The author [14] studied the integration between digital technologies and lean tools in hospitals and healthcare treatment centers. In these places, basic Lean manufacturing systems without technological implementations did not provide much competitive advantage in terms of operational performance. In this case, Industry 4.0 enables real-time production management planning along with dynamic self-optimization. With the use of Lean and LSS, factories that have the best technologies and algorithms do not perform this adaptation and continue with classic Lean thinking, which in the medium term generates the loss of competitive advantage [15]. Real-time capability is the principle that most supports Lean tools, while decentralization and modularity would be obstacles for time-taking [3]. This adaptation and combination can be an effective form of agile production, and the weaknesses of each of the systems can be supplied by the other [24].

Lean alone may not be able to keep up with the customization demanded by today's market, so it enters the concept of Industry 4.0 connectivity [25]. The integration of Lean and technologies offers cost saving benefits in areas where it is difficult to implement simple Lean techniques [20]. From a Lean perspective, [4] studied the points of synergy between Lean and technologies and came to the conclusion that five key Lean 4.0 attributes resulted in a total of 68 points of contribution among the six relationship diagrams. The dimensions of integration between processes, devices and stakeholders, minimization and/or elimination of waste and autonomy presented the highest amount of indication points, resulting in 16 points each. In summary, Lean enables waste reduction, while digital technologies support Lean manufacturing, avoiding problems and inefficiencies with the aid of digitalization. The mapping of the main research fields observed from the analysis of the 44 structured articles in the research portfolio can be observed according to Table 1. The mapping was supported by the automatic coding tool allowed by the QSR-NVIVO software version 10.

The main research areas observed in Table 1 are related to the Lean Philosophy, production systems, management of technologies involved in the different processes within an organization, and aspects related to manufacturing management. With this, it is possible to observe the relationship between the research themes, keywords, and research fields (or research topics), and the importance of the integration between Lean and the digital technologies of Industry 4.0. All research fields indicate the digital technologies to integrate and improve their processes and management in their different research topics, which could be deepened for a broader and more detailed construction of the theme, contributing to the research on this subject.

4 Conclusion

This study aimed to identify (1) the integration of digital technologies in Lean 4.0 tools, (2) the benefits of this integration, and (3) its main areas of research. To fulfill the proposed objective, it was necessary to carry out a systematic review of the literature to map the main works in relation to the theme "Lean 4.0". To assist in the literature review, the PRISMA methodology was used to identify the relevant works, then the QSR-NVIVO software version 10 was used for further analysis. After reviewing the literature, the works relevant to the theme were analyzed, where 44 articles were considered for the final bibliographic portfolio, then the authors and keywords were analyzed [4, 5, 13]. were discarded in the portfolio as a substantial part of the research due to the number of references obtained from

Table 1 Areas of research and research fields

Main areas of research	Related keywords	Main research topics	Main portfolio authors
Lean philosophy	"Lean principles", "lean practices", "lean manufacturing", "lean tools", "lean thinking"	Methods and tools to introduce lean principles to simulation models; relationship between lean principles and organization's ability to innovate; the interdependent relationship between industry 4.0 tools and lean practices	[4, 5, 11, 23, 24, 26–28]
Production systems	"Production line", "production process", "lean production style"	Integration between the technologies and lean process with the principles and automation technologies of the industry 4.0; relationship between the adoption of new technologies and the evolution of organizational structures; identification of waste in the production process and its exclusion	[4, 11, 13, 19, 22, 24, 29, 30]
Technologies management	"Digital technologies", "communication technologies", "technological advancement"	The role of digital technologies within a lean company; how the tracking of information provided by IPS can be used in the digital transformation of lean manufacturing	[4, 5, 11, 25, 27, 28, 30]
Manufacturing management	"Continuous improvement", "improving productivity"	Integration of lean manufacturing principles and advanced digital manufacturing; relationship between lean manufacturing and lean philosophy, in terms of managerial aspects	[13, 19, 28]

these authors. Despite this, [13] stands out in the analysis of VOSVIEWER for being a highly cited author on the subject. It was possible to map within the works the concept of Lean 4.0 and some of its applications. Manual nodes were created using the software NVIVO version 10 to obtain Fig. 3, fulfilling the objective (1). Later, some results wore obtained from the automatic coding using the NVIVO software, which illustrates the growing need to study the synergies of each of the Lean tools with each of the technologies. The results were presented in Table 1 and session 3.2.2 for objectives (2–3). There are few practical works that study it, so the creation of operational frameworks would have good adherence to the theme and would provide several future types of research on the subject. Manual nodes were created using the software NVIVO version 10 to create figures that meet the objectives proposed in this work. Furthermore, Sect. 3.8 highlights the main benefits of this integration. This paper seeks to contribute: (i) to the industry that uses lean and intends to use digital technologies from the identification of how lean tools can be better used from the insertion of digital technologies and improve the level of digitalization from lean tools integrated with digital technology; (ii) to the society and the workforce from the identification of the benefits of integration of digital technologies to lean tools, such as agility, real-time analysis, connectivity, and cost reduction, stimulating lean programs and capacity building and training for workers and future workers that use the tools; (iii) to researches about the lean 4.0 from the identification of four main research areas on Lean and digital technologies pertinent to Industry 4.0. As a limitation of this study, the research was based on 2 databases (SCOPUS and WEB OF SCIENCE) and there were no articles in the portfolio related to Industry 5.0 and lean, although they were searched. With this, we suggest for future works the research about (i) Lean 5.0 and main themes driving research; (ii) research of the theme in more databases; (iii) research agenda to identify and catalog the main challenges about the integration of Lean 4.0 and 5.0 in smart factories, as well as (iv) identify the main opportunities and success factors about the research theme.

References

1. Pagliosa, M., Tortorella, G., & Ferreira, J. C. E. (2019). Industry 4.0 and Lean Manufacturing. *Journal of Manufacturing Technology Management*, *32*(3), 543–569. https://doi.org/10.1108/JMTM-12-2018-0446
2. Ohno, T. (1982). How the Toyota Production System was Created. *Japanese Economic Studies*, *10*(4), 83–101. https://doi.org/10.2753/JES1097-203X100483
3. Rosin, F., Forget, P., Lamouri, S., & Pellerin, R. (2020). Impacts of Industry 4.0 technologies on Lean principles. *International Journal of Production Research*, *58*(6), 1644–1661. https://doi.org/10.1080/00207543.2019.1672902
4. Valamede, L. S., & Akkari, A. C. S. (2020). Lean 4.0: A new holistic approach for the integration of lean manufacturing tools and digital technologies. *International Journal of Mathematical, Engineering and Management Sciences*, *5*(5), 854–868. https://doi.org/10.33889/IJMEMS.2020.5.5.066
5. Nedjwa, E., Bertrand, R., & Sassi Boudemagh, S. (2022). Impacts of Industry 4.0 technologies on Lean management tools: a bibliometric analysis. *International Journal on Interactive Design and Manufacturing*, *16*(1), 135–150. https://doi.org/10.1007/s12008-021-00795-9
6. Alieva, J., & Haartman, R. (2020). Digital Muda – The New Form of Waste by Industry 4.0. *Operations and Supply Chain Management: An International Journal*, 269–278. https://doi.org/10.31387/oscm0420268
7. Sony, M. (2018). Industry 4.0 and lean management: a proposed integration model and research propositions. *Production and Manufacturing Research*, *6*(1), 416–432. https://doi.org/10.1080/21693277.2018.1540949
8. MARCONDES, G. B., ROSSI, A. H. G., SOUZA, M. P. de, & PONTES, J. (2022). DESPERDÍCIO DIGITAL NO CONTEXTO DO LEAN 4.0: PRINCIPAIS DIRECIONAMENTOS DE PESQUISA. https://doi.org/10.14488/ENEGEP2022_TN_WG_382_1886_43896
9. Rossi, A. H. G., Marcondes, G. B., Pontes, J., Leitão, P., Treinta, F. T., de Resende, L. M. M., . . . Yoshino, R. T. (2022). Lean Tools in the Context of Industry 4.0: Literature Review, Implementation and Trends. *Sustainability*, *14*(19), 12295. https://doi.org/10.3390/su141912295

10. Moher, D. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement (Chinese edition). *Journal of Chinese Integrative Medicine*, *7*(9), 889–896. https://doi.org/10.3736/jcim20090918
11. Tortorella, G. L., & Fettermann, D. (2018). Implementation of industry 4.0 and lean production in brazilian manufacturing companies. *International Journal of Production Research*, *56*(8), 2975–2987. https://doi.org/10.1080/00207543.2017.1391420
12. Kumar, S., Suhaib, M., & Asjad, M. (2020). Industry 4.0: Complex, disruptive, but inevitable. *Management and Production Engineering Review*, *11*(1), 43–51. https://doi.org/10.24425/mper.2020.132942
13. Pagliosa, M., & Tortorella, G. (2021). Lean Manufacturing future research directions, *32*(3), 543–569.
14. Ilangakoon, T. S., Weerabahu, S. K., Samaranayake, P., & Wickramarachchi, R. (2021). Adoption of Industry 4.0 and lean concepts in hospitals for healthcare operational performance improvement. *International Journal of Productivity and Performance Management*. https://doi.org/10.1108/IJPPM-12-2020-0654
15. Arcidiacono, G., & Pieroni, A. (2018). The revolution Lean Six Sigma 4.0. *International Journal on Advanced Science, Engineering and Information Technology*, *8*(1), 141–149. https://doi.org/10.18517/ijaseit.8.1.4593
16. Ding, B., Ferràs Hernández, X., & Agell Jané, N. (2021). Combining lean and agile manufacturing competitive advantages through Industry 4.0 technologies: an integrative approach. *Production Planning and Control*. https://doi.org/10.1080/09537287.2021.1934587
17. Sanders, A., Elangeswaran, C., & Wulfsberg, J. (2016). Industry 4.0 implies lean manufacturing: Research activities in industry 4.0 function as enablers for lean manufacturing. *Journal of Industrial Engineering and Management*, *9*(3), 811–833. https://doi.org/10.3926/jiem.1940
18. Tortorella, G. L., Giglio, R., & van Dun, D. H. (2019). Industry 4.0 adoption as a moderator of the impact of lean production practices on operational performance improvement. *International Journal of Operations and Production Management*, *39*, 860–886. https://doi.org/10.1108/IJOPM-01-2019-0005
19. Shahin, M., Chen, F. F., Bouzary, H., & Krishnaiyer, K. (2020). Integration of Lean practices and Industry 4.0 technologies: smart manufacturing for next-generation enterprises. *International Journal of Advanced Manufacturing Technology*, *107*(5–6), 2927–2936. https://doi.org/10.1007/s00170-020-05124-0
20. Kamble, S., Gunasekaran, A., & Dhone, N. C. (2020). Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies. *International Journal of Production Research*, *58*(5), 1319–1337. https://doi.org/10.1080/00207543.2019.1630772
21. Spenhoff, P., Wortmann, J. C., & Semini, M. (2020). EPEC 4.0: an Industry 4.0-supported lean production control concept for the semi-process industry. *Production Planning and Control*, 1–18. https://doi.org/10.1080/09537287.2020.1864496
22. Chiarini, A., & Kumar, M. (2021). Lean Six Sigma and Industry 4.0 integration for Operational Excellence: evidence from Italian manufacturing companies. *Production Planning and Control*, *32*(13), 1084–1101. https://doi.org/10.1080/09537287.2020.1784485
23. Goienetxea Uriarte, A., Ng, A. H. C., & Urenda Moris, M. (2020, January). Bringing together Lean and simulation: a comprehensive review. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2019.1643512
24. Buer, S. V., Semini, M., Strandhagen, J. O., & Sgarbossa, F. (2021). The complementary effect of lean manufacturing and digitalisation on operational performance. *International Journal of Production Research*, *59*(7), 1976–1992. https://doi.org/10.1080/00207543.2020.1790684
25. Cifone, F. D., & Portioli Staudacher, A. (2022). Do repetitive and non-repetitive companies equally benefit from Lean 4.0? *Journal of Manufacturing Technology Management*, *33*(1), 84–102. https://doi.org/10.1108/JMTM-12-2020-0500

26. Dixit, A. R. R., & Mishra, P. K. K. (2008). Design of flexible manufacturing cell considering uncertain product mix requirement. *International Journal of Agile Systems and Management*, *3*(1–2), 37–60. https://doi.org/10.1504/IJASM.2008.019598
27. Raji, I. O., Shevtshenko, E., Rossi, T., & Strozzi, F. (2021). Industry 4.0 technologies as enablers of lean and agile supply chain strategies: an exploratory investigation. *International Journal of Logistics Management*. https://doi.org/10.1108/IJLM-04-2020-0157
28. Tortorella, G. L., Rossini, M., Costa, F., Portioli Staudacher, A., & Sawhney, R. (2021). A comparison on Industry 4.0 and Lean Production between manufacturers from emerging and developed economies. *Total Quality Management and Business Excellence*, *32*(11–12), 1249–1270. https://doi.org/10.1080/14783363.2019.1696184
29. Buer, S. V., Strandhagen, J. O., & Chan, F. T. S. (2018). The link between industry 4.0 and lean manufacturing: Mapping current research and establishing a research agenda. *International Journal of Production Research*, *56*(8), 2924–2940. https://doi.org/10.1080/00207543.2018.1442945
30. Tran, T. A., Ruppert, T., & Abonyi, J. (2021). Indoor positioning systems can revolutionise digital lean. *Applied Sciences (Switzerland)*, *11*(11). https://doi.org/10.3390/app11115291

Continuous Improvement Related Performance: A Bibliometric Study and Content Analysis

Giovanni Cláudio Pinto Condé and José Carlos de Toledo

Abstract Continuous Improvement (CI) can be useful as dynamic capability for the organization, therefore, an important factor for the organizational and operational performance. There are many publications on different aspects of CI, and it is essential to identify what the themes are being researched recently. A significant part of CI research is directly related to performance and, to point out those which are the main, this research aims to answer the following research questions (RQ): RQ1: What is the structure of the CI literature related to performance (CIrP)? RQ2: Which CIrP' themes are present in the past 5 years? The research was conducted through means of bibliographic coupling and content analysis. The themes present in the past 5 years are: (1) performance measurement and sustainability, covering performance measurement systems, key process indicators (KPI), green management, environmental performance; (2) kaizen and Lean thinking, what encompasses Lean and quality tools and concepts (e.g., cause and effect diagram, VSM, kanban); (3) quality, composed by TQM and its practices, organizational culture, quality management, quality standards, quality performance and ISO 9000; (4) Strategy and Innovation, that also cover innovation performance, innovation orientation, management innovation, innovation strategy and organizational learning; (5) Lean Six Sigma, considering that it also cover research related to CI projects and their failures; and (6) Lean, considering that the researches that form this cluster deal with Lean systems, Lean practices; Lean production; Lean implementation; Lean leadership, dynamic capabilities, systematic problem solving. In addition, this study identified IC research related to different performance modalities.

Keywords Continuous improvement · Performance · Bibliometric analysis · Bibliographic coupling · Content analysis · VOSviewer

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1 Introduction

Organizational performance is positively related to its dynamic capabilities [15]. Continuous improvement (CI) is described as a systematic effort to seek and apply new ways of doing work, that is, actively and repeatedly making process improvements and can be useful as dynamic capabilities for the organization [4]. Furthermore, continuous improvement is one of the measurable variables of operations management [13]. Research around CI has been carried out year after year since the late 1980s, and an important part of CI' research has been related to performance. Bibliometric analysis has been applied in the CI domain, such as statistical process control [21], Lean Six Sigma [41], Kaizen [3], or Six Sigma [31], while others explore intersections, for example, with Industry 4.0 [43]. However, there are other methodologies besides Lean, Six Sigma, Lean Six Sigma, such as, for example, Total Quality Management [40]. Moreover, there is no essay to understand the whole research structure on CIrP, using bibliometric techniques and content analysis. The present study aims to fill this gap in the literature as a way to contribute to research on CIrP.

In the present study techniques were organized to answer the following research questions: RQ1: What is the structure of the CI' literature related to performance (CIrP)? RQ2: Which CIrP' themes are present in the past 5 years? To answer these questions, a bibliometric and content analysis were applied. This paper makes the first essay to understand the research structure on CIrP, using bibliometric techniques and content analysis.

The remaining sections of this article are structured as follows: first, the research methodology used to perform the study is explained. The presentation and discussion of the findings follows. Finally, the conclusions are presented, including contributions, limitations, and proposition for further research.

2 Research Methodology

2.1 Bibliometric Analysis

To assure the accuracy of this study, it was used the 5-steps procedure based on Zupic and Čater [50]. In the step 1 (Research Design) it was defined the study goal. The purpose of this study is to answer the two research questions of this research. To answer those RQs, it was defined the methodology to achieve goals: bibliometric techniques were selected to answer the RQ1.

Bibliometric analysis encompasses several scientific mapping techniques [10]. One of these techniques is bibliographic coupling. The assumption for bibliographic coupling is that two documents that share common references are similar in content [49]. The focus of this analysis is on the division of published documents into themes clusters based on their shared references [50]. Bibliographic coupling

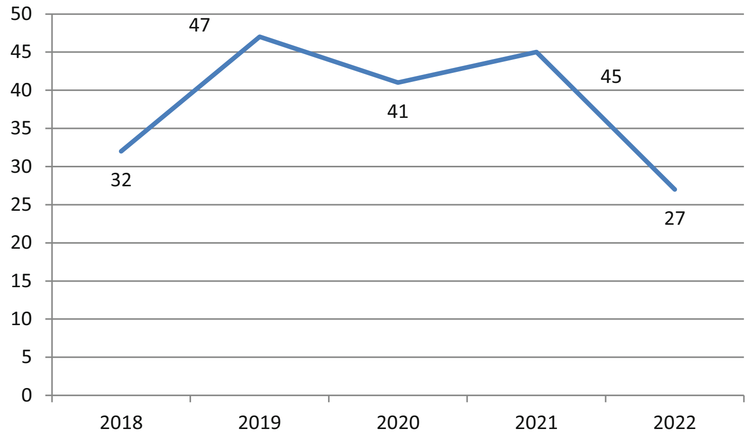

Fig. 1 Number of articles and reviews published per year – research on CIrP for 2018–2022' period (only approved documents)

should be used to analyze the relationships among citing publications to understand the periodical or present development of themes in a research field [10].

Content analysis of references was used to answer RQ2. In the step 2 (Compilation of bibliometric data) it was defined how many and which scientific databases would be used to perform the searches. In line with Niñerola et al. [31], it was chosen Web of Science (WoS) [8] and also Scopus to generate the document sample since they are the most important in Management [32] and also they allow the generation of metadata such as authors, number of citations; cited references, among others that is required to accomplish the bibliometric analysis.

Search string "continuous improvement" and "performance" was used with the following filters: year of publication from 2018 to 2022; articles and reviews published in journals; English language; nine Scopus' subject areas related to Operations Management: Engineering; Business, Management, and Accounting; Computer Science; Social Sciences; Decision Sciences; Environmental Science; Economics, Econometrics and Finance, Psychology and Multidisciplinary resulting in 985 documents (articles and reviews). Subsequently, the abstracts of those documents were read to eliminate those that did not deal with CIrP as a central theme, resulting in 192 approved documents. For this final document set, metadata were exported from Scopus database for using in the VOSviewer software (Fig. 1).

In the step 3 (Analysis) the decision for VOSviewer was motivated mainly for the possibility of use of two different databases: Web of Science (WoS), and Scopus [31, 48]. In the Step 4 (Visualization) graphical analysis using VOSviewer software enhances the investigation [48] (Fig. 2). Finally, in the Step 5 (Interpretation) it was followed the guidelines from Van Eck and Waltman [48]. Main references from each cluster allowed the identification of present development of themes on continuous improvement related performance.

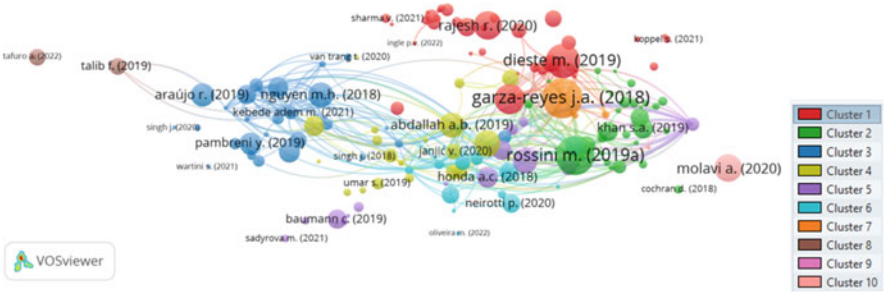

Fig. 2 Bibliographic coupling network research on CIrP for 2018–2022' period

2.2 *Content Analysis*

Content analysis consisted of reading the selected documents (articles and reviews) that stood out in each of document cluster from the bibliographic coupling analysis. Work files were built to organize and summarize information (authors, year of publication, keywords, number of citations) related to each document cluster identified in the bibliographic coupling analysis. The identification of present development of themes and main documents from the main clusters was obtained through bibliographic coupling technique and content analysis.

3 Results

In this section, the results of the bibliometric analysis and content analysis are presented.

3.1 *Bibliometric Analysis Results*

Evolution of CIrP Research Publications

After filtering process previously indicated, the evolution of 192 CIrP research publications, considering the number of articles and reviews per year, was obtained for the 2018–2022' period is shown in Fig. 1.

Cluster Analysis

The VOSviewer software processes the metadata and generates the bibliographic coupling network resulting, automatically, in a certain number of clusters, which depends on the diversity of treatment of the topic within the document sample [48]. Each cluster is considered to share common references, and therefore is considered similar in content [49]. For the final document sample of this study, ten clusters were identified (Fig. 2). In addition to automatically generating clusters,

Table 1 Clusters for bibliographic coupling

Cluster #	Number of linked documents[a]	Most cited documents	Number of citations[b]
#1	35	Choudhary et al. [7]	72
		Rajesh [35]	64
		Medne and Lapina [25]	27
#2	32	Rossini et al. [37]	116
		Tortorella et al. [45]	53
		Khan et al. [19]	32
#3	30	Nguyen et al. [33]	51
		Araújo et al. [5]	43
		Pambreni et al. [34]	37
#4	19	Abdallah et al. [1]	49
		Jimoh et al. [18]	33
#5	17	Costa et al. [9]	46
		Honda et al. [16]	34
# 6	13	Secchi and Camuffo [39]	29
		van Assen [47]	28
		Mohaghegh et al. [26]	13
#7	3	Garza-Reyes et al. [14]	128
#8	3	Talib et al. [44]	23
#9	2	Nae and Severin [30]	5
#10	2	Molavi et al. [27]	62

Note: [a]Only 156 out of 192 approved documents take part of the 10 clusters; [b]Number of citations according Scopus database

VOSviewer software informs which references make up each cluster. More cited documents and number of linked documents for the ten clusters is shown in Table 1. This result answers the RQ1: What is the structure of the CI' literature related to performance (CIrP)?

Cluster Nomenclature

Clusters can receive a nomenclature based on terms from their title, keywords, and abstract of those documents (articles and reviews) that make up each cluster [12]. To ensure understanding and naming the clusters, it was performed a content analysis by reading the documents.

3.2 *Content Analysis Results*

The CIrP research is presented below, answering the RQ2: Which CIrP' themes are present in the past 5 years? The CIrP was divided into ten themes clusters based on their shared references [50]. It includes the name chosen for the main clusters (numbered from cluster #1 to cluster #6, according to Table 1) and also theirs respective main topics of the most cited and the more recent document from each named cluster.

Cluster#1 named "performance measurement and sustainability" since it bring together the largest set of research related to performance measurement systems, key process indicators (KPI), green management, environmental performance. Choudhary et al. [7] performed one of the main studies in this research theme. It was a case study using the Green Integrated Value Stream Mapping (GIVSM), a new tool that integrates Lean and Green management paradigms in a company in the United Kingdom, demonstrating a positive effect on operational efficiency and effectiveness and on environmental performance. Another influential study was the research that was oriented to deal with sustainability issues and questions emerging from assessments as a means to improve future sustainability performance in Indian companies [35]. Another popular study was carried out by Medne and Lapina [25] who investigated the process of measuring sustainability by seeking to identify how process-oriented indicators are linked to an organization's strategy in the context of sustainable development. Lai et al. [20] established a model that allows pragmatically evaluating the performance of hospital facilities management, using ten KPIs and use of the process analytical network (ANP) method.

Cluster#2 named "kaizen and Lean thinking" considering that this set of research applies these concepts together with other Lean and quality tools and concepts (e.g., cause and effect diagram, VSM, kanban, 5S, takt time, among others. Rossini et al. [37] examined the impact of the interrelationship between the adoption of Industry 4.0 technologies and the implementation of Lean practices on the operational performance of 108 European companies, performing data analysis using multivariate techniques. Another important research in this theme investigated and confirmed that employee's involvement (EI) constitutes the mediating link between Industry 4.0 technologies and improved operational performance, reinforcing the importance of practices related to EI [45]. Moreover, in an interior design case company CI techniques (kaizen, 5S and project selection) were implemented, studied and analyzed resulting in money and time savings [19]. Recently, a 5S implementation study in a plastic machine manufacturing company determined the relationship of 5S with productivity using hypothesis testing and thus revealed the perspective of 5S to realize business performance parameters [23].

Cluster#3 named "Quality" considering that it covers TQM and its practices, organizational culture, quality management, quality standards, quality performance and ISO 9000. Nguyen et al. [33] investigated the relationship between quality management practices and sustainability performance in companies in Vietnam and also identified four quality management practices that result in a positive impact on sustainability performance. In another important research in this theme, textile industries in Portugal were studied through a research model consisting of three hypotheses, to analyze how the culture of quality influences the performance of the organization. The results indicated that the error detection culture negatively influences performance, while the creative culture and continuous improvement positively influence performance [5]. Moreover, in small and medium enterprises in the service sector in Malaysia it was investigated, through questionnaires and multiple linear regression analysis, the impact of each of the four critical elements of TQM (customer focus, continuous improvement, strategic basis and total employee involvement), taken as variables, and confirmed that all they positively impact organization performance [34]. Recently, a study dedicated to improving the operational performance and competitiveness of microenterprises through the action research approach was performed. In such a study, specific characteristics of the companies were identified and considered filtering which initiatives to improve performance according to the specific needs of each micro-enterprise. Initiatives such as 5S, single minute exchange of die (SMED), suggestion schemes, layout improvements, management training, visual management, capacity building, were considered adequate to improve operational performance [17].

Cluster#4 named "Strategy and Innovation", that also cover innovation performance, innovation orientation, management innovation, innovation strategy and organizational learning. Abdallah et al. [1] empirically investigated the relationships between innovation orientation (IO), Lean manufacturing (LM) and innovation performance using exploratory factor analysis, confirmatory factor analysis and structural equation modeling. The results indicate that innovation-oriented companies tend to adopt both soft and hard LM aspects; however these do not have a significant effect on innovation. These results indicate that having an IO is vital to improving both LM and innovation performance. Another important research in this theme analyzed the nature of the relationships between TQM practices and organizational performance on different performance measures and thereby confirmed their significant effects. In addition, the study highlights the importance of valuing the implementation of TQM practices and adopting the correct CI strategies [18].

Cluster#5 named "Lean Six Sigma" considering that it also cover research related to CI projects and their failures. An important study analyzed the cause and effect association between the human factors as a means of fostering a Sustainable Continuous Improvement (SCI) environment. It results to the generation of a relationship map that distinguishes the different forms of action from soft practices and also revealed that the key to an SCI lies in the total engagement of the workforce to be mobilized and supported by top management, using kaizen events, effective communication and training [9]. Another significant research in this theme was a literature review regarding the implementation of Six Sigma and Lean Six Sigma (LSS) principles in hospitals, including 33 case studies that concluded that LSS can significantly contribute to improving process performance by reducing operating costs resulting in significant savings [16].

Cluster#6 named "Lean" considering that the researches that form this cluster deal with Lean systems, Lean practices; Lean production; Lean implementation; Lean leadership, dynamic capabilities, systematic problem solving and also aspects related to Lean soft practices. In an important unsuccessful case study of Lean implementation, it was abducted that the allocation of implementation tasks led to the failure of the initiative and a testable research proposition was also presented [39]. In another influential study dedicated to contribute to research on culture for continuous improvement, the relationship between top management leadership styles and Lean was explored in Dutch organizations. In that study, a positive relationship was found between Lean sponsorship and encouragement of improvement by senior management; a negative relationship was also identified between servant leadership and the use of Lean tools, while a positive relationship was found in relation to empowered leadership. At the end, a relationship between contemporary leadership styles and Lean practices were not found [47]. Recently, an empirical study analyzed the relationship between continuous improvement in product performance and process innovation. It as compared the results in different CI programs and evaluating four CI practices (culture, people, strategy and top management) through a web survey applied in Brazilian manufactures. The results indicated that continuous improvement is related to the four types of innovation performance regardless of the continuous improvement program applied [22]. Finally, Mohaghegh et al. [26] empirically investigated the relationships between lean management practices, dynamic capabilities, and sustainable business performance, using the dynamic capabilities approach. This study deals with concepts involving systematic problem solving that seem to be effective for sustainable development. It involved the application of interaction in 99 Italian manufacturing companies and the use of partial least squares structural modeling.

It was not possible to determine an appropriate name that represented each of the last four clusters due to the small number of documents that compose them: cluster #7 has 3 documents; cluster #8 has 2; cluster #9 has 2, and cluster #10 has 2 documents. Standing out among these are the studies of Garza-Reyes et al. [14] and Molavi et al. [27].

3.3 Performance Modalities Related to Continuous Improvement

In addition to pointing out CirP cluster themes, the present study showed that the literature offers different performance modalities related to continuous improvement. The three most recurrent performance modalities related to continuous improvement are: (a) operational performance ([36, 38, 45]; and, [17]); (b) organizational performance (e.g., [19, 34]; and, [18]); and, (c) financial performance [6, 24, 42]. Other modalities were also identified: innovation performance (e.g., [1, 22]); environmental performance (e.g., [46]); sustainability performance (e.g., [33]); employee performance (e.g., [2]); safety performance [11], market performance (e.g., [29]) and supply chain performance (e.g., [28]).

4 Conclusion

A methodology merging bibliographic coupling and content analysis was able to answer the two research questions: RQ1, what is the structure of the CI literature related to performance (CIrP)? and RQ2, which CIrP' themes are present in the past 5 years? The structure of the CI related to performance, in this case represented by bibliographic coupling network, is shown in Fig. 2 and it is complemented by its main documents for each cluster (Table 1).

The CIrP' themes present in the past 5 years are: [1] performance measurement and sustainability, covering performance measurement systems, key process indicators (KPI), green management, environmental performance; [2] kaizen and Lean thinking, what encompasses and quality tools and concepts (e.g., cause and effect diagram, VSM, kanban, 5S, takt time); [3] quality, composed by TQM and its practices, organizational culture, quality management, quality standards, quality performance and ISO 9000; [4] Strategy and Innovation, that also cover innovation performance, innovation orientation, management innovation, innovation strategy and organizational learning; [5] Lean Six Sigma, considering that it also cover research related to CI projects and their failures; and [6] Lean, considering that the researches that form this cluster deal with Lean systems, Lean practices; Lean production; Lean implementation; Lean leadership, dynamic capabilities, systematic problem solving and also aspects related to Lean soft practices.

It was observed that several topics were not listed as part of the six clusters identified in this study. This is the case, for example, of Industry 4.0, mentioned in the content analysis of the works in clusters #2 [37, 45], but which are not characterized as part of the six cluster themes. Likewise, publications dealing with other popular topics such as knowledge management, decision marking, among others, are also dispersed in different clusters and, for this reason, do not make up any of the six indicated in this study.

This study is limited to two scientific databases (Scopus and Web of Sciences). Future studies could explore the other ones. Moreover, further research should be undertaken by delving deeper into one or more of the six main cluster themes identified in this study. Furthermore, the research gaps indicated in the publications that compose each of the six clusters themes need to be mapped. Finally, it could be important to know which affiliations and researchers are conducting research on each of the six themes present and which journals are publishing such research.

At the end, each of the six present themes represent a different starting points for researches on CIrP. Moreover, this paper makes the first essay to understand the research structure on CIrP, using bibliometric techniques and content analysis.

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References

1. Abdallah, A. B., Dahiyat, S. E., Matsui, Y.: Lean management and innovation performance: Evidence from international manufacturing companies. Management Research Review 42(2), 239–262 (2018).
2. Abukhader, K., Onbaşıoğlu, D.: The effects of total quality management practices on employee performance and the effect of training as a moderating variable. Uncertain Supply Chain Management 9(3), 521–528 (2021).
3. Álvarez-Garcia, J., Durán-Sánchez, A., and del Río, M.D.L.C.: Systematic bibliometric analysis on Kaizen in scientific journals. The TQM Journal 30(4), 356–370 (2018).
4. Anand G., Ward, P.T., Tatikonda, M.V., Schilling, D.A.: Dynamic capabilities through continuous improvement infrastructure. Journal of operations management, 27(6), 444–461 (2009)
5. Araújo, R., Santos, G., da Costa, J. B., Sá, J. C.: The quality management system as a driver of organizational culture: An empirical study in the Portuguese textile industry. Quality Innovation Prosperity, 23(1), 1–24 (2019).
6. Beyhan Yasar, N., Sezen, B., Karakadilar, I. S.: Mediating effect of continuous improvement on the relationship between innovation and financial performance. Total Quality Management & Business Excellence 30(7–8), 893–907 (2019).
7. Choudhary, S., Nayak, R., Dora, M., Mishra, N., Ghadge, A.: An integrated lean and green approach for improving sustainability performance: a case study of a packaging manufacturing SME in the UK. Production planning & control, 30(5–6), 353–368 (2019).
8. Clarivate Analytics. Web of Science Database (2018).
9. Costa, F., Lispi, L., Staudacher, A. P., Rossini, M., Kundu, K., Cifone, F. D.: How to foster Sustainable Continuous Improvement: A cause-effect relations map of Lean soft practices. Operations Research Perspectives, 6, 100091 (2019).
10. Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., Lim, W.M.: How to conduct a bibliometric analysis: an overview and guidelines. Journal of Business Research 133, 285–296 (2021).
11. Eskandari, D., Gharabagh, M. J., Barkhordari, A., Gharari, N., Panahi, D., Gholami, A., Teimori-Boghsani, G.: Development of a scale for assessing the organization's safety performance based fuzzy ANP. Journal of Loss Prevention in the Process Industries 69, 104342 (2021).
12. Facin, A.L.F., Barbosa, A.P.F.P.L., Matsumoto, C., Cruz, A.F.S.D.G, Salermo, M.S.: Featured topics in research on digital transformation: evidence from a bibliometric study and content analysis. Revista de Administração de Empresas, 62(6) (2022).
13. García, S.M., Torres, G.C.L., Ramos, M.D.J.P., García, R.M.C.: Administración de operaciones y su impacto en el desempeño de las empresas. Revista de ciencias sociales 27(1), 112–126 (2021).
14. Garza-Reyes, J.A., Kumar, V., Chaikittisilp, S., Tan, K.H.: The effect of Lean methods and tools on the environmental performance of manufacturing organisations. International Journal of Production Economics 200, 170–180 (2018).
15. Hung, R.Y.Y., Yang, B., Lien, B.Y.H., McLean, G.N., Kuo, Y.M.: Dynamic capability: impact of process alignment and organizational learning culture on performance. Journal of world business, 45(3), 285–294 (2010).
16. Honda, A. C., Bernardo, V. Z., Gerolamo, M. C., Davis, M. M.: How lean six sigma principles improve hospital performance. Quality Management Journal, 25(2), 70–82 (2018).
17. Inan, G.G., Gungor, Z.E., Bititci, U.S., Halim-Lim, S.A.: Operational performance improvement through continuous improvement initiatives in micro-enterprises of Turkey. Asia-Pacific Journal of Business Administration, 14(3), 335–361 (2022).
18. Jimoh, R., Oyewobi, L., Isa, R., Waziri, I.: Total quality management practices and organizational performance: the mediating roles of strategies for continuous improvement. International Journal of Construction Management, 19(2), 162–177 (2019).

19. Khan, S. A., Kaviani, M. A., Galli, B. J., Ishtiaq, P.: Application of continuous improvement techniques to improve organization performance: A case study. International Journal of Lean Six Sigma 10(2), 542–565 (2019).
20. Lai, J.H., Hou, H.C., Edwards, D.J., Yuen, P.L.: An analytic network process model for hospital facilities management performance evaluation. Facilities 40 (5/6), 333–352 (2021).
21. Lizarelli, F.L., Bessi, N.C., Oprime, P.C., Amaral, R.M.D., Chakraborti, S.: A bibliometric analysis of 50 years of worldwide research on statistical process control. Gestão & Produção 23, 853–870 (2016).
22. Lizarelli, F.L., de Toledo, J.C., Alliprandini, D.H.: Relationship between continuous improvement and innovation performance: an empirical study in Brazilian manufacturing companies. Total Quality Management & Business Excellence 32 (9–10) 981–1004 (2021).
23. Makwana, A.D., Patange, G.S.: Strategic implementation of 5S and its effect on productivity of plastic machinery manufacturing company. Australian Journal of Mechanical Engineering 20(1), 111–120 (2022).
24. Maswadeh, S., Zumot, R.: The effect of total quality management on the financial performance by moderating organizational culture. Accounting, 7(2) 441–450 (2021).
25. Medne, A., Lapina, I.: Sustainability and continuous improvement of organization: Review of process-oriented performance indicators. Journal of Open Innovation: Technology, Market, and Complexity 5(3), 49 (2019).
26. Mohaghegh, M., Blasi, S., Größler, A.: Dynamic capabilities linking lean practices and sustainable business performance. Journal of Cleaner Production 322, 129073. (2021).
27. Molavi, A., Lim, G. J., Race, B.: A framework for building a smart port and smart port index. International journal of sustainable transportation 14(9), 686–700 (2020).
28. Mouhsene, F. R. I., Faycal, F., Kaoutar, K., Charif, M., El Alami, S.: Supply chain performance evaluation models, state-of-the-art and future directions. International Journal of Engineering and Advanced Technology 9(1), 6336–6347 (2019).
29. Muganyi, P., Madanhire, I., Mbohwa, C.: Business survival and market performance through Lean Six Sigma in the chemical manufacturing industry. International Journal of Lean Six Sigma 10(2), 566–600 (2018).
30. Nae, I., Severin, I.: Performance management model for third party logistics companies. UPB Scientific Bulletin, Series D: Mechanical Engineering 80(4), 279–286 (2018).
31. Niñerola, A., Sánchez-Rebull, M.V., Hernández-Lara, A.B.: Six Sigma literature:' a bibliometric analysis. Total Quality Management & Business Excellence 32(9–10), 959–980 (2021).
32. Norris, M.; Oppenheim, C.: Comparing alternatives to the Web of Sciences for coverage of the social sciences' literature. Journal of Infometrics 1(2), 161–169 (2007).
33. Nguyen, M. H., Phan, A. C., Matsui, Y.: Contribution of quality management practices to sustainability performance of Vietnamese firms. Sustainability 10(2), 375 (2018).
34. Pambreni, Y., Khatibi, A., Azam, S., Tham, J. J. M. S. L.: The influence of total quality management toward organization performance. Management Science Letters 9(9), 1397–1406 (2019).
35. Rajesh, R.: Exploring the sustainability performances of firms using environmental, social, and governance scores. Journal of Cleaner Production 247, 119600 (2020).
36. Randhawa, J.S., Ahuja, I.S.: An investigation into manufacturing performance achievements accrued by Indian manufacturing organization through strategic 5S practices. International Journal of Productivity and Performance Management 67(4), 754–787 (2018).
37. Rossini, M., Costa, F., Tortorella, G. L., Portioli-Staudacher, A.: The interrelation between Industry 4.0 and lean production: an empirical study on European manufacturers. The International Journal of Advanced Manufacturing Technology 102(9), 3963–3976 (2019).
38. Saleh, R. A., Sweis, R. J., Saleh, F. I. M.: Investigating the impact of hard total quality management practices on operational performance in manufacturing organizations: Evidence from Jordan. Benchmarking: An International Journal 25(7), 2040–2064 (2018).

39. Secchi, R., Camuffo, A.: Lean implementation failures: the role of organizational ambidexterity. International journal of production economics 210, 145–154 (2019).
40. Schroeder, R.G., Linderman, K., Ledtke, C., Choo, A.S.: Six Sigma: definition and underlying theory. Journal of Operations Management 26(4), 536–554 (2008).
41. da Silva, F. F., Filser, L. D., Juliani, F., de Oliveira, O. J.: Where to direct research in lean six sigma? Bibliometric analysis, scientific gaps and trends on literature. International Journal of Lean Six Sigma 9(3), 324–330 (2018).
42. Soewarno, N., Mardijuwono, A. W.: Mediating Effect of continuous improvements on management accounting innovations-information capital maturity level-organizational performance relationships. Problems and Perspectives in Management 16(3), 356–365 (2018).
43. Sordan, J.E., Oprime, P.C., Pimenta, M.L., da Silva, S.L. González, M.O.A.: Contact points between Lean Six Sigma and Industry 4.0: a systematic review and conceptual framework. International Journal of Quality & Reliability Management 39(9), 2155–2183 (2021).
44. Talib, F., Asjad, M., Attri, R., Siddiquee, A. N., Khan, Z. A.: Ranking model of total quality management enablers in healthcare establishments using the best-worst method. The TQM Journal 31(5), 790–814 (2019).
45. Tortorella, G., Miorando, R., Caiado, R., Nascimento, D., Portioli Staudacher, A.: The mediating effect of employees' involvement on the relationship between Industry 4.0 and operational performance improvement. Total Quality Management & Business Excellence 32(1–2), 119–133 (2021).
46. Trujillo-Gallego, M., Sarache, W., Sellitto, M.A.: Environmental performance in manufacturing companies: a benchmarking study. Benchmarking: An International Journal 28(2), 670–694 (2020).
47. van Assen, M. F.: The moderating effect of management behavior for Lean and process improvement. Operations Management Research 11(1), 1–13 (2018).
48. van Eck, N., Waltman, L.: Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84(2), 523–538 (2010).
49. Weinberg, B.H.: Bibliographic coupling: a review. Information Storage and Retrieval 10 (5–6), 189–196 (1974).
50. Zupic, I.; Čater, T.: Bibliometric methods in management and organization. Organizational research methods 18(3) 49–472 (2015).

Process Monitoring Applied to Performance Indicators of Manufacturing Process

Walmir Rodrigues Luz and Ângelo Márcio Oliveira Sant'Anna

Abstract Intelligent manufacturing constantly uses integrated systems based on industry 4.0 technologies to evaluate process efficiency with a constant increase in productivity. One of these approaches is data science analytics which makes performance monitoring in real-time and provides relevant information for better decision-making with probabilistic maximization.

Performance evaluation based on process monitoring has been proposed in the literature and has gained the attention of many practitioners and researchers to support great decision-making. This paper proposes to monitor the overall equipment effectiveness indicator based on control charts in the rolling process of the wire machine. Analyses were carried out in the literature of the main performance indicators and conceived through the overall equipment effectiveness indicator. The performance indicator was evaluated about the availability, performance, and quality efficiency from the rolling process. The paper demonstrated how the overall equipment effectiveness could assist the continuous improvement of equipment and efficient production from a smart manufacturing system. New applications will be needed to expand the performance indicator database over time and conduct predictive statistical process monitoring.

Keywords OEE · Overall equipment effectiveness · Process monitoring · Control charts

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1 Introduction

Industrial manufacturing began to stand out at the beginning of the first Industrial Revolution in England in the eighteenth century. This evolution propitiated to the man the possibility of producing products on a bigger scale containing innovative technologies. Among the innovations stand out the machines, which increased precision and streamlined production. In addition, new energy sources, such as steam, were used to replace energy hydraulics of the time [1].

In recent years, the world has gone through the fourth Industrial Revolution, known as Industry 4.0. This new revolution searches for full industry automation, making factories independent of human labor. This new level of automation happens due to Cyber Physics Systems and Artificial Intelligence, which are possible thanks to the Internet of Things and Big Data, which make intelligent factories self-manageable [2].

In the twenty-first century, with the great development of sensor technology, software, and hardware and the evolution of the internet, which enabled the communication of several systems, a new industrial transformation began and greatly impacted society and the economy. In addition to the term Industry 4.0, this new revolution is also known as smart manufacturing, intelligent manufacturing, or the factory of the future. Although your names are different, they portray the same foundation, which describes Industry 4.0 as one industry that is flexible, dynamic, and agile, in which the products are smart. They are produced by machines that talk to each other [3].

Linked to a high degree of technology aggregated to the industries, the fourth Industrial Revolution also considers the total control of the information and its flow. Based on this need, metrics known to gauge The line efficiency productive also must be automated. Among the more known metrics stands out Overall Equipment Effectiveness (OEE), which aims to increase factory performance using quality, availability, and performance data, enabling the review of strategies for decision-making assertive decision-making that will optimize the production line [4].

The measures that influence the result are machine availability, productivity, and product quality. The lower result means there are one or arere factors that need improvement. Through the OEE, it is possible to assess the company results and losses since the capacity productive is compromised when there is low availability and productivity. He also allows identifying the quality of the products, a time when everything that is produced becomes product finished due to some no compliance [5].

Machinery efficiency is monitored daily through the OEE. However, due to the industry profile of steel works and a large variety of mounting platforms, setup times and machine performance usually vary. It is a variation directly linked to the type of components constant at product structure and component density inserted in the wire processing machine. By field observations, the rolling process wire machine with high speed tends to have a higher performance index than the wire rolling process wire machine default. Each turn is more common, companies realize in a digital environment, allowing the manager to evaluate possible interventions, such as continuous improvement options and action plan design, and technology provides the simulation of many different scenarios.

Statistical process monitoring (SPM) has presented challenges and potential solutions as an analytical tool for monitoring the process performance in smart manufacturing. SPM-based process performance analysis is a promising route for characteristics or feature extraction processes and could play a significant role in intelligent manufacturing [6].

This paper proposes to monitor the overall equipment effectiveness indicator based on control charts in the rolling process of the wire machine. The accuracy is evaluated by classical and special control charts, checking your adequacy to the process, and comparing identification of out-of-control measurements, from the determination of the control chart more appropriate to establish the proper tool for the daily control of the OEE indicator. To evidence criteria for evaluating the acceptability of the indices registered to assess the variation registered at the sample, it is within the standards statisticians settled down or if you configure high standard deviations helping managers and methods.

2 Materials and Methods

2.1 Overall Equipment Effectiveness

The Overall Equipment Effectiveness (OEE) is an indicator used to measure the performance of a manufacturing plant globally. Increased equipment efficiency is achieved not only through quantitative activities, such as increased availability and improved performance but also through qualitative activities resulting from reducing waste and rework inside the factory. OEE can be expressed as the ratio of current equipment outputs divided by the maximum output of the equipment under conditions performance ratios [7, 8].

OEE originates from Total Productive Maintenance (TPM) practices developed by Nakajima in 1988 [9] to meet the goal of zero defects. Due to easy interpretation and quick exposure of losses in the process, the OEE acts as a productivity indicator key. In [10] asserted the OEE serves multiple goals, such as product quality improvement, cost product improvement, cost reduction, and avoiding waste, especially by machine stoppages and equipment performance. The OEE indicator is an important metric for focusing on improvement in the process, allowing identifying the major loss impact on process efficiency. Another important factor in knowing the OEE accurately is its influence on the effectiveness of production planning, as equipment availability directly affects complying with the production plan. If the performance of the plan consistently hits the value of 100%, the OEE and capacity effectiveness probably are underestimated, indicating that the capacity equipment theory is greater than the estimated. In this case, it is important that the OEE measures and effective capacity must be revised and recalculated [11].

Performance Indicator

The indicators used to measure production performance are based on the terms used in industrial processes. The form of calculation is demonstrated based on construction methods for each subarea of production management.

$$OEE = \text{Availability} \times \text{Efficiency} \times \text{Quality} \tag{1}$$

Availability

This indicator provides an overview of the availability of items in general that will be needed by the production system, prioritizing product output according to established standards (quality standards, production time, delivery time, etc.). These items can be characterized according to the process area, with the most relevant areas such as Maintenance. Internal availability is related to the equipment available for the production process to start and finish manufacturing the product associated with the Maintenance sector. Two indicators represent internal availability internal being the mean time between failures (MTBF) and mean time to repair (MTTR),

$$\text{MTBF} = \frac{hours\ (working)}{hours\ (interval)} \tag{2}$$

$$\text{MTTR} = \frac{hours\ (repairs)}{hours\ (interval)} \tag{3}$$

The MTTR is a measure of the serviceability of a repairable item, and it tells you the average time necessary for the equipment to be likely to return to normal operating condition. MTBF measures the average time of device or product works until its failures, without including the time to repair it [12]. The MTBF and MTTF units are usually measured in hours. The process study for the case study will also be in hours. Thus, we have the Availability equation, constituted by the ratio (in percentage),

$$Availability = \frac{MTBF}{MTBF + MTTR} \tag{4}$$

Performance

The performance parameter is calculated considering the factory's production capacity in relation to the time available. The definition of this value is important for the accuracy of the performance index, for this is important to use the data provided for the planning of the factory and the employees who experience the process all your days.

Performance represents the ability to produce efficiently when referring to machinery and equipment [7]. The performance in driving the strategy requires one change in the way of looking at actions and needs to be inserted into the philosophy of work, it is a complex recipe to be executed.

$$Performance = \frac{Planned\ capacity}{Executed\ capacity} \tag{5}$$

Quality

For a process with low failure rates related to the final product and not to the process or equipment (these terms are associated with maintenance management and not product quality), the process must be performed as it is pre-defined. in writing and that Quality management carries out efficient control regarding the input of inputs and the output of the finished product for the final consumer [13].

In this study, an indicator of the rate of conforming products is carried out, where at the end of the process, it is possible to calculate how much of the final product will be sent to the consumer customer and how much of the finished product will be transformed into scrap or reprocessed. Even if the scraps are sold or the product is being reprocessed, these values reduce the quality efficiency since efforts were made (machine, labor, inputs) that will not be directed in monetary return since they will not be with the final consumer in the expected team.

$$Quality = \frac{Parts\ produced - (scrap\ parts + rework\ parts)}{Parts\ produced} \tag{6}$$

Most industrial processes have these indicators and continuously monitor them. The indicators present weights for the process equal 1. These weights depend on the criticality of each indicator. Some processes require more maintenance (in the case of machines with frequent breakdowns).

2.2 Process Monitoring

The performance of a process can be evaluated in several ways, such as how to monitor the performance process indicators. This proposal implies that if the variability inherent to the process decreases, the performance of the process increases. So, statistical process monitoring (SPM) allows the evaluation of industrial processes' stability, performance, and improvement. These SPM tools are frequently used for monitoring and change detection in the manufacturing process, aiming to decrease waste and increase productivity. That increase in productivity is realized by minimizing variability, providing levels best quality results, and cost reduction [14].

Studies about control charts he has introduced growing evolution, one of the main reasons for the importance of the application of this SPM tool to analyze and direct improvement actions for an increase in quality control [15]. Although control chart studies monitoring process performance indicators in the industrial process has on a smaller scale.

Control charts are statistical process control tools used to monitor the presence of variability and causes specials in the process. The chart contains one center line and two horizontal lines called upper control limit (UCL) and lower control limit (LCL). The central line variable's average value corresponds to the state under control.

The control charts can be divided according to the ability to monitor large or small changes around the process mean. Control charts for large changes, such as the control chart for Individuals Values (I-MR chart) proposed by Shewhart in 1924, feature great ease for implementation and analysis of the process with a standard deviation above 1.5σ.

$$[LCL; UCL] = \overline{x} \pm w \cdot \sqrt{s^2(\overline{x})} \tag{7}$$

Control charts for large changes, such as the Cumulative Sum (CUSUM) control chart proposed by Page in 1954 and the Exponentially Weighted Moving Average (EWMA) proposed by Roberts in 1959, present one big sensitivity to small changes within a process with a standard deviation of 1.5σ or less. The CUSUM and EWMA control charts have as the goal of analyzing information accumulated in miscellaneous samples previous and not only in a single point. This makes these control charts more effective at signaling the lack of control, as well as identifying the time at which the change occurs within the process analyzed [16].

The CUSUM control chart directly incorporates all information on sample values are plots the cumulative sums of sample deviations from a target value and the cumulative sum is a walk random with zero mean [17]. Assuming it x_i is the *ith* sample at time t with $1 < t \leq T$, k is the amount of change expressed in units of standard deviation $k = \frac{|\mu_1 - \mu_0|}{2}$, and the bounds produce a signal whenever C_i^- or C_i^+ is greater than δ. Then, the CUSUM letter can be formulated according to you control limits defined by:

$$[LCL; UCL] = \begin{matrix} C_i^- = max\left[0; (\mu_0 + k) - x_i + C_{i-1}^-\right] \\ C_i^+ = max\left[0; x_i - (\mu_0 + k) + C_{i-1}^+\right] \end{matrix} \tag{8}$$

The EWMA control card is commonly used in variable measurement process, where statistics analyzed is the mean weighted sampling or the weighted individual value. This control chart presents speed and precision in the identification of causes special in processes and indicated for the control automated [18]. Assuming it x_i is the *ith* sample at time t with $1 < t \leq T$, λ is the power value expressed at $0 < \lambda \leq 1$, the value expressed at the instant initial is equal to mean $z_0 = \mu_0$, and limits produce a signal whenever C_i^- or C_i^+ is greater than δ. Then, the CUSUM chart can be formulated as per the control limits defined by:

$$Z_i = \lambda \sum_{k=0}^{i-1} (1-\lambda)^k x_{i-k} + (1-\lambda)^k \cdot Z_0$$
$$[LCL; UCL] = z_i \pm w \cdot \sqrt{\left(\frac{\lambda}{2-\lambda}\right)\left[1-(1-\lambda)^{2i}\right]} \tag{9}$$

Chart I-MR, CUSUM and EWMA control charts are performed similarly if the process is under control, the behavior describes a route random with zero mean. But if there are changing trends in mean value for some value above, then the accumulated value will present one trend ascending. So, if any measurement surpasses your control limits it is said that this process is out of control.

3 Results and Discussions

The company in study is a leader worldwide at steel fabrication and steel supplier long and special. It is present in more than 150 countries with a trajectory of almost 100 years of existence. In Brazil, it has five units established, where the evaluated plant he has around 3000 employees (direct and indirect) and produces approximately 215,000 products per month.

The rolling process of wire machine was indicated for the performance evaluation through the OEE indicator. The thread machine refers to a product round hot rolled with a diameter that can range from 4.75–44.0 mm. The rolling process wire high machine speed refers to laminate which is commonly known as high-speed non-twist rolling. The rolling speed can arrive at 80–160 m/s.

During the rolling process, the process parameters can be adjusted to ensure you meet many different product requirements. The thread machine features one small cross section and large length, which requires high dimensional accuracy and surface quality. The high spiral former speed is composed mainly of transmission devices, axles tubes, tubes formers and bearings. After the thread machine laminate raisin for the block discharge finisher velocity is introduced into the tube former by the pinch roll. Inside the tube coil former, wire machine is ejected to the along the direction tangential to the circle and, in then falls on Stelmor's roller table, in the form of loose spirals per half of its own weight. Figure 1 shows the rolling process of wire machine high speed studied.

To manage steps of that rolling process are used operational indicators. The indicators are divided into availability, performance, and quality. The data were collected information for calculating the OEE indicator in real time daily. In then the control charts were applied and compared to the results obtained for the process performance analysis. Figure 2 illustrates the distribution of measurements monthly process OEE.

After collecting the data carried out by the operation were analyzed the estimates parameter statistics. Table 1 shows the estimates OEE performance indicator statistics. The analysis preliminary sample, ratio metrics average of the OEE indicator

Fig. 1 Wire machine manufacturing process in the studied company

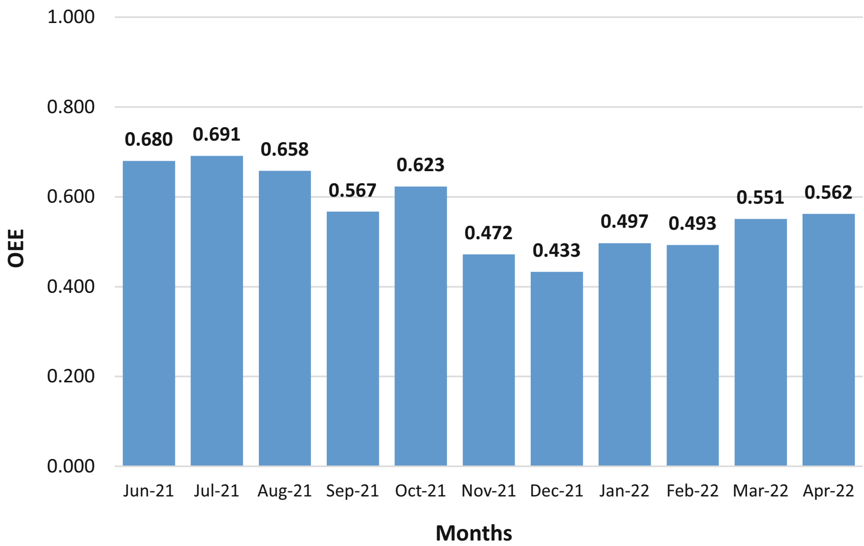

Fig. 2 Monthly distribution of OEE measurements process studied

Table 1 Summary statistics of the OEE performance indicator

Variable	Minimum	Maximum	Mean	Std. Dev.	Coef. Var
OEE	0.01279	0.96057	0.57239	0.2458	42.9%

were minimum of 0.5724, standard deviation of 0.2458 and coefficient of variation of 42.9%. The value of the OEE indicator of the yarn production process machine does not follow the Normal distribution based on the Shapiro-Wilk adherence test (W = 0.927), with 95% confidence ($\alpha = 0.05$), with the value obtained for p-value <0.01. All analyzes were performed with the open-source software R® [19].

In this paper, the I-MR, CUSUM and EWMA control charts are applied for profile monitoring of the OEE indicator from rolling process of wire machine. All control charts were calculated for the probability of occurring false alarms of $\alpha = 0.0027$ and confidence level of *99.73%* $(1 - \alpha)$. The constant values were $w = 3$, $k = 0.10$, and $\lambda = 0.2$ for calculating the limits of the control charts presented in the Eqs. 7, 8 and 9.

In this application, it can see the I-MR control chart describes the under-control behavior for the OEE indicator, however, the CUSUM and EWMA control charts show bigger sensitivity for detection small changes of OEE indicator in a way efficient, presenting a monitoring more accurate about performance indicator (see in Fig. 3). It is possible to identify which periods when the overall performance value of the rolling process of wire machine was very below with expected value of 55%. From this process monitoring study is possible to determine the operating conditions of the rolling process, making your daily performance indicator increase, bringing the index above the global average.

4 Conclusions

This paper proposed to monitor the OEE performance indicator based on the control charts in the rolling process of wire machine. The application of statistical process monitoring technique consisted in evaluating the behavior of the OEE indicator and identifying which periods that the process presented low performance. This tool presents relevant contribution to monitor intelligence manufacturing processes from real-time data to support accurate and timely decision-making.

The paper demonstrated how the overall equipment effectiveness can assist in improvement continuous use of equipment and efficiency production from smart manufacturing system – the small losses, up to then no quantified no was the target of improvement actions. With OEE measurement and monitoring, these stops began to be seen as problems and people involved passed to intervene in these losses – so that these become productive hours.

The study accomplished demonstrates that the use undue use of control charts for measures individual it is not fully suitable for monitoring the OEE indicator. For this case got better results using control charts specials such as CUSUM and EWMA, which present adequate performance and accuracy. Although only measure the OEE indicator with a process analysis strategy does not solve the problem of variability, it is essential to application of control charts for identification more needs low performance and visualization more quick results for future process improvement interventions.

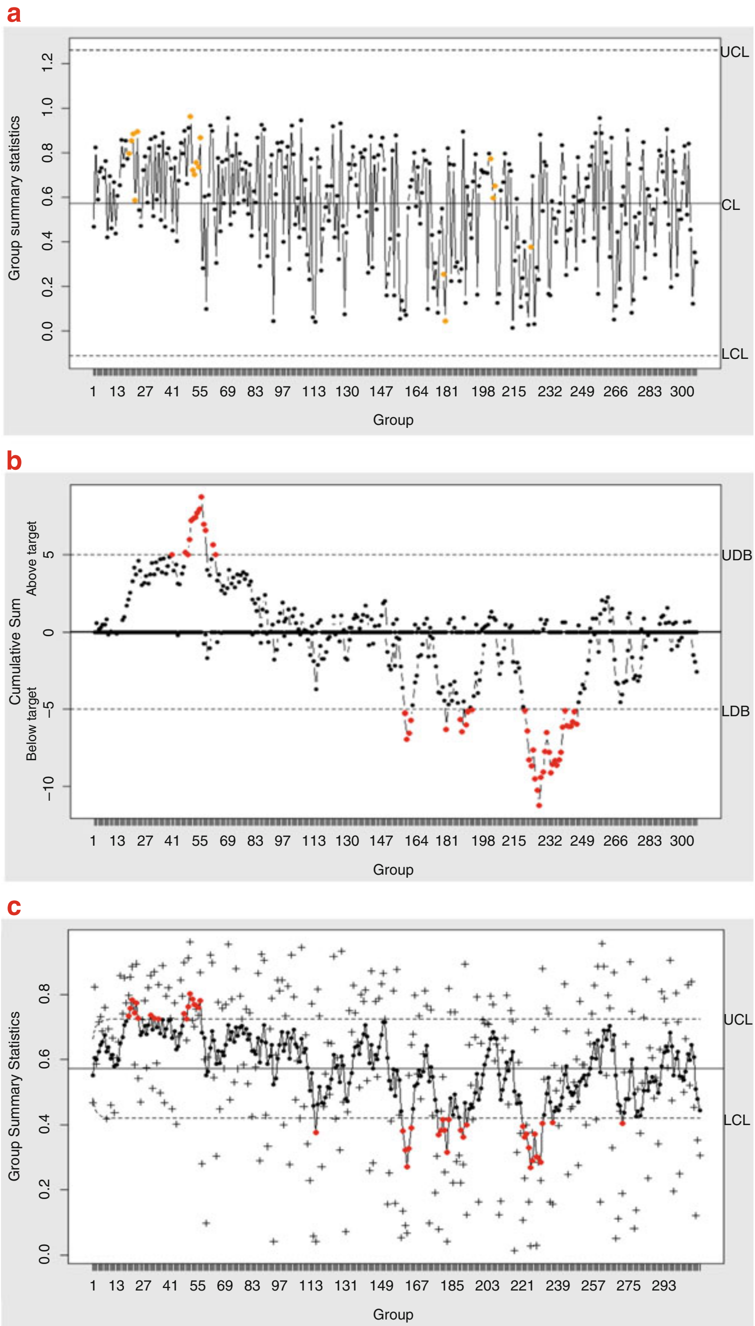

Fig. 3 I-MR (**a**), CUSUM (**b**), and EWMA (**c**) control charts for monitoring OEE indicator

The integration of technologies related to Industry 4.0 could raise the OEE indicator by means of automatic solutions. In one factory with level of integration discussed per This one work is possible improve the efficiency of the industrial process in manufacturing smart to allow decision making autonomous. For example, to implement online monitoring to OEE indicator through control charts allows to create a system based on artificial intelligence for identifying abnormality, detecting the causes of stoppages, and carrying out the decision-making.

The performance of the rolling process of wire machine is not expected, so the production system must be improved immediately. Furthermore, to avoid the impact drawback of flaws in the rolling process, it is highly suggested upgrade spare parts and maintenance requirements operation management equipment predictive. The use of a Big Data Analytics tool for monitoring production line performance can help minimize failures and repair times. Thus, the operation and efficiency of the production line can be improved.

References

1. Francisco, M.G., Canciglieri Junior, O., Sant'Anna, AMO. Design for six sigma integrated product development reference model through a systematic review. *International Journal of Lean Six Sigma*. 27511(4), 767–795, 2020. https://doi.org/10.1108/IJLSS-05-2019-0052
2. Sanchez, M., Exposito, E., Aguilar, J. Industry 4.0: survey from a system integration perspective, *International Journal of Computer Integrated Manufacturing*, 33(10), 1017–1041. 2020. https://doi.org/10.1080/0951192X.2020.1775295
3. Acosta, SM., Oliveira, RMA., Sant'Anna, AMO. Machine learning algorithms applied to intelligent tire manufacturing. *International Journal of Computer Integrated Manufacturing*, ahead-of-print, 2023. https://doi.org/10.1080/0951192X.2023.2177734
4. Reyes, JAG., Eldridge, S., Barber, KD., Meier, HS. Overall equipment effectiveness (OEE) and process capability (PC) measures. *International Journal of Quality & Reliability Management*, 27(1): 48–62, 2010. https://doi.org/10.1108/02656711011009308
5. Cheng, CY. A novel approach of information visualization for machine operation states in industrial 4.0. *Computers & Industrial Engineering*, 125, 563–573, 2018. https://doi.org/10.1016/j.cie.2018.05.024
6. He, Q., Wang, J. Statistical process monitoring as a big data analytics tool for smart manufacturing, *Journal of Process Control*, 67: 35–43. 2018. https://doi.org/10.1016/j.jprocont.2017.06.012
7. Muchiri, P., Pintelon, L. Performance measurement using overall equipment effectiveness (OEE): literature review and practical application discussion, *International Journal of Production Research*, 46(13), 3517–3535, 2008. https://doi.org/10.1080/00207540601142645
8. Wohlgemuth, M., Fries, CE., Sant'Anna, AMO. Giglio, R. Fettermann DC. Assessment of the technical efficiency of Brazilian logistic operators using data envelopment analysis and one inflated beta regression, *Annals of Operations Research,* 286:703–717, 2020. https://doi.org/10.1007/s10479-018-3105-7
9. Nakajima, S. *Introduction to TPM*. Cambridge: Productivity Press, 1988.
10. Wudhikarn, R. Improving overall equipment cost loss adding cost of quality, *International Journal of Production Research*, 50(12), 3434–3449, 2012. https://doi.org/10.1108/00207543.2011.587841

11. Jain, A., Bhatti, RS., Singh, H. OEE enhancement in SMEs through mobile maintenance: a TPM concept, *International Journal of Quality & Reliability Management*, 32(5): 503–516, 2015. https://doi. org/10.1108/IJQRM-05-2013-0088
12. Patil, A., Soni, G., Prakash, A., Karwasra, K. Maintenance strategy selection: a comprehensive review of current paradigms and solution approaches, *International Journal of Quality & Reliability Management*, 39(3),675–703. 2022. https://doi.org/10.1108/IJQRM-04-2021-0105
13. Acosta, SM., Amoroso, AL., Sant'Anna, AMO., Canciglieri Junior, O. Relevance vector machine with tuning based on self-adaptive differential evolution approach for predictive modeling of a chemical process. *Applied Mathematical Modeling*, 95:125–142, 2021. https://doi.org/10.1016/j.apm.2021.01.057
14. Gumz, J., Fettermann, DC., Sant'Anna, AMO., Tortorella, GL. Social influence as a major factor in smart meters' acceptance: findings from Brazil. *Results in Engineering*, 15, 100510, (2022). https://doi.org/10.1016/j.rineng.2022.100510
15. Acosta, SM., Sant'Anna, AMO. Machine learning-based control charts for monitoring fraction nonconforming product in smart manufacturing. International Journal of Quality and Reliability Management, ahead-of-print, 1–35, 2022. https://doi.org/10.1108/IJQRM-07-2021-0210
16. Qiu, P. *Introduction to Statistical Process Control*. Boca Raton: Taylor & Francis, 2014.
17. Hawkins, DM., Olwell, DH. *Cumulative Sum Charts and Charting for Quality Improvement*. New York: Springer-Verlag, 1998.
18. Kalgonda, AA., Koshti, VV. *Exponentially Weighted Moving Average Control Chart*. London: Lambert Academic Publishing, 2013.
19. R. R language and environment for statistical computing. R Foundation for Statistical Computing. ISBN 3-900051-07-0. 2022. Available at http://www.r-project.org.

Selective Openness in the Additive Manufacturing Industry: An Exploratory Modeling Analysis

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Abstract Selective openness is an R&D strategy in which firms allow portions of their technology to be accessed by other firms to attract adopters and supplier complements. While open-source software (OSS) has been widely embraced by software firms, it is unclear if open-source hardware (OSH) will be similarly embraced by technology-intensive manufacturing firms. This paper extends a competitive dynamics model to investigate tradeoffs associated with selective openness R&D strategies in the professional-grade additive manufacturing (AM) industry. We start by examining whether a competitive dynamics model supports selective openness strategies from a profit-maximization standpoint. We then evaluate the industry-level impacts of selective openness. While our results do not support the adoption of selective openness strategies from a strict profit-maximization standpoint, firms may pursue this strategy if they place value on advancing the overall product quality and accessibility in their industry.

Keywords 3D printing · Additive manufacturing · Open source · Selective openness · Robust decision making · Decision making under deep uncertainty

1 Introduction

Selective openness is an R&D strategy in which firms allow portions of their technology to be accessed by other firms to attract adopters and supplier complements [1, 2]. Firms selectively allow other actors access to some of their product and

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technology outputs while retaining property rights to other products or parts [3]. The open-source software strategy sees firms form communities to produce and govern the resulting products [4, 5]. Empirical evidence has shown that the feeling of involvement by members of a community increases their contribution to open innovation [6].

While open-source software (OSS) is now widely prevalent and embraced by mainstream software firms, it is unclear whether open-source hardware (OSH) will be widely adopted by technology-intensive manufacturing firms. The additive manufacturing (AM) industry may be an early example of a marketplace where OSH early adopters have thrived. Prusa Research, a one-man 3D printer start-up founded in 2012, has grown to produce one of the most popular fused deposition modeling (FDM) printers in the world by fully embracing open-source hardware. Its website states: "*…we wouldn't exist without open source. Prusa i3 3D printers were born from the idea of an open-source machine and we are faithful to this ideology*" [7]. Although Prusa's success may be encouraging to those committed to the open-source ethos, it is still unclear whether incumbent AM firms operating at the industrial-grade tier have incentives to adopt this strategy. Several factors may discourage incumbent industrial-grade AM systems manufacturers (AMSMs) from adopting open-source hardware more broadly. Technological breakthroughs by rivals, expiring patents, open-source firms, and fierce competition all limit profitability.

Confronted by those challenges, incumbent AMSMs have highly consequential and irreversible strategic decisions to make. This paper focuses its attention on two interrelated decision levers: (i) R&D selective openness – the extent an incumbent firm allows external communities, or even its rivals, to use its intellectual property [2], and (ii) pricing and market share aggressiveness – the extent to which the firm decides to gain and defend its market share position through competitive pricing. This paper is organized as follows. First, we review the related literature on selective openness and new product diffusion. Second, we present an extension to the Sterman et al. [8] competitive dynamics model by accounting for relevant aspects of the AM industry, namely R&D investments, patent dynamics and expiration, and product performance. Third, we explore the effects of selective openness strategies from the perspective of leading AMSM firms and their consumers. Finally, we discuss the broader implications of our results for the selective openness literature.

2 Background

2.1 Selective Openness in the AM Industry

Selective openness yields many benefits to companies [3]. First, firms can access technical knowledge from other actors that adopt and contribute to their products. Second, firms may leverage innovation they otherwise would not afford. Third, selective openness helps firms to obtain knowledge, resources, and assets from other firms that complement their own knowledge, resources, and assets [3, 9]. Finally, firms can increase their reputation since other actors become familiar with the innovation [10].

However, selective openness may have adverse effects. The most important is the risk of a firm losing its competitive advantage by having rivals imitate their innovation and then compete with the innovator firm [2]. The challenge is to determine how open the firm should be. The firm must decide strategically what should be open and which property rights to retain. One predictor of openness/closeness is the degree to which the actors compete. If they compete, there are fewer incentives to open the innovation [11, 12]. Henkel and Baldwin [13] show that firms shared Linux code for those routines that were not critical to their competitiveness while retaining property rights on those at the core of their competitive competence.

West and Kuk [2] investigated the case of a 3D printing hardware firm that leveraged an open-source community to generate value for its products. More specifically, they show how a 3D printing manufacturer used selective openness, created a community of users, and benefited from user-generated content complementing its proprietary hardware and software. Kwak et al. [14] introduce the concept of complementary platforms in which four platforms, including the open-source hardware platform, contribute to the innovation ecosystem of 3D printing technology. These findings vindicate open-source advocates, but it is unclear whether a strong case for selective openness can be made in other industries, such as professional-grade AM.

2.2 *Competitive Dynamics Amidst New Product Diffusion*

The diffusion of innovative products is a highly dynamic and complex phenomenon related to strategic pricing decisions, R&D budgeting, and investment in manufacturing capacity [15]. The canonical diffusion model presented by Bass [16] represents word-of-mouth new product diffusion from innovators to imitators. Sterman et al. [8] present a model that features competitive dynamics among firms in a nascent market undergoing new product diffusion. The model features two firms competing for market share as the nascent market unfolds. While companies can forecast future sales based on past data, none have perfect foresight into demand and are susceptible to missing their forecast of future sales due to the non-linear dynamics of new product diffusion. Further, the model considers delays introduced by capacity and price adjustments [8]. Sterman et al. [8] demonstrate that “Get Big Fast” strategies might be counterproductive when market dynamics occur quickly relative to capacity adjustment leading firms to build excess capacity.

The Sterman et al. [8] model is helpful to illuminate some of the tradeoffs AM firms face. The model usefully portrays an industry with decaying costs driven by a learning curve, product diffusion, and imperfect foresight – all of which arguably characterizes the professional-grade AM industry. However, the model does not include product performance as a factor that influences consumers’ choice. Hence, this paper extends the Sterman et al. [8] model to account for critical relevant characteristics in the AM industry, including research and development, patent expiration dynamics, and product performance.

3 Methods

This study draws from the Exploratory Modeling [17] paradigm and the Robust Decision Making (RDM) approach [18] to illuminate tradeoffs involved in an AMSM's decision to pursue selectively open R&D strategies. RDM studies often use the XLRM framework to explore choice among alternative courses of action (framed as portfolios of specific levers (L)) by assessing the implications of alternative metrics (M) for evaluating outcomes, different assumptions regarding uncertainties beyond the decision maker's control (X), and plausible alternative specifications of the causal relationships (R) mapping levers and uncertainties to those outcomes [18]. Table 1 summarizes the XLRM components considered in this study.

Relationships
Sterman et al. [8] propose a system dynamics model of competition between two firms in a generic nascent market where costs are abated by a learning curve. Product diffusion occurs as firms adjust their capacity and prices based on their pricing strategies. We expand the original Sterman et al. [8] model to allow the analysis of open and closed-source R&D investments. In our model, firms' R&D investments

Table 1 XLRM framework

<table>
<tr><th>X – Uncertainties</th><th colspan="2">R – Relationships</th></tr>
<tr><td>35 model parameters describing:
∘ Speed of product diffusion
∘ Market preference for low price over high performance
∘ Other AM systems manufacturers' strategies.</td><td colspan="2">∘ Modified competitive dynamics model [8] including R&D and printer performance as a market share criterion</td></tr>
<tr><th>L – Decision Levers</th><th colspan="2">M – Outcome Metrics</th></tr>
<tr><td rowspan="4">Market share levers:
• Pricing strategy
• Target market share
R&D levers:
• R&D budget
• R&D openness</td><td colspan="2">Upper-quartile regret of:</td></tr>
<tr><td>Stakeholders</td><td>Metrics</td></tr>
<tr><td>AM firm</td><td>Net present value ▲
Order share ▲
Printer perf. ▲</td></tr>
<tr><td>Consumers</td><td>Avg. printer perf. ▲
Avg. printer price ▼
Number of adopters ▲</td></tr>
</table>

result in intellectual property which influences product quality and ultimately market share. As patents expire, R&D investments improve the quality of other firms' products. Firms can also pursue selectively open R&D strategies whereby they devote a fraction of their R&D investments to open-source intellectual property while other firms may independently pursue closed-source strategies.

We also modified the model to include four firms to better characterize the existing market-share distribution in the 3D printer professional market [19] in which the three leading firms account for roughly 70% of the market. In our model, the fourth firm aggregates all remaining AMSMs. The supplementary appendix presents our modifications to the original model.

Decision Levers and Strategies

In this analysis, AMSMs control four decision levers. The first two decision levers are also included in the original Sterman et al. [9] analysis and are related to the firm's **market share strategy** – how aggressively the firm adjusts their prices to seek market share by pursuing a **pricing strategy** and a **target market share**. A firm pursuing an **aggressive** pricing strategy adjusts its price dynamically to claim a minimum target market share even if this leads to capacity overbuilding in the industry. Conversely, a firm may pursue a **conservative** pricing strategy by avoiding overbuilding capacity when it perceives that the overall production capacity in its market will exceed demand. Hence, aggressive firms pursue a "Get Big Fast" strategy seeking to stay ahead in the learning curve relative to their peers. This analysis considers firms pursuing aggressive or conservative market share strategies with target market shares of 20, 30, or 40%. The third and fourth decision levers are introduced in this analysis and control how a firm manages its R&D investments. The firm controls its **R&D budget**, defined as a percentage of revenue (5, 10, or 15%) and its **R&D openness** – the share of their R&D budget directed to open-source intellectual property (0, 50, or 90%). We investigate the full-factorial design of the four decision levers and their levels resulting in 54 unique strategies.

Uncertainties

Several deeply uncertain factors challenge the strategic decisions of incumbent AMSMs. First, there is uncertainty related to the market for 3D printing. The total addressable market size for professional 3D printing is unknown since new segments are still experimenting with the technology. Second, the diffusion velocity is uncertain, as effectively adopting 3D printing for final parts production often requires a complete redesign of parts and engineering processes [20]. Third, there is uncertainty endogenous to the AMSMs. It is difficult to predict whether and when AMSMs' R&D investments will yield improved printer performance and to what extent these improvements can translate into higher market share. These impacts are also influenced by the extent to which other AMSMs were successful in their R&D investments and to what extent customers will value performance over price in the future. Since this analysis aims to evaluate the strategies of a single incumbent AMSM (hereafter also referred to as firm 1), the variables considered as decision variables for firm 1 are treated in our analysis as uncertainties for firms 2, 3, and

4. Those uncertainties are represented by 35 parameters that control key characteristics of the market in the model (discussed in a supplementary appendix).

Outcome Metrics

The Outcome metrics (M) considered in this analysis represent the interests of a representative incumbent AMSM firm and consumers in this market. Firm 1 primarily seeks high net present value but also may seek to dominate the market by achieving a high share of orders in this market (order share) and may want to improve their own printers' performance. Conversely, consumers would prefer having access to high-quality products (proxied by the average printer performance index in the market), low-price products (proxied by average printer price) and collectively would like to maximize the number of adopters of the 3D printing technology. The latter criteria can be seen as representing the interests of the marginal 3D printing industry consumer that would rather have access to this technology than not be priced out of the 3d printing market. We use the upper quartile [8] of a regret metric computed for each outcome of interest. Each outcome is computed for each combination of the 54 strategies and a quasi-random Latin hypercube sample of 2000 parameter vectors representing the uncertainties discussed earlier. The model is simulated for 10 years, a relatively long timeframe in this industry.

4 Results

4.1 Firm-Level Outcomes

We first present a single-objective analysis of strategies across all scenarios, using the net present value (NPV) regret for an incumbent firm as the outcome to be minimized. Figure 1 displays the distribution of NPV regret across all strategies and cases. In Fig. 1, the upper limit of each box represents the upper-quartile regret, meaning that the strategy loses less than the corresponding value in 75% of cases. A ranking with the top 15 strategies ranked by their upper-quartile NPV regret is presented in Table 2.

Figure 1 and Table 2 reveal a few important results. First, the dispersed NPV Regret (i.e., opportunity cost) distribution shows that no single strategy dominates all others in all scenarios, hence there is not a single "best" strategy that exhibits strong dominance in the ensemble of conditions simulated. Second, strategies that aggressively build capacity to expand market share often outperform their conservative counterparts in the experimental design. This is not to say that conservative strategies are inferior to aggressive strategies in all scenarios, but it does suggest that aggressive strategies lead to less regret across the cases ensemble. Third, closed-source strategies dominate the upper ranking, suggesting their higher ability to withstand competition in the presence of aggressive firms. Yet, this analysis demonstrates that even a strict profit-maximizer would prefer a moderately open-source

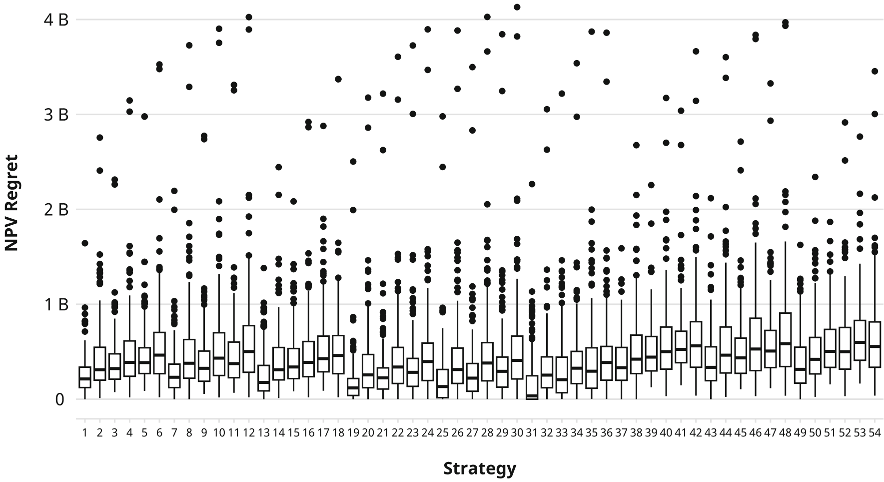

Fig. 1 NPV regret distribution across strategies. This box plot presents each strategy's net present value (NPV) regret across the ensemble of futures considered in this study

Table 2 Top 15 strategies ranked by their upper-quartile NPV regret

		Market share levers		R&D levers		
	Strategy	Pricing strategy	Target market share (%)	R&D budget (%)	R&D openness (%)	Upper-quartile NPV regret (millions)
1	19	Aggressive	30	5	0	$241
2	31	Aggressive	40	5	0	$265
3	25	Aggressive	20	5	0	$296
4	13	Aggressive	40	10	0	$326
5	1	Aggressive	30	10	0	$347
6	21	Aggressive	30	5	50	$378
7	7	Aggressive	20	10	0	$395
8	27	Aggressive	20	5	50	$408
9	33	Aggressive	40	5	50	$441
10	23	Aggressive	30	5	90	$476
11	3	Aggressive	30	10	50	$485
12	32	Conservative	40	5	0	$486
13	29	Aggressive	20	5	90	$494
14	9	Aggressive	20	10	50	$506
15	20	Conservative	30	5	0	$516

strategy (i.e., investing 50% of their R&D budget on open-source) to a conservative market share strategy, suggesting that the relative regret of open sourcing might be lower than the regret of pursuing conservative market share strategies.

Figure 2 presents each strategy's performance over three criteria used by firm 1 to judge its success in four parallel plots. Each plot shows the same 54 strategies with

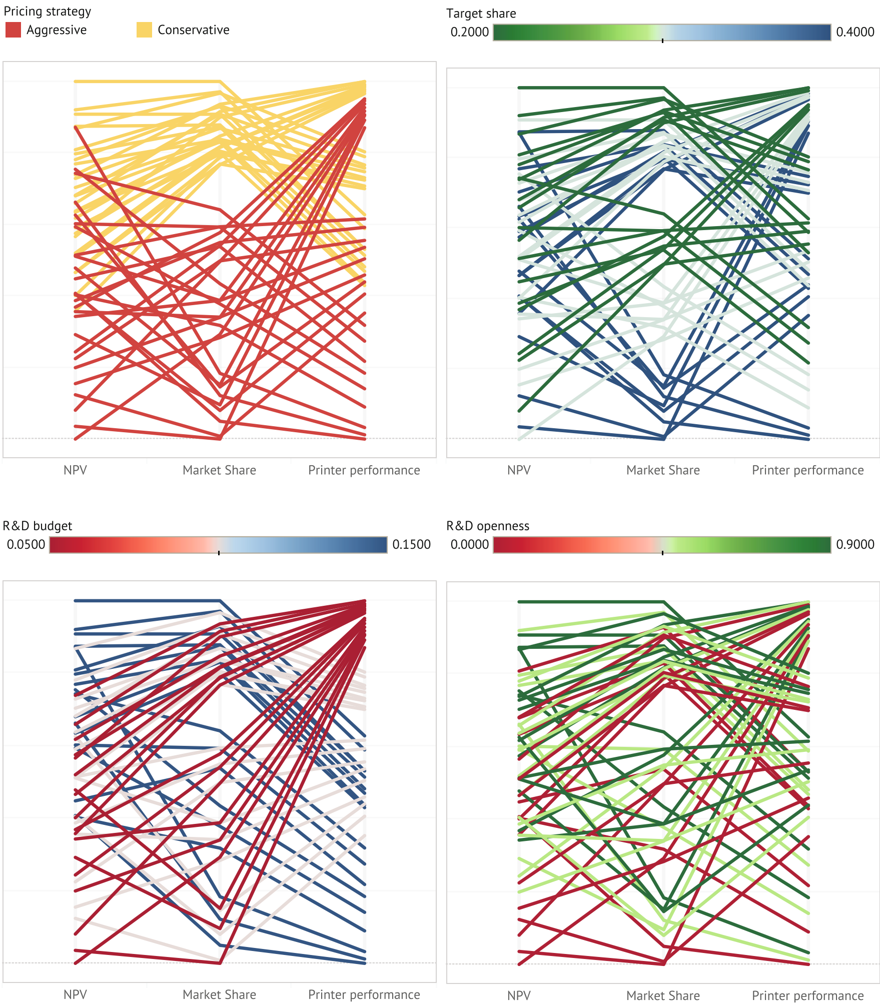

Fig. 2 Tradeoffs among NPV, Order Share, and Product Performance. Vertical axes represent the 75th percentile of each outcome's regret across all simulated scenarios. Each line represents one of the 54 strategies. Outcomes are scaled (min – max): NPV ($ 240 million – $900 million), Order share (0–45%), Printer performance (0–2)

colors representing decision variables values. The four plots show how each decision variable shapes the tradeoffs between the three objectives. Figure 2a shows aggressive strategies outperforming Conservative ones in all three criteria (albeit the best-performing aggressive strategy in NPV regret performs poorly in Product Performance.) Figure 2b suggests that strategies with a moderate target market share might hedge better than strategies with extreme target market share values.

The relationship between R&D strategies and outcomes is more tenuous. Not surprisingly, increasing the R & D budget results in moderate profit regret and improves product performance. However, its effect on order share is ambiguous (Fig. 2c). Finally, although increasing open R & D often increases NPV regret, strategies with moderate open R & D investment are also among the low-regret strategies regarding order share and product performance (Fig. 2d).

4.2 Industry-Level Outcomes

Figure 3 presents the consequences of our representative AMSM incumbent choices on three industry-level outcomes: the average printer price, the average printer performance and the final size of pool of 3D printing adopters. We compute regret for each metric adopting the perspective of customers – they want abundant access to high-quality 3D printers at low prices. Price and printer performance metrics are industry-level averages, weighted by each firm's market share. Figure 3 shows that open-source strategies are more desirable from the customers' perspective than from an incumbent's AM Systems Manufacturer perspective. Open R & D strategies lead to higher average printer performance, and higher number of adopters. On the other hand, open-source strategies tend to degrade the incumbent's net present value. These results reveal a tradeoff between the interests of AMSM firms and their

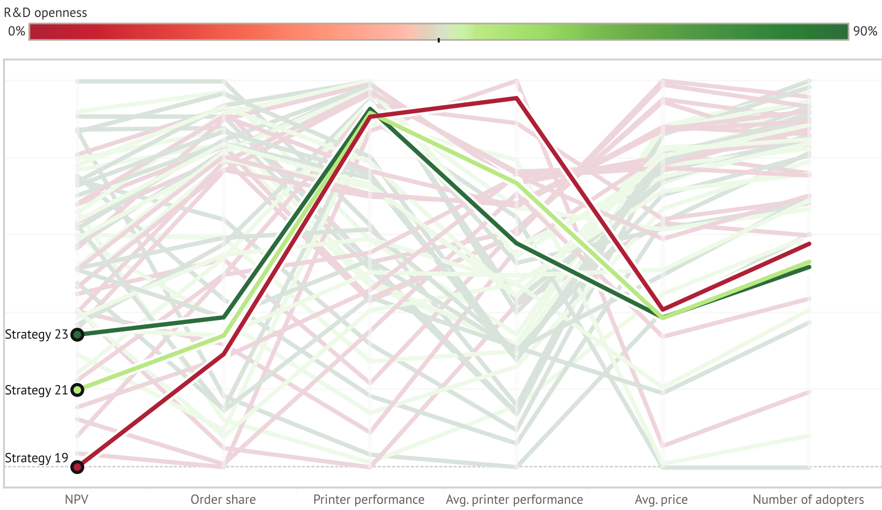

Fig. 3 Firm vs industry-level tradeoffs for select strategies. The first three axes represent outcomes that AMSM firms would like to minimize, whereas the three other axes represent outcomes that Consumers wish to minimize. All axes present the upper quartile of each outcome's regret (see methods). Outcomes are scaled (min – max): NPV ($ 240 million – $900 million), order share (0–45%), printer performance (0–2), average printer performance (0–1.3), average price ($500–9000), and number of adopters (240–2000 units)

consumers. Consumers would like to have ample access to high-quality printers at affordable prices, but firms may prioritize profit maximization over other goals.

These results resemble to the behavior of AMSM firms. Leading, publicly-traded incumbent AMSM firms have not fully embraced the open-source ethos and might find it difficult to do so given their low (or negative) profit margins. In contrast, smaller, new entrants that build upon expiring patents (i.e. Prusa Research) have embraced open-source hardware, but do not appear to have a profit maximization motivation as the primary reason for open sourcing. Our results demonstrate that the open-source movement is likely to continue if new entrants see their mission as making high-quality 3D printing affordable, but it is unlikely to be broadly embraced by incumbent firms.

5 Conclusion

The analysis presented before has several implications for selective openness in the 3D printing and other knowledge-intensive industries [21–23]. First, our model suggests that selective openness R&D strategies are unlikely to be fully pursued by firms that are purely profit maximizers. Yet, firms that seek to improve overall product quality in their industry might pursue open-source strategies to achieve a greater objective of popularizing 3D printing.

These conclusions should be interpreted considering the limitations of our model. Our model does not include all plausible mechanisms that may confer advantages to firms pursuing selectively open R&D strategies. For instance, our model does not feature network effects nor any sort of “warm glow” that consumers may ascribe to supporting a firm that subscribes to the open-source ethos. Yet, this model seems to be compatible with the observed behaviors of industry players – publicly traded incumbent firms do not fully adopt open sourcing while select smaller companies do. This result may suggest entrepreneurs may be making these strategic decisions weighing consumers’ interests above profitability.

While we used the additive manufacturing industry as an example, our findings have implications for other technology-intensive industries undergoing product diffusion. While the model may have to be expanded to account for other industries’ idiosyncrasies, the fundamental result that there is a conflict between the interest of firms (maximizing profits) and consumers (accessing high-quality products at a low cost) may apply to firms operating in industries as diverse as the AM industry, the pharmaceutical industry, and the scientific enterprise. Future research may expand on this model and discuss the implications of selective openness in other industries.

Supplementary Appendix: Model Extensions

Our model includes 4 firms. Firm i invests a fraction η_i of their revenue R_i on R&D to improve product performance within υ^r years on average. The stock variable M_i represents the monetary sum the firm has invested in R&D that has not yet been translated into improved product performance.

$$dM_i/dt = R_i * \eta_i - M_i/\upsilon^r \tag{1}$$

The number of patent claims by a company T_i^r depends on the amount of money invested M_i, the average time from investment to claim υ^r and the average cost per patent c_p. As patents are evaluated, this stock variable decreases depending on the average patent evaluation time υ^a.

$$dT_i^r/dt = \frac{M_i}{\upsilon^r c_p} - T_i^r/\upsilon^a \tag{2}$$

A fraction ψ of patent claims are rejected. Selective openness is operationalized by the fraction κ_i of R&D investment open to the public. These two parameters and the number of expiring patents T_i^p/υ^e influence the number of closed-source patents T_i^p a company owns.

$$dT_i^p/dt = \left[(1-\kappa_i)(1-\psi)T_i^r/\upsilon^a\right] - T_i^p/\upsilon^e \tag{3}$$

Similarly, the number of open-source patents available to all firms is defined by the sum of open-source patents owned by all firms.

$$dT^o/dt = \sum_i \left[\kappa_i(1-\psi)T_i^r/\upsilon^a\right] - T^o/\upsilon^e \tag{4}$$

Expired patents T^e accumulate as closed T_i^p or open-source T^o patents expire. Nevertheless, expired patents do not maintain their utility indefinitely. We model this phenomenon by allowing expired patents to lose utility with an average time to deprecation υ^i.

$$dT^e/dt = \left(\sum_i T_i^p + T^o\right)/\upsilon^e - T^e/\upsilon^i \tag{5}$$

AMSMs monitor the environment aiming to seize opportunities generated by expiring T^e and open source T^o patents. This behavior was observed in the 3D printing industry, notably during the FDM patent expiration, as market entrants adopt technologies of expired patents. Thus, the total number of patents accessed by a firm T_i^T is the sum of available patents.

$$T_i^T = T_i^r + T_i^p + T^o + T^e \tag{6}$$

R&D investment improves product performance and allows firms to better compete for increased market share. 3D printer performance is represented by an aggregate index X_i varying between 0 (X^{min}) and 10 (X^{max}). We consider a linear relationship between patents and printer performance, characterized by an industry-wide uncertain slope ϕ.

$$X_i = \max\left(X^{min}, \min\left(X^{max}, \phi * T_i^T\right)\right) \tag{7}$$

R&D investment possibly increases product performance in the future but necessarily increases product costs. R&D investments enter each firm's balance sheets stock variable as a liability M_i^D and are paid back following the total timeframe of the investment ($\upsilon^r + \upsilon^e + \upsilon^a$).

$$dM_i{}^D/dt = \eta_i R_i - M_i{}^D/(\upsilon^r + \upsilon^e + \upsilon^a) \tag{8}$$

Finally, the firm's fixed costs related to research and development u_i^p is obtained by the ratio between the total cost subtracted from the M_i^D variable and the firm's sales S_i.

$$u_i^p = \frac{M_i{}^D/(\upsilon^r + \upsilon^e + \upsilon^a)}{S_i} \tag{9}$$

References

1. West J (2003) How open is open enough? Melding proprietary and open source platform strategies. Res Policy 32:1259–1285.
2. West J, Kuk G (2016) The complementarity of openness: How MakerBot leveraged Thingiverse in 3D printing. Technol Forecast Soc Change 102:169–181.
3. Henkel J (2006) Selective revealing in open innovation processes: The case of embedded Linux. Res Policy 35:953–969.
4. Dahlander L, Magnusson M (2008) How do Firms Make Use of Open Source Communities? Long Range Plann 41:629–649.
5. West J, O'mahony S (2008) The Role of Participation Architecture in Growing Sponsored Open Source Communities. Ind Innov 15:145–168.
6. Balka K, Raasch C, Herstatt C (2014) The effect of selective openness on value creation in user innovation communities. Journal of Product Innovation Management 31:392–407.
7. Prusa Research About Us | Prusa Research. https://www.prusa3d.com/page/about-us_77/. Accessed 7 Apr 2023
8. Sterman JD, Henderson R, Beinhocker ED, Newman LI (2007) Getting Big Too Fast: Strategic Dynamics with Increasing Returns and Bounded Rationality. Manage Sci 53:683–696.

9. Alexy O, West J, Klapper H, Reitzig M (2018) Surrendering control to gain advantage: Reconciling openness and the resource-based view of the firm. Strategic Management Journal 39:1704–1727.
10. Henkel J, Schöberl S, Alexy O (2014) The emergence of openness: How and why firms adopt selective revealing in open innovation. Res Policy 43:879–890.
11. Franke N, Shah S (2003) How communities support innovative activities: an exploration of assistance and sharing among end-users. Res Policy 32:157–178.
12. Baldwin C, Hienerth C, von Hippel E (2006) How user innovations become commercial products: A theoretical investigation and case study. Res Policy 35:1291–1313.
13. Henkel J, Baldwin CY (2010) Modularity for Value Appropriation – How to Draw the Boundaries of Intellectual Property
14. Kwak K, Kim W, Park K (2018) Technological Forecasting & Social Change Complementary multiplatforms in the growing innovation ecosystem: Evidence from 3D printing technology. Technol Forecast Soc Change 136:192–207.
15. Maier FH (1998) New product diffusion models in innovation management—a system dynamics perspective. System Dynamics Review (Wiley) 14:285–308
16. Bass FM (1969) A New Product Growth for Model Consumer Durables. Manage Sci 15:215–227.
17. Bankes S (1993) Exploratory Modeling for Policy Analysis. Oper Res 41:435–449.
18. Lempert RJ, Groves DG, Popper SW, Bankes SC (2006) A General, Analytic Method for Generating Robust Strategies and Narrative Scenarios. Manage Sci 52:514–528.
19. Ernst & Young Gmbh (2016) How Will 3D Printing Make Your Company the Strongest Link in the Value Chain? – EY's Global 3D printing Report 2016. Ernst & Young Gmbh 1–26
20. Aston R (2017) 3D Printing Done Right. In: Innovation Quarterly – November 2017. http://www.boeing.com/features/innovation-quarterly/nov2017/feature-thought-leadership-3d-printing.page
21. Calderaro, D. R., Lacerda, D. P., & Veit, D. R. (2020). Selection of additive manufacturing technologies in productive systems: a decision support model. Gestão & Produção, 27.
22. Teixeira, R., Suzin, J.B., Pacheco, D.J, Santos, J.B. (2023). An empirical taxonomy of Knowledge-Intensive Business Service buyers: an Absorptive Capacity approach. Industrial Marketing Management, 108, 149–164.
23. Piran, F. A. S., Lacerda, D. P., Camargo, L. F. R., Viero, C. F., Teixeira, R., & Dresch, A. (2017). Product modularity and its effects on the production process: An analysis in a bus manufacturer. The International Journal of Advanced Manufacturing Technology, 88, 2331–2343.

Marketing Campaigns and Consumer Behavior: The Long and Winding Road to Induce Sustainable Practices

Camila Kolling, Ciro Eduardo Gusatti, Nicole Cecchele Lago, Janine Fleith de Medeiros, and Jose Luis Duarte Ribeiro

Abstract Based on the evolutionary theory, this study aims to understand marketing practices that can be used to induce environmentally sustainable consumption behavior in consumers. More precisely, it seeks to confirm that advertising text can instill a greater stimulus to choose green products. We conducted a quantitative study, where a project involving experiments was prepared. The findings broaden the empirical basis concerning advertising texts that motivate consumers to choose green products. The results provide evidence that consumers, in the context of regular purchasing and low-involvement products, more readily accept ads based on Apollonian (rational) text and common arguments. However, it was found that using tangible aspects and short-term goals also tends to induce environmentally sustainable purchasing behavior effectively. We also observed differences concerning the preference for a particular type of advertising text according to factors such as psychological type, age, education, and gender. Such information can contribute to advertising promoting environmentally sustainable products. The research also contributes to stimulating pro-environmental purchasing behavior and developing sustainable and circular initiatives.

Keywords Advertising · Sustainable behavior · Environmental awareness

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1 Introduction

With the advancement of sustainable issues, consumer interest in more environmental and sustainable options has increased. However, there is a gap regarding intentions and what is actually consumed [1]. An existing challenge involves motivating consumers to participate in circular initiatives and perform pro-environmental behaviors [2]. Studies indicate that marketing and communication strategies have a remarkable role in changing unsustainable consumption dynamics [3, 4].

In the field of marketing surveys, the explanatory potential of evolutionary psychology has broadened the understanding of human behavior and the use of products [5, 6]. Studies carried out in this area point out that natural selection shapes not only morphological characteristics but also behavior and moral and emotional choices [7, 8]. These studies also indicate possible paths for achieving contemporary behavior change objectives [9, 10].

Thus, based on the contributions of evolutionary psychology, this study aims to understand marketing practices that can be used to induce environmentally sustainable consumption behavior in consumers. Specifically, it seeks to confirm that advertising text can instill a greater stimulus to choose green products. A marketing tool to promote goods, services, ideas, images, and concepts advertising has long been considered an important communication instrument [11]. It, therefore, serves as a relevant means not only for informing but also persuading (either positively or negatively) [12, 13].

There are theoretical, practical, and social justifications for conducting the study. Comprehending what predisposes individuals to adopt pro-environmental behavior is a complex issue that is still not fully understood [14]. Although a broad set of studies have been carried out in recent years, potential barriers to eco-friendly practices are noted in the daily activities of global populations, such as social influence and habits [15]. Additionally, contributions about communication and campaigns to achieve sustainable consumption are still limited [4].

Also, buying ecologically correct products represents less than 4% of the value of overall product purchases [16]. Expanding the adoption of green products and recycled products, reducing waste, and involving individuals in processes such as composting, among other actions, strongly depends on changes in people's behavior [17]. Finally, a better world arises from people and organizations that make better decisions, are healthier, have a better quality of life, reduce waste and use assets more efficiently [18]. Based on the above, the research contributes to stimulating pro-environmental purchasing behavior and developing sustainable and circular initiatives.

2 Theoretical Background

Pro-environmental behavior occurs when individuals consciously seek to minimize the negative impact of their actions, such as reducing energy consumption, using non-toxic substances, and reducing waste production [19]. The purchase of green products is also a form of pro-environmental behavior [20]. Green products or environmentally sustainable products respect the environmental commitment in their production and consumption processes [21].

2.1 Five Adaptive Tendencies of Human Behavior

According to some authors, social and environmental problems of modernity are caused or exacerbated by five adaptive tendencies rooted in evolutionary history [22, 23]. For each of these tendencies, these authors present strategies to minimize them or use them to promote environmentally sustainable behaviors, as described below.

The (i) propensity for self-interest refers to the conflict between personal and collective interests, where personal issues are prioritized to the detriment of the common good. From the evolutionary perspective, people are more willing to behave proactively in support of sustainability if they perceive benefits for themselves, their kin, their community, or their organization. Strategies must focus on kin interests, use of fictitious kin labels in slogans, use of kin suggestions for motivating pro-environmental behavior, and the creation of small and interdependent social networks. Also, donations made by companies to environmental causes and the creation of communities to promote conservation can also be effective.

Various environmental challenges result in a conflict between having sufficient resources versus having more than others. In this sense, individuals are more concerned about (ii) relative than absolute status. Although competition for status is frequently viewed as negative, it can, under certain conditions, be positive in terms of social and environmental benefits. Strategies in this regard involve encouraging competition on pro-environmental outcomes, publicizing lists ranking the most pro-social and environmental companies, celebrities, or citizens, and increasing the relative status of green products. Another option is making pro-environmental choices visible to others.

The third factor refers to the tendency of human beings to (iii) copy others unconsciously. Rather than trying to prevent people from seeing the bad behavior of others, good behavior can be used to motivate pro-environmental actions. People are more inclined to voluntarily engage in these actions when they see that many others are doing the same or when others who are successful, prestigious, and with leadership qualities embrace this behavior. Therefore, strategies can show the prevalence of certain common pro-environmental behaviors, use prestigious people in pro-environmental behaviors, and use social approval to encourage those above average to continue their behavior.

Some social and environmental problems are also due to valuing immediate rewards, where present desires normally prevail over future needs, (iv) making people more prone to being shortsighted. Therefore, it is suggested to use strategies that emphasize the consequences of no sustainable behavior for the present, and not future generations and which focus on predictability, stability, and the safety of the world in which people live. Differences between gender can also be considered, such as the fact that men are more likely to ignore environmental threats than women are.

Finally, human beings have difficulties (v) reacting to new evolutionary threats that they cannot detect with their senses, making them likely to disregard impalpable concerns. People are not easily influenced by environmental threats that they cannot feel, smell, touch, see or hear. Interventions to motivate environmental action must trigger people's sensory mechanisms through tangible and visceral stimuli. In like manner, the use of positive experiences from nature and the visible creation regarding behavior and its immediate environmental consequences is suggested.

2.2 Advertising Text: Apollonian Versus Dionysian

Based on the theoretical framework of Nietzsche, the plot of advertising texts has two major lines of persuasion, called Apollonian (which prioritizes rational elements) and Dionysian (supported by emotion and/or humor) [24]. The lines are not mutually exclusive but complementary and may be mixed in ads. However, each one contains specific persuasive resources, characterizing distinct models.

According to the Nietzschean concept, plots of Apollonian advertising texts have a logical-formal discourse, are similar to deliberative discourse, and are intended to advise or advise someone against a matter in a more direct way, where the speaker's opinion is explicitly expressed. In this model, efforts are made to persuade the public through idyllic content built more on the audience's ideals and dreams than on reality. Regarding genre, Apollonian ads are dominated by dissertation texts and should focus on just one issue, already informed in the title. Another persuasive characteristic of this model is circularity, where the proposition is presented at the beginning of the discourse and is picked up again at the end. The use of quotations from experts and affirmation and repetitions are also determinants in this advertising discourse.

On the other hand, in Dionysian advertising texts, the intention of the advertiser is disguised and does not directly express an opinion to advise readers/listeners but instead achieves this through actions and depictions of characters. The invitation to consume a particular service or product is only insinuated and not clearly or directly revealed. In this model, attempts are made to persuade the public by tapping into the senses, which arouse delight and emotions. Dionysian ads adopt a narrative genre, assuming formats similar to fables, tales, or storytelling. Thus, elements from the fiction universe become important, such as narrative focus, plot, characters, setting, and time. The use of testimonies and illustrations is also relevant.

3 Method

We conducted a quantitative study, where a project involving experiments was prepared to determine which types of advertising texts promote choosing green products. The factors and levels examined were: (i) adapted advertising message from the five evolutionary behavior arguments; (ii) type of creative approach of the text (Apollonian rational versus Dionysian emotional); demographic variables; (iii) sex, (iv) age; (v) education and (vi) psychographics (introverted/extroverted behavior).

Based on the factors listed, we created ten ads, combining five arguments with two levels of creative approach: Apollonian rational (information) and Dionysian emotional (humor). Two ads with a traditional argument, varying the type of creative approach, were also prepared. For proper control of the demographic and psychological variables, sets of balanced ads concerning argument and creative approach were presented to the respondents. This is an important aspect since previous studies have confirmed the influence of demographic and psychological variables on the decision to purchase green products [25–27]. As for the product used as the object for the creation of the ads, we decided to work with a regularly purchased, low-involvement product, where the influence of advertising is higher than in medium/high-involvement purchases [28].

Each respondent received an envelope with six ads (as defined in the experimental plan), which were carefully balanced so that the demographic and psychographic aspects would not influence the outcomes. Sixty-four respondents participated in the experiment. The envelopes were prepared beforehand, and the collection was done personally. First, the selected respondents completed a brief questionnaire to confirm their profile following the experimental plan. The subjects then opened their envelope and placed the six ads on the table. After reading them, they indicated, in order, the three ads that impacted them the most (first, second and third) and that could influence purchase intent more positively. The ads and the research design can be viewed at the link:http://www.producao.ufrgs.br/arquivos/SupplementaryMaterial_MarketingCampaigns.pdf.

For the data analysis, ANOVA was used to test the effect of the four control factors (sex, age, behavior, and education) on the creative approach (humor/information) and on the six advertising messages (based on propensity for self-interest, relative rather than absolute status, copying others, short-term goals, tangible aspects, and common arguments). All the response variables were normalized to the 0–1 range to run ANOVA. These normalized results can be interpreted as an acceptance index of the creative approach and advertising messages.

4 Results: Statistical Analysis for Acceptance of Ads

Concerning the creative approach, ads lying on Info show higher acceptance than ads based on Humor (55% acceptance for Info-based ads, 45% acceptance for Humor-based ads). ANOVA results reveal one main factor significant at the 5% level (Behavior, p-value = 0.032). Extroverts show higher acceptance to Humor-based ads (52% against 48%), while introverts show higher acceptance to Info-based ads (63% against 38%). Relaxing the significant level to 15%, the effect of a second main factor is also detected (Schooling, p-value = 0.122). Non-graduates show higher acceptance to Info-based ads (60% against 40%), while for graduates, the acceptance of Humor and Info-based ads is quite similar. Figures 1 and 2 depict the acceptance index of Humor/Info depending respectively on Behavior and Schooling.

Regarding the advertising messages, ads based on common arguments present the higher acceptance (62.5%) followed by tangible aspects (48.0%), short-term goals (36.7%), and self-interest (34.8%). Ads based on relative rather than absolute status and copying others reveal lower acceptance (24.6% and 18.4%, respectively).

ANOVA results for self-interest-based ads reveal only one significant effect at the relaxed 15% level: Age x Schooling interaction (p-value = 0.14). Older non-graduate people show higher acceptance to self-interest-based ads (48%),

Fig. 1 Effect of behavior on the acceptance of humor and info-based ads

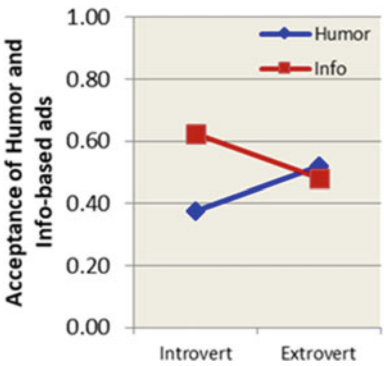
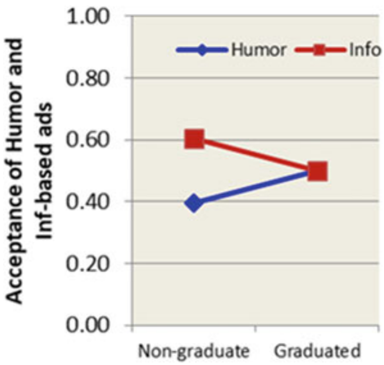


Fig. 2 Effect of schooling on the acceptance of humor and info-based ads



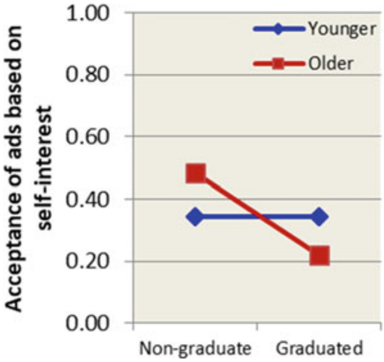


Fig. 3 Effect of age and schooling on the acceptance of ads based on self-interest

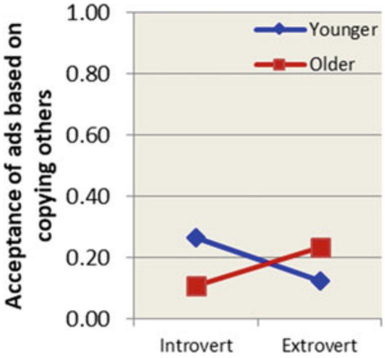


Fig. 4 Effect of age and behavior on the acceptance of ads based on copying others

while older graduate people reveal lower acceptance to this type of message. For younger, the acceptance is quite similar for non-graduates and graduates (34%). Figure 3 presents the interaction effect of Age and Schooling on the acceptance of self-interest-based ads.

ANOVA results for ads based on copying others also reveal only one significant effect but at the more restricted 5% level: Age x behavior interaction (p-value = 0.058). The acceptance of this type of message is low. Nevertheless, younger introverts show a higher acceptance to copying others-based ads (27% acceptance) than older extroverts (11% acceptance). Figure 4 presents the interaction effect of Age and behavior on the acceptance of copying others-based ads.

Concerning the ads lying on relative rather than absolute status, two significant interaction effects are detected by ANOVA: Gender x Age (p-value = 0.056) and Gender x Schooling (p-value = 0.019). Younger females show a higher acceptance to ads lying on relative status (38% acceptance) than older males (only 6% acceptance). Female non-graduates reveal a higher acceptance to ads lying on relative status (44% acceptance) than males non-graduates (only 8% acceptance). Figures 5 and 6 present these interactions effects.

The analysis of ads lying on tangible aspects shows weak effects significant at the relaxed 15% level: Behavior (p-value = 0.147) and Age x Schooling

Fig. 5 Effect of gender and age on the acceptance of ads based on relative status

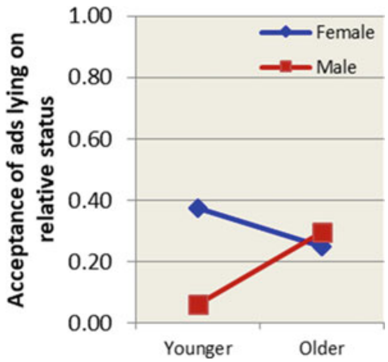


Fig. 6 Effect of gender and schooling on the acceptance of ads based on relative status

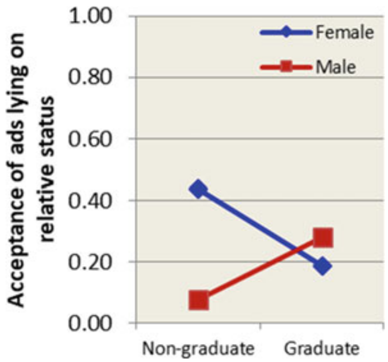
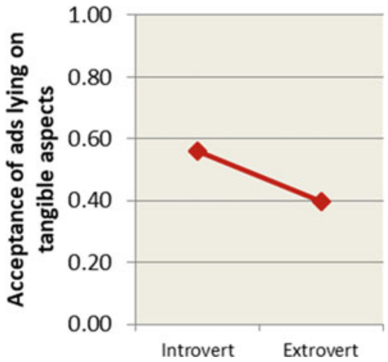


Fig. 7 Effect of behavior on the acceptance of ads lying on tangible aspects



(p-value = 0.143). Introverts reveal a higher acceptance to ads lying on tangible aspects (56% acceptance) than extroverts (40% acceptance). Graduate females show a higher acceptance to ads lying on tangible aspects (58% acceptance) than graduate males (38% acceptance). Figures 7 and 8 present these interactions effects.

ANOVA results for ads based on common arguments reveal the effect of an interaction and a main factor: Gender x Behavior (p-value = 0.0099) and Behavior (p-value = 0.0802). Regarding the interaction (see Fig. 9), extrovert males show a

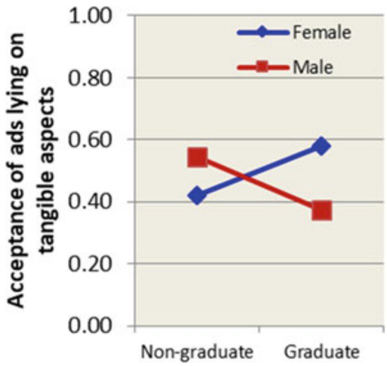


Fig. 8 Effect of gender and schooling on the acceptance of ads lying on tangible aspects

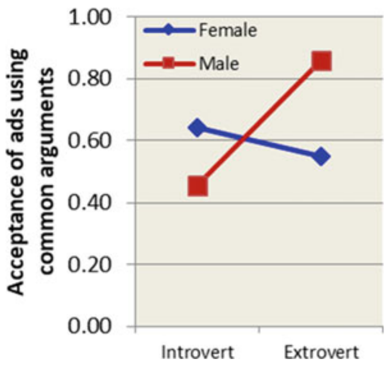


Fig. 9 Effect of gender and behavior on the acceptance of ads lying on common arguments

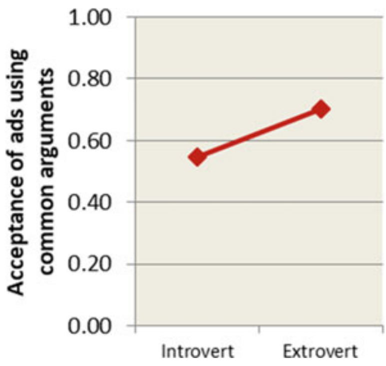


Fig. 10 Effect of behavior on the acceptance of ads lying on common arguments

higher acceptance to common arguments (86% acceptance) than introverted males (45% acceptance). As for the main factor (see Fig. 10), extroverts show a higher acceptance to this type of message (70% acceptance) than introverts (55% acceptance).

Figure 11 resumes results of the acceptance index for all combination levels of two-factor interactions. The two first numeric columns refer to the creative approach options tested in this study (Humor and Info). The others refer to the six advertising

		Humor	Info	Self-interest	Relative status	Copying others	Short term	Tangible aspects	Commom argum.
Female	Younger	41%	59%	28%	38%	16%	44%	50%	50%
Female	Older	47%	53%	41%	25%	17%	23%	50%	69%
Male	Younger	50%	50%	41%	6%	23%	53%	44%	58%
Male	Older	42%	58%	30%	30%	17%	27%	48%	73%
Female	Introvert	36%	64%	30%	27%	13%	33%	59%	64%
Female	Extrovert	51%	49%	39%	36%	20%	34%	41%	55%
Male	Introvert	39%	61%	36%	23%	25%	42%	53%	45%
Male	Extrovert	53%	47%	34%	13%	16%	38%	39%	86%
Female	Non-graduate	35%	65%	44%	44%	22%	23%	42%	50%
Female	Graduate	52%	48%	25%	19%	11%	44%	58%	69%
Male	Non-graduate	44%	56%	39%	8%	17%	36%	55%	70%
Male	Graduate	48%	52%	31%	28%	23%	44%	38%	61%
Younger	Introvert	43%	57%	27%	27%	27%	53%	52%	41%
Younger	Extrovert	48%	52%	42%	17%	13%	44%	42%	67%
Older	Introvert	32%	68%	39%	23%	11%	22%	61%	69%
Older	Extrovert	56%	44%	31%	31%	23%	28%	38%	73%
Younger	Non-graduate	38%	63%	34%	22%	27%	38%	47%	58%
Younger	Graduated	53%	47%	34%	22%	13%	59%	47%	50%
Older	Non-graduate	42%	58%	48%	30%	13%	22%	50%	63%
Older	Graduate	47%	53%	22%	25%	22%	28%	48%	80%
Introvert	Non-graduate	31%	69%	36%	23%	20%	42%	58%	45%
Introvert	Graduate	44%	56%	30%	27%	17%	33%	55%	64%
Extrovert	Non-graduate	48%	52%	47%	28%	19%	17%	39%	75%
Extrovert	Graduate	56%	44%	27%	20%	17%	55%	41%	66%

Fig. 11 Average results of acceptance index for all combination levels of two-factor interactions

messages. Special attention is given to the highest acceptance levels for each combination (assigned in green). Figure 11 is useful for defining the creative approach and type of message to be employed in a particular advertisement. For example, if someone is interested in building ads oriented to a public that can be characterized as Female and Younger (first numeric line), based on the results, the best creative approach would be Info, combined with a message lying on tangible aspects or common arguments.

Discussing the creative approach and considering the specificities of the product analyzed in this study, Fig. 11 indicates that, for most combination levels, Info-based ads present a higher acceptance index than Humor-based ads. Concerning the type of advertising message, ads lying on common arguments, tangible aspects, and short-term goals (in this order) provided the most accepted messages. Messages lying on self-interest, relative status, or copying others did not present the highest average acceptance for any combination level. Nevertheless, even without being the most attractive option, messages lying on self-interest are attractive to older non-graduates and extrovert non-graduates (see yellow signed cells in the corresponding column). Similarly, messages based on relative status are attractive to non-graduate females.

5 Discussion and Conclusion

Looking at the results obtained from the experiment, two points stand out: (i) texts with an Apollonian appeal (rational) were preferred over Dionysian text (emotional); and (ii) preference and motivation to purchase were higher when traditional arguments were used, as opposed to those centered on the five adaptive tendencies of human behavior.

A possible rejection of the Dionysian ads may be due to the triggering of fear, whether being considered less intelligent, less good-looking, or sloppy in appearance. In this case, although the text was crafted with humor, which can help reduce resistance to advertising, it did not have the desired effect, and the ads with this approach were rejected. However, it should be noted that, when examining the profiles where the Dionysian ads were preferred, it was found that personal factors such as education (higher level of studies) and psychological factors (extroverted behavior) tend to reduce the unconscious rejection generated by the ironic humor of those ads.

Regarding the preference for traditional arguments, the authors believe that social norms may have influenced this behavioral manifestation of the sample. Conceptually, social norms are composed of a set of beliefs about what most people do (descriptive norms) or approve (injunctive norms) [29]. Based on this, it can be inferred that most of the respondents preferred ads with a traditional appeal due to believing that this type of argument conformed with what other people approved and were, therefore, safe, and convenient. Previous studies have already pointed out the effect of social norms on pro-environmental intent or behavior [30–32].

Therefore, considering the type of product investigated and the results obtained for the ads based on the five adaptive tendencies of human behavior, it is suggested that ads seeking to promote pro-environmental behavior prioritize apollonian (rational) text and arguments centered around the following tendencies: proneness to disregard impalpable concerns (v) and predisposition to be shortsighted (iv), aligned with social norms. The social norms to be used for creating advertising text should reflect widely shared beliefs or manifest descriptive norms and/or normative information and feedback on both the social impact of a person on the environment and the impact of a group. This can be effective since people feel more motivated to behave pro-environmentally when personal feedback is worse than group feedback [31].

Regarding demographic and psychographic variables, the results obtained, along with previous studies, demonstrate their influence in the decision-making process for purchasing green products [25, 26]. We observed differences concerning the preference for a particular type of advertising text according to factors such as psychological type, age, education, and gender. Based on our results, although most respondents showed greater acceptance for ads based on the information and common arguments, ads aimed at young female audiences should prioritize the information approach, combined with messages that also present tangible aspects. Whereas ads targeting young men can use humor and information, addressing common arguments and short-term issues. Concerning young introverted people, the information approach can be combined with advertisements about tangible and short-term aspects, while for older and introverted audiences, advertisements based on information, common arguments, and tangible aspects are indicated. Finally, for the older and more outgoing audience, the ideal combination is messages based on humor and common arguments.

The research broadens the empirical basis concerning advertising texts that create a greater motivation to choose green products. For regularly purchased, low-involvement products, the overall results provide evidence that ads based on Apollonian (rational) text and common arguments are more readily accepted by consumers. However, it was found that using tangible aspects and short-term goals (resulting from the five adaptive tendencies) also tend to be effective in inducing sustainable purchasing behaviors. Such information can contribute to advertising promoting environmentally sustainable products. Based on this, we provide insights to stimulate pro-environmental consumer behavior.

One possible limitation of the study was the use of ironic humor, which triggered fear and, consequently, rejection of the ads with Dionysian text. Another was the fact that it did not consider social norms as a factor to be controlled and assessed in the experiments conducted. A suggestion for future research is the enlargement of the sample and replication of the study, considering other types of products and appeals.

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References

1. Sarja, M., Onkila, T., Mäkelä, M.: A systematic literature review of the transition to the circular economy in business organizations: Obstacles, catalysts and ambivalences. J. Clean. Prod. 286, (2021). https://doi.org/10.1016/j.jclepro.2020.125492

2. Abdelmeguid, A., Afy-Shararah, M., Salonitis, K.: Investigating the challenges of applying the principles of the circular economy in the fashion industry: A systematic review. Sustain. Prod. Consum. 32, 505–518 (2022). https://doi.org/10.1016/j.spc.2022.05.009
3. Vehmas, K., Raudaskoski, A., Heikkilä, P., Harlin, A., Mensonen, A.: Consumer attitudes and communication in circular fashion. J. Fash. Mark. Manag. 22, 286–300 (2018). https://doi.org/10.1108/JFMM-08-2017-0079
4. Fischer, D., Reinermann, J.L., Guillen Mandujano, G., DesRoches, C.T., Diddi, S., Vergragt, P. J.: Sustainable consumption communication: A review of an emerging field of research. J. Clean. Prod. 300, (2021). https://doi.org/10.1016/j.jclepro.2021.126880
5. Saad, G., Vongas, J.G.: The effect of conspicuous consumption on men's testosterone levels. Organ. Behav. Hum. Decis. Process. 110, 80–92 (2009). https://doi.org/10.1016/j.obhdp.2009.06.001
6. Van Den Bergh, B., Dewitte, S., Warlop, L.: Bikinis instigate generalized impatience in intertemporal choice. J. Consum. Res. 35, 85–97 (2008). https://doi.org/10.1086/525505
7. Dawkins, R.: The Selfish Gene. Oxford University Press (2006)
8. Kenrick, D.T., Griskevicius, V., Neuberg, S.L., Schaller, M.: Renovating the pyramid of needs: Contemporary extensions built upon ancient foundations. Perspect. Psychol. Sci. 5, 292–314 (2010). https://doi.org/10.1177/1745691610369469
9. Kenrick, D.T., Griskevicius, V., Sundie, J.M., Li, N.P., Li, Y.J., Neuberg, S.L.: Deep rationality: The evolutionary economics of decision making. Soc. Cogn. 27, 764–785 (2009). https://doi.org/10.1521/soco.2009.27.5.764
10. Griskevicius, V., Shiota, M.N., Nowlis, S.M.: The many shades of rose-colored glasses: An evolutionary approach to the influence of different positive emotions. J. Consum. Res. 37, 238–250 (2010). https://doi.org/10.1086/651442
11. Shimp, T.A., Andrews, J.C.: Advertising, Promotion, and other aspects of Integrated Marketing Communications. Integr. Mark. Commun. 9, 614 (2013). https://doi.org/10.1300/J057v01n01
12. Moschis, G.P., Moore, R.L.: A Longitudinal Study of Television Advertising Effects. J. Consum. Res. 9, 279 (1982). https://doi.org/10.1086/208923
13. Ackerberg, D.A.: Advertising, learning, and consumer choice in experience good markets: An empirical examination. Int. Econ. Rev. (Philadelphia). 44, 1007–1040 (2003). https://doi.org/10.1111/1468-2354.t01-2-00098
14. Coelho, F., Pereira, M.C., Cruz, L., Simões, P., Barata, E.: Affect and the adoption of pro-environmental behaviour: A structural model. J. Environ. Psychol. 54, 127–138 (2017). https://doi.org/10.1016/j.jenvp.2017.10.008
15. White, K., Habib, R., Hardisty, D.J.: How to SHIFT consumer behaviors to be more sustainable: A literature review and guiding framework. J. Mark. 83, 22–49 (2019). https://doi.org/10.1177/0022242919825649
16. Blok, V., Long, T.B., Gaziulusoy, A.I., Ciliz, N., Lozano, R., Huisingh, D., Csutora, M., Boks, C.: From best practices to bridges for a more sustainable future: Advances and challenges in the transition to global sustainable production and consumption: Introduction to the ERSCP stream of the Special volume. J. Clean. Prod. 108, 19–30 (2015). https://doi.org/10.1016/j.jclepro.2015.04.119
17. Anholon, G.T., Ordoñez, R.C., Silva, R.E., Quelhas, D.: Avaliação da Integração das Práticas de Responsabilidade Social Corporativa com Processos Gerenciais em empresas brasileiras. (2017)
18. Kohli, A.K.: Rethinking Marketing: Ajay Kohli, https://www.ama.org/2019/02/03/rethinking-marketing-ajay-kohli/
19. Kollmus, A., Agyeman, J.: Mind the Gap: Why Do People Act Environmentally and What Are the Barriers Mind the Gap: why do people act environmentally and what are the barriers to. Environ. Educ. Res. 37–41 (2015). https://doi.org/10.1080/1350462022014540
20. Lucarelli, C., Mazzoli, C., Severini, S.: Applying the theory of planned behavior to examine pro-environmental behavior: The moderating effect of covid-19 beliefs. Sustain. 12, 1–17 (2020). https://doi.org/10.3390/su122410556

21. Saraiva, A., Fernandes, E., von Schwedler, M.: The pro-environmental consumer discourse: A political perspective on organic food consumption. Int. J. Consum. Stud. 45, 188–204 (2021). https://doi.org/10.1111/ijcs.12611
22. Griskevicius, V., Cantú, S.M., Van Vugt, M.: The evolutionary bases for sustainable behavior: Implications for marketing, policy, and social entrepreneurship. J. Public Policy Mark. 31, 115–128 (2012). https://doi.org/10.1509/jppm.11.040
23. Van Vugt, M., Griskevicius, V., Schultz, P.W.: Naturally green: Harnessing stone age psychological biases to foster environmental behavior. Soc. Issues Policy Rev. 8, 1–32 (2014). https://doi.org/10.1111/sipr.12000
24. Carrascoza, J.A.: O Apolíneo e o Dionisíaco no Texto Publicitário. Cad. da Esc. Comun. (2004)
25. Babin, B.J., Griffin, M., Borges, A., Boles, J.S.: Negative emotions, value and relationships: Differences between women and men. J. Retail. Consum. Serv. 20, 471–478 (2013). https://doi.org/10.1016/j.jretconser.2013.04.007
26. Xie, C., Bagozzi, R.P., Grønhaug, K.: The role of moral emotions and individual differences in consumer responses to corporate green and non-green actions. J. Acad. Mark. Sci. 43, 333–356 (2015). https://doi.org/10.1007/s11747-014-0394-5
27. Fraj, E., Martinez, E.: Influence of personality on ecological consumer behaviour. J. Consum. Behav. 5, 167–181 (2006). https://doi.org/10.1002/cb
28. Blackwell, R.., Miniard, P.., Engel, M..: Consumer Behavior. Thomson/South-Western (2011)
29. Farrow, K., Grolleau, G., Ibanez, L.: Social Norms and Pro-environmental Behavior: A Review of the Evidence. Ecol. Econ. 140, 1–13 (2017). https://doi.org/10.1016/j.ecolecon.2017.04.017
30. Jaeger, C.M., Schultz, P.W.: Coupling social norms and commitments: Testing the underdetected nature of social influence. J. Environ. Psychol. 51, 199–208 (2017). https://doi.org/10.1016/j.jenvp.2017.03.015
31. Schultz, P.W., Messina, A., Tronu, G., Limas, E.F., Gupta, R., Estrada, M.: Personalized Normative Feedback and the Moderating Role of Personal Norms: A Field Experiment to Reduce Residential Water Consumption. Environ. Behav. 48, 686–710 (2016). https://doi.org/10.1177/0013916514553835
32. Demarque, C., Charalambides, L., Hilton, D.J., Waroquier, L.: Nudging sustainable consumption: The use of descriptive norms to promote a minority behavior in a realistic online shopping environment. J. Environ. Psychol. 43, 166–174 (2015). https://doi.org/10.1016/j.jenvp.2015.06.008

Design of a Controller by Pole Placement Applied to a Production and Inventory System

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Abstract In recent decades there have been several studies and proposals based on the theory of automatic control as a mechanism for the analysis and representation of the dynamic conditions of production models. The model of Automatic Pipelines Inventory and Order-Based Production Control System (APIOBPCS) model considers inputs, demand, and the desired inventory level. In the present work, the theory of control is applied to guarantee the profitability of the inventory starting the analysis in an open loop and later in a closed loop. This production and inventory system is represented by a block diagram and equations of state, and from this, control is designed by the feedback of states and applying the technique of design by pole placement. With the simulation, it is verified that the found value of these leads the system to maintain the level of inventory desired by the company. The behavior of the system is analyzed by assigning theoretical values which can be replaced by real data from a production system.

Keywords Inventories · Production system · APIOBPCS · Pole placement

1 Introduction

Inventories are an important part of the current assets of the company, the amount of product that is not sold is kept in the inventory generating costs for companies, inventory management seeks to maintain a level of inventory that covers demand at a minimum cost. Inventories do not operate on their own since they are directly related to the production system, however, few models integrate them and analyze them as dynamic systems. Since the 1950s, research has been carried out on the modeling and simulation of inventory control problems using dynamic systems. The control theory applied to a production and inventory system lows the system to remain stable

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in the presence of uncertainties [1], approaches based on control theory are generally proposed for a single product in a system [2]. Control theory has generally been applied to reduce inventory variation and thereby minimize inventory costs, as well as to optimize production policies to meet demand at minimum cost.

Derived from the interest in production control systems based on orders and inventories (IOBPCS) and the objective of this work is to analyze the behavior of a production system and inventories from the state space model, determine its stability and controllability to propose a control design solution. Checking the stability and controllability of the system based on the APIOBPCS it is proposed to perform feedback of states by means of a technique of control called pole placement.

2 Literature Review

Among the first proposals for a control system with feedback is the one raised by Towill in 1982 considered that the Inventory and Order-Based Production Control System (IOBPCS) has three fundamental parameters: the time of delay in production, the time to adjust inventory and the average time of demand, also demonstrated that the feedback path is of fundamental importance in control and developed a normalized transfer function to relate inventory level and consumption rate [3].

The model APIOBPCS proposed by John et al, in 1994 [4], is a model capable of minimizing the sum of inventory costs and adaptation in production through proportional feedback controllers.

The APIOBPCS model is a production control model for a single-stage manufacturing system, a single product with continuous flow, unrestricted production capacity, and infinite availability of raw material. Production is organized according to a manufacturing-to-warehouse scheme, the product is manufactured and placed in the warehouse while external demand is met with available finished product inventory. Since production is continuously developed, the production control system continuously emits the level of the manufacturing rate to be achieved, considering market demand as deterministic [5].

The APIOBPCS model has been documented as representative of the dynamic behavior of production planning and control systems, its behavior resembles the continuous review and periodic review model [6]. The model incorporates a feedback loop of work in process (WIP), which can be controlled to maintain a specific inventory level, has second feedback that is responsible for comparing the final inventory with the desired inventory and through a proportional controller performs the correction of this difference [7] proposed proportional control with the parameters of the average time of consumption, time to adjust the variation of the inventory, and time of adjustment between the WIP real and the desired, applies control to the APIOBPCS model, the structure of the control system consists of a PID controller with a Kalman filter that is used to forecast future values of demand, the objective of this controller is to stabilize and regulate inventory levels in the function of a desired set point level, this proposal is useful for making a decision on the desired inventory level for a given demand, the inventory control system was evaluated through simulations performed in Matlab. After the APIOBPCS model [8], proposed a new feedback control strategy by adding a second feedback loop with the aim of improving the damping performance of the control system. The controller uses a feedforward to generate a decision to determine the manufacturing rate of the system. The new feedback loop compares the average consumption with the actual rate of production and the error is adjusted using a constant time for the completion rate on this model was named 2APIOBPCS (Two Automatic Pipelines Inventory and Order-Based Production Control System).

The control systems mentioned above are based on the proposal of the IOBPCS model, in all recurrent components are identified as a feedback loop given by the level of the actual inventory, a pre-feeding loop given by demand, and a desired inventory level; the difference between the systems is observed in the feedback loops and the control technique applied to bring the system to the desired inventory.

3 Analysis of a Production System Based on Open Loop Orders and Inventories

A production system based on orders and inventories can be modeled by means of a block diagram as shown in Fig. 1, the time constants indispensable for the model of this system are the T_a constant of the average time of consumption and the T_p constant of time it takes to produce a product. It is assumed that the production lead time is known from the feedback of the production area.

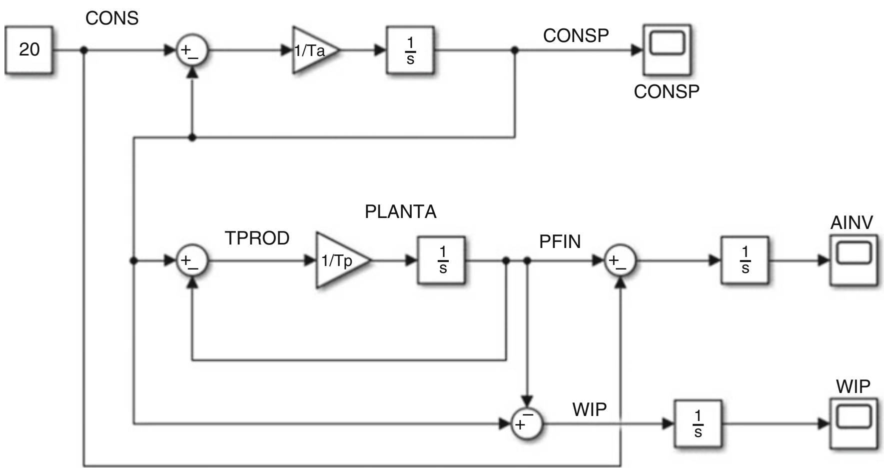

Fig. 1 Block diagram of the production system based on orders and inventories in open loop with a work-in-process loop

The system has as input the consumption or market demand, denoted as CONS (consumption or market demand CONS) and as output the average consumption defined as CONSP, the above is described in the time domain with the following equation

$$\frac{d}{dt}\ CONSP = \frac{1}{T_a} CONS - \frac{1}{T_a} CONSP \tag{1}$$

The modeling in is of a first-order system that has as a response to the variable P_{FIN} and the excitation variable to the rate is denoted as T_{PROD} and is described with the following equation

$$T_P \frac{d}{dt}\ P_{FIN} = T_{PROD} - P_{FIN} \tag{2}$$

By including the variable defined as work in progress A_{WIP}, it is considered as the integral of the difference of the order rate T_{PROD} and the completion rate P_{FIN} that when derived with respect to the time results to next equation

$$\frac{d}{dt}\ A_{WIP} = T_{PROD} - P_{FIN} \tag{3}$$

Comparing Eqs. (2) and (3) and integrating yields that the state variable A_{WIP} can be described by the equation

$$\frac{d}{dt}\ A_{WIP} = T_{PROD} - \frac{1}{T_P}\ A_{WIP} \tag{4}$$

The integral of the difference of completion rate P_{FIN} and consumption CONS denoted as current inventory A_{INV} (Current Inventory) when deriving with respect to time has the equation

$$\frac{d}{dt}\ A_{INV} = \frac{1}{T_P}\ A_{WIP} - CONS \tag{5}$$

The expressions given in (4) and (5) form a system of first-order differential equations which are linear and time-invariant. Therefore, these can be expressed as a system in state space represented by

$$\frac{d}{dt}\begin{bmatrix} A_{WIP} \\ A_{INV} \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_P} & 0 \\ \frac{1}{T_P} & 0 \end{bmatrix}\begin{bmatrix} A_{WIP} \\ A_{INV} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} T_{PROD} + \begin{bmatrix} 0 \\ -1 \end{bmatrix} CONS$$
$$y = \begin{bmatrix} 0 & 1 \end{bmatrix}\begin{bmatrix} A_{WIP} \\ A_{INV} \end{bmatrix} \tag{6}$$

Where x $= [A_{WIP}\, A_{INV}]^T \in \mathbb{R}^2$ is the state vector, $u = T_{PROD} \in \mathbb{R}$ is the input vector, $v = CONS \in \mathbb{R}$ a perturbation vector and the output vector is $y \in \mathbb{R}$.

The consumption variable is $CONS$ deterministic and cannot be altered so the third term of can be considered as a disturbance input. The excitation variable to the order rate if it can be altered is T_{PROD} therefore the input to the system and is also influenced by the variable of average consumption $CONSP$.

The system proposed in (6) has several properties: one involves stability and another to controllability. By calculating the eigenvalues of the state matrix, it is determined that the system is stable in the Lyapunov sense since these values are non-negative, one in $\lambda = 0$ and the other in $\lambda = -\frac{1}{T_P}$. By means of controllability it is determined whether all states are controllable or not, one way to know if a system is completely controllable is through knowledge of the range of the controllability matrix. For the system raised in (6) the range of the controllability matrix is 2, which indicates that it has full range and therefore a feedback of states can be performed to the system.

3.1 Open Loop Simulation

When performing the simulation of the open loop system given in (6), considering a demand of 20 units, the response of the system can be observed in Fig. 2. In response

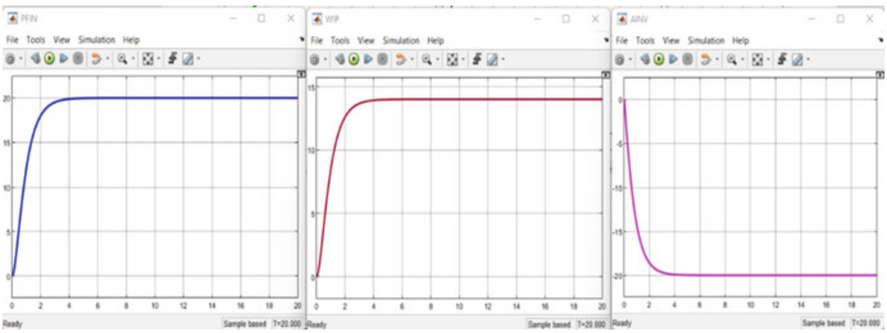

Fig. 2 Response of the production system based on orders and inventories in open loop, WIP and inventory

to the P_{FIN} there is a total of 20 units, the WIP has a production of approximately 15 units, as final inventory there will be a shortage of 20 units, because what is being produced is equal to demand and no inventory is generated. For the simulation, values of $T_a = 0.3$ and $T_p = 0.7$ were used, these values are considered from what was proposed by Towill in 1982 [3].

In this simulation you can clearly observe the behavior of an open loop system, that is, there is no feedback between the output and input of a production and inventory system.

4 Problem Statement

The amount of inventory that is not sold generates costs to the companies, in the same way they have losses by not having enough inventory to cover the demand at a minimum cost. The level of inventory is directly related to the production system, so applying control techniques in space of states is desired to take the current inventory A_{INV} at a default or desired value D_{INV}, which will change according to the needs of the company, to ensure the profitability of the inventory.

Therefore, consider the model in state spaces given in (6), which is fed by two consumption-dependent variables CONS and CONSP and as output you have the current inventory that is defined as A_{INV} and the work-in-process variable denoted as A_{WIP}. These last two variables are the system state variables.

4.1 Augmented System

As stated in the problem, the two variables of states of the system considered are available, so it is feasible to establish feedback of linear states to the system, so that this linear feedback law can be implemented as

$$u = -Kx + r$$

Where K is a profit matrix and r is a reference input vector to the system, since the system is completely controllable. If this is done, there is a disadvantage of the feedback of state variables, which is that the output of the system A_{INV} would not be directly involved in the control. This means that the controller design will not provide the possibility of assigning a predetermined stationary relationship between input and output [9], that is, with a state feedback control only with the variables A_{INV} and A_{WIP} there is no way to ensure a direct relationship between D_{INV} and A_{INV}.

One way to try to ensure that the output A_{INV} remains at steady state to reference D_{INV} is to augment the system with integrators [9]. With the above, the two state variables are fed back and the output is fed back in an external loop to a new initial sum point whose output is an error vector of the system, so it can be ensured that the system can be in steady state by an integral action of said error.

Therefore, considering that the current inventory variable A_{INV} is used as output, the output equation is as

$$y = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} A_{WIP} \\ A_{INV} \end{bmatrix} \tag{7}$$

Therefore, a new state can be defined as the integral of the error of a reference signal and the output, giving the equation

$$\frac{d}{dt} x_{new} = D_{INV} - \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} A_{WIP} \\ A_{INV} \end{bmatrix} \tag{8}$$

With the systems given in (7) and (8) you have an augmented system like the following

$$\frac{d}{dt} \begin{bmatrix} A_{WIP} \\ A_{INV} \\ x_{new} \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_P} & 0 & 0 \\ \frac{1}{T_P} & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} A_{WIP} \\ A_{INV} \\ x_{new} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} T_{PROD} + \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix} CONS \tag{9}$$

The state matrix given in (9) has three eigenvalues, $\lambda = 0$, $\lambda = 0$ and $\lambda = -\frac{1}{T_P}$ so the system is stable, therefore $-\frac{1}{T_P}$ the controllability matrix of this augmented system is

$$M_{au} = \begin{bmatrix} 1 & -\frac{1}{T_P} & \frac{1}{Tp^2} \\ 0 & \frac{1}{T_P} & -\frac{1}{Tp^2} \\ 0 & 0 & -\frac{1}{T_P} \end{bmatrix}$$

The determinant of M_{au} is $-\frac{1}{Tp^2}$, so it implies that M_{au} has rank 3, therefore the augmented system is completely controllable. Controllability is a sufficient and necessary condition for locating eigenvalues arbitrarily in feedback of states [9], therefore, the system given in (6) and the augmented system given in (9) are both completely controllable, so that they can be performed feedback of states by means of location of poles arbitrarily.

5 Closed Loop System

In the design method known as pole assignment, all poles are placed in a closed loop in the desired positions. All state variables are assumed to be measurable and available for feedback. If the original system is fully controllable state, the poles of the closed-loop system can be placed in any desired position by means of state feedback through an adequate state feedback gain matrix [10]. Be a control system

$$\overline{\mathrm{x}} = \overline{\mathrm{A}}\overline{\mathrm{x}} + \overline{\mathrm{B}}\mathrm{u} + \overline{\mathrm{B}}_{\mathrm{v}}\mathrm{v}$$

$$\overline{\mathrm{y}} = \overline{\mathrm{C}}\overline{\mathrm{x}}$$

Where $\overline{\mathbf{x}} = [\mathrm{A_{WIP}} \quad \mathrm{A_{INV}} \quad \mathrm{x_{new}}]^{\mathrm{T}} \in \mathbb{R}^3$ is the state vector, $\mathrm{u} = \mathrm{T_{PROD}} \in \mathbb{R}$ is the input vector, $\mathrm{v} = \mathrm{CONS} \in \mathbb{R}$ is a perturbation vector, $\overline{\mathrm{y}} \in \mathbb{R}$ and the output vector. The state matrices A, the input matrix B, the disturbance matrix $\mathrm{B_v}$ and the output matrix C are

$$\overline{\mathbf{A}} = \begin{bmatrix} -\frac{1}{T_P} & 0 & 0 \\ \frac{1}{T_P} & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix} \in \mathbb{R}^{3x3}$$

$$\overline{\mathbf{B}} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \in \mathbb{R}^{3x1}$$

$$\overline{\mathbf{B}}_{\mathbf{v}} = \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix} \in \mathbb{R}^{3x1}$$

$$\overline{\mathbf{C}} = [0 \quad 1 \quad 0] \in \mathbb{R}^{1x3}$$

The K matrix is called the state feedback gain matrix as

$$\mathbf{K} = [\mathrm{K}_1 \quad \mathrm{K}_2 \quad \mathrm{K}_3]$$

All state variables are assumed to be available for feedback.

The control input T_{PROD} is defined as

$$T_{PROD} = CONSP - \begin{bmatrix} K_{11} & K_{12} & -K_i \end{bmatrix} \begin{bmatrix} A_{WIP} \\ A_{INV} \\ x_{new} \end{bmatrix} \tag{10}$$

Substituting (9) into (10) and performing algebraic manipulation of the equation leads to the representation of a closed-loop system as

$$\begin{bmatrix} A_{WIP} \\ A_{INV} \\ x_{new} \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{T_P} - K_{11} & -K_{12} & K_i \\ \dfrac{1}{T_P} & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix} \begin{bmatrix} A_{WIP} \\ A_{INV} \\ x_{new} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & -1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} CONSP \\ CONS \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} D_{INV}$$

$$y = [0 \quad 1 \quad 0] \begin{bmatrix} A_{WIP} \\ A_{INV} \\ x_{new} \end{bmatrix} \tag{11}$$

The eigenvalues of the augmented state matrix are

$$det \left[\begin{bmatrix} \lambda & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda \end{bmatrix} - \begin{bmatrix} -\dfrac{1}{T_P} - K_{11} & -K_{12} & K_i \\ \dfrac{1}{T_P} & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix} \right] = \begin{bmatrix} \lambda + \dfrac{1}{T_P} + K_{11} & K_{12} & -K_i \\ -\dfrac{1}{T_P} & \lambda & 0 \\ 0 & 1 & \lambda \end{bmatrix}$$

The characteristic equation is given by

$$det = \lambda^3 + \left(\frac{1}{T_P} + K_{11} \right) \lambda^2 + \frac{1}{T_P} K_{12} \lambda + \frac{1}{T_P} K_i \tag{12}$$

With the polynomial obtained in (12) and because the augmented system is completely controllable, the eigenvalues of the closed-loop system can be assigned arbitrarily. For this, a desired polynomial with eigenvalues $p_1, p_2 \; y \; p_3$ is considered as follows

$$\begin{aligned} p_d &= (\lambda + p_1)(\lambda + p_2)(\lambda + p_3) \\ p_d &= \lambda^3 + (p_1 + p_2 + p_3)\lambda^2 + (p_1 p_2 + p_1 p_3 + p_2 p_3)\lambda + p_1 p_2 p_3 \end{aligned} \tag{13}$$

Comparing the coefficients of (12) and (13) we have the following system of linear equations

$$\left(\frac{1}{T_P} + K_{11} \right) = (p_1 + p_2 + p_3)$$

$$\frac{1}{T_P} K_{12} = (p_1 p_2 + p_1 p_3 + p_2 p_3)$$

$$\frac{1}{T_P} K_i = p_1 p_2 p_3$$

With the system formed by the three equations above are the values of the gains $K_{11} K_{12} \; K_i$, and arbitrarily assigning the values to p_1, p_2 and p_3.

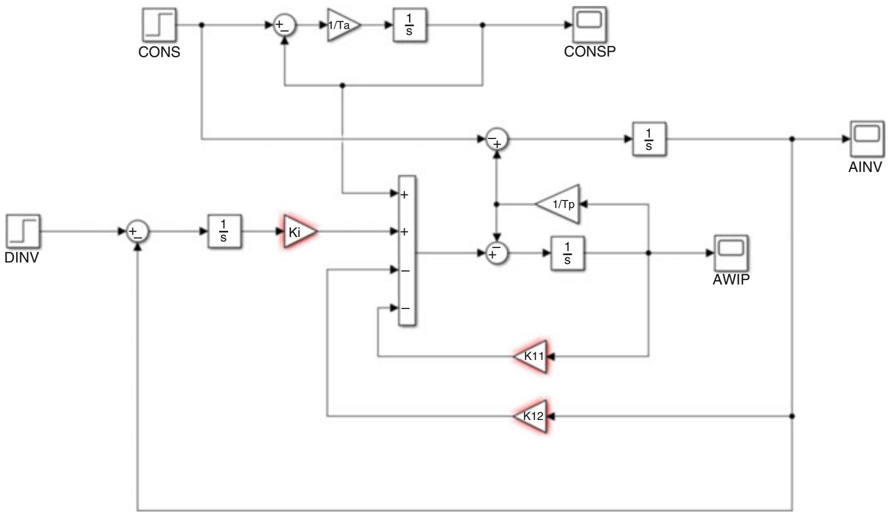

Fig. 3 Block diagram of an APIOBPCS with state feedback control applying by pole placement

Considering a $T_p = 3$ and locating the poles in $p_1 = -1, p_2 = -0.5\ y\ p_3 = -0.3$ the gain vector K is calculated

$$\mathrm{K} = \begin{bmatrix} 1.46 & 2.8 & -0.45 \end{bmatrix}$$

The block diagram of Fig. 3, corresponds to the system (11) starting from an APIOBPCS to which a control of feedback of states by allocation of poles where $K_{11}\ K_{12}\ K_i$, is applied and the values of the gain vector K previously calculated are assigned.

5.1 *Close Loop Simulation*

In the diagram of Fig. 3, the desired inventory level and the demand for a unit step are simulated; running the simulation with the aforementioned values, the behavior graphs of T_{PROD}, A_{WIP} and A_{INV} are obtained, shown in Fig. 4. The response of the T_{PROD} reaches a maximum request of 2 units, but stabilizes at one unit, while that work-in-progress stabilizes at 3 units and beginning ending inventory has shortages, but later stabilizes at 1 unit as desired.

The level of inventory desired by the company can be specified according to its needs, the implementation of controllers to the APIOBPCS allows regulating the level of production that, based on a deterministic demand, the system maintains the inventory at the desired level.

In this work, only the behavior is shown before a unitary value input, but this can be modified to any other value and with change of values in time intervals.

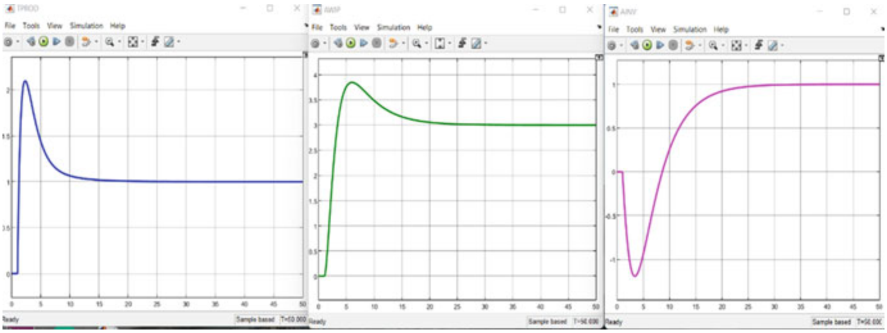

Fig. 4 Response from an APIOBPCS with state feedback control

6 Conclusions

From the analysis carried out by means of block diagrams and equations of state of the production systems and inventories in open loop and closed loop, the importance of the feedback loops and the variant that is generated in the behavior of the systems for inventory control was identified. In this work the variable that seeks to control is the level of inventory generated from production and market demand, so the control system includes the measurement of inventory and based on this measurement, the controller decides what to do to keep the inventory at the desired value, from the result of the controller's decision, an action is carried out in the production system on the parts to be produced.

The APIOBPCS model according to literature is representative of the production control systems so in this work a feedback control of states by pole placement is applied and the behavior of the system is analyzed from assigning theoretical values which can be replaced by real data of a production system.

References

1. Zemzam, A., Maataoui, M. E., Hlyal, M., Alami, J. E., and Alami, N. E. (2017). Inventory management of supply chain with robust control theory: literature review. International Journal of Logistics Systems and Management, 27(4):438–465.
2. Jackson, I., Tolujevs, J., and Kegenbekov, Z. (2020). Review of inventory control models: A classification based on methods of obtaining optimal control parameters. Transport and Telecommunication, 21(3):191–202.
3. Towill, D. R. (1982). Dynamic analysis of an inventory and order-based production control system. The international journal of production research, 20(6):671–687.
4. John, S., Naim, M. M., and Towill, D. R. (1994). Dynamic analysis of a wip compensated decision support system. International Journal of Manufacturing System.
5. Capozzi, D. L., Del Vecchio, C., and Glielmo, L. (2003). A novel work in progress-based production control system. In 2003 European Control Conference (ECC), pages 2351–2357. IEEE.

6. Wiendahl, H.-P. and Breithaupt, J.-W. (1998). Production planning and control on the basis of control theory. In Advances in Production Management Systems, pages 351–362. Springer.
7. Tosetti, S., Patino, D., Capraro, F., and Gambier, A. (2008). Control of a production-inventory system using a pid controller and demand prediction. IFAC Proceedings Volumes, 41(2): 1869–1874.
8. Huthaifa, A.-K., Cole, C., and Guo, W. (2017). Dynamics analysis of a production-inventory control system with two pipelines feedback. Kybernetes.
9. Hendricks, E., Jannerup, O., & Sørensen, P. H. (2008). Linear systems control: deterministic and stochastic methods. Berlin: Springer.
10. Ogata, K. (2003). Ingeniería de Control Moderna. Editorial Prentice Hall. Cuarta edición. México.

Project Management in Hospital Environments: A 5-Year Systematic Literature Review

Erik T. Lopes, Derek C. Lopes, Thiago A. Souza, Rui M. Lima, and André L. A. C. Souza

Abstract Health systems have countless examples of adaptations of existing project management approaches to improve hospital operations and deliver value to the patient. This article aims to review the project management publications of the last 5 years, to establish findings in relation to what has been published, to allow the visualization of knowledge gaps and future research to be carried out. Thus, 50 articles and reviews of the last 5 years were initially considered and after the exclusion criteria, 26 articles were listed for review. The analysis allowed identifying publications, sources, universities, countries, and authors that stand out in the theme, in addition to the domains of performance, artefacts used and type of projects. The results indicate publications mainly in two large groups: improvement in service quality and increase in hospital efficiency. Based on this initial study, the authors suggest that further research may be carried out covering project management in the entire health ecosystem, as well as an analysis of the types of health projects and the practices adopted in their management.

Keywords Project management · Healthcare management · Hospital operations management · Effectiveness

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1 Introduction

Health systems processes involve several interactions between patients and the various components of the flow occurring all the time with changes being implemented through many possible approaches, extrapolating tools and concepts of project management [1]. Taner et al. [2], when reviewing the use of six sigma, identified initiatives that resulted in reduced waste, improved scheduling, maximization of resources, financial savings and increased satisfaction of professionals and patients. However, several factors are critical to the success of these initiatives. Rosacker et al. [3] demonstrated that from the project manager's point of view, the clear notion of the company's mission, the existence of an adequate schedule and the constant monitoring, communication and feedback between the concerned parts are examples of these limiters.

Work on project management has been developed in various sectors of hospitals, such as analysis of efficiency and operations, participatory management, quality accreditation, dealing with different types of projects, and innovation [4]. Lima et al. [5] point to the growth of publications on the implementation of lean healthcare between 2000 and 2015, using project management tools integrated with operational improvement.

In recent years, these approaches have gained greater visibility, with several scientific publications [4]. Some authors have reviewed this material, with a specific eye on tools or through empirical research [3]. However, the literature lacks reviews of project management in hospitals to characterize the current approaches in this area of knowledge. Thus, this article aims to review project management publications in hospitals of the last 5 years, to establish findings in relation to what has been published, to allow the visualization of knowledge gaps and future research possibilities.

In the next section, a theoretical framework of the topics addressed in this research is presented. Then, the methodology used is described and the main results are presented and discussed in Sect. 4. Finally, the last section presents final considerations and research conclusions.

2 Theoretical Background

2.1 Project Management

Project management (PM) is a subject that has been studied for several years, with applications in different sectors. According to the Project Management Body of Knowledge (PMBOK) [6], one can define a project as a temporary effort to create a unique result, and its management is the application of different knowledge, skills, tools, and techniques to conduct the work and achieve the expected results.

However, using these approaches presents different challenges, depending on the application context. Santos et al. [7] highlight factors that lead to failures, such as lack of management support, resistance to change, ill-defined scope and little evidence of expected benefits. These factors are related to the authors' own findings about the success criteria of a project, such as stakeholder management, cohesive communication, assertive planning, and resource management [7], which corroborate some of performance domains discussed in the PMBOK [6].

There are several project management approaches, such as agile methodologies, lean and six sigma, to adapt practices to different contexts. They have advantages and disadvantages, and their combined use allows the development of hybrid models, which are of great importance both for academia and companies [8]. Among the advantages of hybrid models are the mitigation of risks of agile approaches, maintaining the benefits of flexibility to changes, lower cost and rapid achievement of goals [8].

Projects are part of larger systems or organizations and can be used to create value for stakeholders. This intensifies when there is an efficient flow of information [6]. In hospital environment Project Management Office (PMO) is important to professionalize project management and decentralize decision-making [1]. Moreover, there is the concept of value-based health, which aims to focus on results for the patient, understanding their journey not as a set of services, but with a humanized vision [9]. Thus, cases using project management methodologies in health contexts are explored in the literature. Dobin and Lazar [10] in their review pointed out that the use of formal PM tools can improve quality outcomes as well as growth in the use of PM in healthcare systems.

2.2 Project Performance Domains and Project Management Artifacts

Project management changed over the years, so did the literature on the subject. Until the 6th edition, the PMBOK divided project management into ten areas of knowledge and five groups of processes: initiation; planning; execution; monitoring and control; and closure. However, in the last edition, the PMBOK was structured around two main concepts, the project management principles and the project performance domains. Performance Domains are interdependent activities that occur during the project to guarantee the expected deliveries. Eight domains are considered [6]:

(a) Stakeholders: Involves working with stakeholders to ensure alignment, satisfaction and positive relationship.
(b) Team: Involves developing the environment and culture that allow high team performance.

(c) Development Approach and Life Cycle: It involves establishing the approach to be used, the cadence of deliveries and the project cycle to guarantee the delivery of results.
(d) Planning: Involves organization and coordination activities at the beginning and during the project, evolving them to guarantee deliveries.
(e) Project Work: Involves establishing and executing processes for delivering results, as well as fostering a learning environment and managing resources.
(f) Delivery: It involves meeting the scope, requirements, and quality expectations for a successful delivery.
(g) Measurement: Involves evaluating the performance of the project and taking actions to ensure high performance.
(h) Uncertainty: Involves activities related to risks and uncertainties.

In such way, the applications of project management knowledge in different contexts will involve one or more of the performance domains, depending on the approach used by the researcher. As an example, Souza et al. [11] production levelling approach allowed the improvement of operating rooms, using domains such as stakeholders, project work, and measurement. In another example, Vida et al. [12] describe a project to identify and prioritize risks in hospital pharmacy processes, developing activities in the following domains: planning, project work, uncertainty, and measurement.

In addition to project management principles and performance domains, models, methods and artifacts can be used for a successful approach. According to PMBOK [6], the first are strategies to explain a process, framework, or phenomenon; the second is the means to achieve results and deliverables; and the last are templates, documents or tools that support the execution. Artifacts are used in the daily life of project teams and can be related to phases and performance domains [6]. In healthcare, one can find different examples of its use. Souza et al. [13] applied the DMAIC, from six sigma, to elaborate a guiding framework for leading lean healthcare projects. Grau et al. [14] used FMEA to assess different forms of use of failure mode and effect analysis methodology for risk prioritization in the ambulatory care process. Analysing lean implementations in health, value chain mapping, 5S, standardization of work, visual management and KPIs are the main tools adopted [5].

3 Methodology

The present study is a systematic literature review with the objective of analyse publications on the topic “project management in the hospital environment”. Systematic review is a type of retrospective study based on the literature already published on a specific topic, with the aim to group, synthetize, and present existing knowledge on the area, as well as identifying any existing gaps. It should start from a

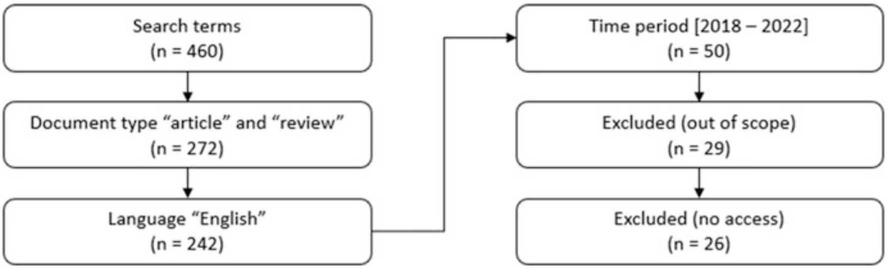

Fig. 1 Structure and organization to conduct the review

previously formulated research question and use search mechanisms and clear inclusion and exclusion criteria, allowing the reproducibility of the method [15].

A search was carried out in the Scopus database with the following terms: TITLE-ABS-KEY ("project management"AND ("healthcare" OR "health care") AND "hospital"). Moreover, following the objective of analysing recent studies published in journals, the results were limited to articles and reviews published in the last 5 years (after 2017) in English. The objective of this stage was to focus on a more recent analysis of the theme and to exclude abstracts or papers presented at conferences. Thus, 50 articles constituted the large group for analysis and adequacy.

Next, the 50 publications were analysed by title and abstract, by two independent researchers, in order to verify adequacy to the scope of the article: publications on project management in health, in the hospital environment. Articles involving management of civil construction projects, comparisons of tools or systems already implemented, such as checklists or clinical protocols, or knowledge management in a strictly academic environment, without assessing its impact on the intra-hospital environment, were excluded. After the first analysis, the researchers compared their results and, in case of disagreement about the inclusion of any paper, a third, senior researcher defined the inclusion or exclusion.

Finally, 21 studies were withdrawn, of which 7 involved civil construction project management, 5 were not directly or indirectly involved with the hospital environment, and 9 were dedicated to assessing technical skills or institutional protocols and did not include the project management theme. Of the remaining 29, 3 publications could not be accessed by the researchers, resulting in 26 articles included in this review, as shown in Fig. 1.

The 26 articles were read in full and analysed under the following aspects, proposed based on the existing literature:

(a) Year, country, journal, authors and home institution, as performed by Padalkar and Gopinath [16].
(b) Methodological approach subdivided into literature review; survey; case study; and action research, as performed by Lima et al. [5].
(c) Focus of the article: clinical care; digital transformation; processes and operations; conceptual analysis of project management; knowledge; classified by the authors based on the reading of the text.

(d) Area of the hospital involved in the project, using the classification adopted by Lima et al. [5].
(e) Project Performance Domains, according to the 7th edition of the PMBOK [6]. Analyzed by Padalkar and Gopinath [16] from PMBOK Knowledge Areas.
(f) Project management tools or artifacts used by the authors of the work, also analyzed by Alves et al. [1].
(g) Focus of the project management approach: waterfall or agile models, identified by reading the articles and the authors' knowledge.

In addition to the criteria, the researchers performed a qualitative analysis on the articles to understand the results obtained and the challenges faced by authors.

4 Results and Discussion

4.1 Overall Analysis

Among the 26 publications evaluated, there were 24 documents typed as articles and 2 as literature reviews. Figure 2 shows the timeline of these publications over last 5 years. It is possible to notice a stable quantity of annual publications over last 4 years.

The countries with the highest number of publications on project management in the hospital environment are United States (10), Canada (2), Germany (2) and Saudi Arabia (2), as shown in Fig. 3. The remaining 10 papers were from different countries, each with 1 publication on last 5 years.

The main author identified on the study period was Gores, G.J, with two publications. All other author had one publication over last 5 years. From an institutional point of view, Mayo Clinic (USA) was the main affiliation of author, with two

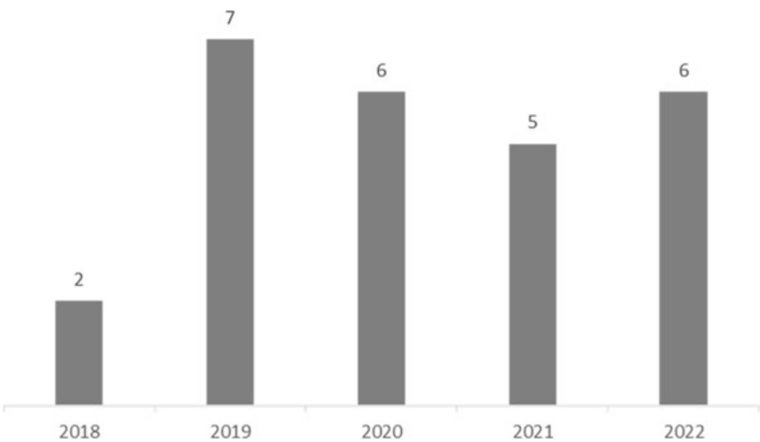

Fig. 2 Evolution of the number of publications per year

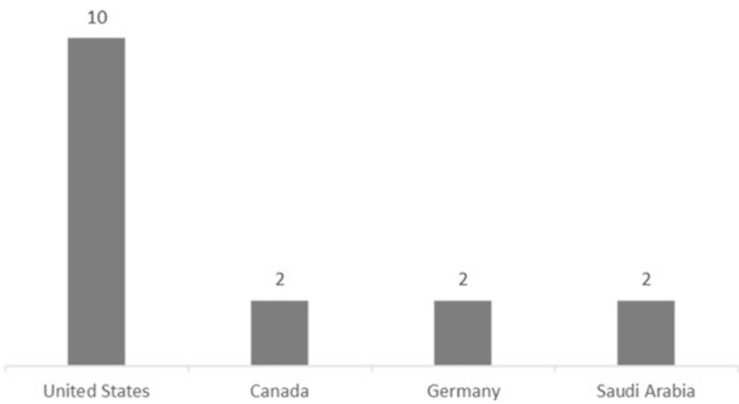

Fig. 3 Number of articles per country

papers. Other institutions had only one publication. Those publications were on sources of different scopes, such as Computer Science, Medicine and Engineering. This finding suggests the involvement of several areas of knowledge in the study of project management in health.

4.2 Characteristics of the Analysed Studies

After applying the inclusion and exclusion criteria described in the methodology, 26 articles made up the present review. Case studies predominated, totalling 20 publications, 2 works used questionnaires and 4 were grouped into "other methodologies", namely: Design science (1); mixed methods, including the use of institutional quantitative data, qualitative data such as interviews and questionnaires, and document analysis (2); opinion articles of the "perspective" type, with a non-systematic literature review (1).

Among the focuses of the works, the following were identified: 9 occurred in the processes and operations category; 6 in clinical care; 5 in conceptual analysis of project management; 4 in knowledge; and 2 in digital transformation. Although there is a predominance of approaches focused on operations, the clinical-assistance assessment appears in second position. This is an interesting finding, both because it allows inferring the involvement of health professionals in project management, as well as the use of tools adapted to the patient's needs. In health care, the concept of "value" involves multiple variables in addition to the correct performance of the process per se and studies that consider this holistic approach is needed [9].

It is also noted that a large part of the work involves the management of hospital projects in general in the hospital. However, there are initiatives in specific areas, such as mental health, emergency and maternal and childcare, with emphasis on the surgery department, as shown in Fig. 4.

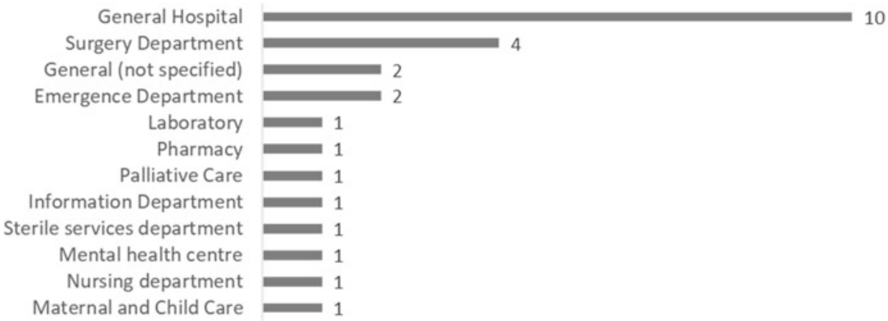

Fig. 4 Hospital areas

In each article included, the predominant project management approach was identified, based on the case description and the tools used, divided between the waterfall and agile models. Thirteen (13) works presented characteristics of waterfall and seven (7) of agile projects, and in six (6) this differentiation was not clearly identified. Other works have already pointed out a series of difficulties in the implementation of agile health projects, however, there is still no consensus in the literature on the superiority between agile or traditional, or even the use of hybrid approaches [8, 17].

Next, the authors proposed the identification of the performance domains addressed in the research. However, a low level of reliability was noted in this process, since several works do not specifically report or characterize the role of the project manager, leading to the need for a series of inferences. Furthermore, the latest version of the PMBOK reports the interdependence of these domains and the actors and processes involved in project management, which may have contributed to this difficulty. In this way, we believe that this can encourage authors of new publications to characterize the proposed domain, since this identification can help in understanding the failures and strengths of the project.

Finally, an analysis of the models, methods and tools used by the authors in the development of the projects was carried out. Only elements mentioned in the texts or presented as images were considered, noting the emphasis on the use of lean healthcare and associated tools. Key outcomes were PDSA/PDCA [18–21], flowcharts/mapping of processes or patient journeys [19, 22–27], indicators/KPI [28–31] and VSM [26, 27, 31].

4.3 Results and Improvements Found

The results found in the analysis can be divided into results for improving service quality and/or operational efficiency. Among the articles analysed, improvement in the quality of service was identified in different areas of hospitals based on projects, with indications of increased value for patients. In an implementation based on lean six-sigma, Murphy et al. [29] intervened in the clinical journey of patients who arrived at the emergency department with hip fractures, increasing the number of operations performed within 48 hours by 30%, an indicator associated with a reduction in length of stay and mortality. Mihaljevic et al. [32] structure a medical education project to train multidisciplinary students in the surgery department, obtaining greater engagement and technical capacity of the participants and improved communication with the patient. Finally, Woeltje et al. [31] analysed the implementation of a program to reduce harm caused by medical errors, with several projects over 10 years. The approach combined project management methods, interventions, determination of minimum standards, use of electronic tools and incorporation of quality reports, which reduced preventable damage by almost 75% in the period.

With regard to efficiency in hospital processes and operations, Gupta et al. [24] and Koike et al. [21] worked in the department of surgeries with lean approaches, obtaining respectively a reduction in the meantime of delay in vascular surgeries and in the duration of surgeries. Some of the concepts and tools used were Kaizen, DMAIC and PDSA. Li et al. [28] performed clinical redesign accompanied by KPIs in more than 170 projects, with emphasis on three that had cost savings of $1075, $2020 and $371 per case. Moon et al. [26] adapt the "user stories" tool for the anamnesis of nurses with a focus on value for the patient, improving the recording and evaluation of their impact on care. Finally, positive results were found in drug production [33] and in the emergency department [27].

In the analysis of the texts, the use of health project management with other objectives and contexts was identified, which reinforces the breadth of the theme. Chung and Caldas [34] discuss risk management and highlight the sensitive data that exist in health, which led them to develop a prototype using blockchain for risk identification and assessment. Some authors highlight the importance of communication with the team and change management actions during projects [25, 35], the use of project management approaches to foster innovations in hospitals [20, 36], and in the management of information and knowledge [37]. Finally, Giasson [30] presents the implementation of a hybrid PMO, highlighting the important characteristics for success and showing good results in engaging health professionals to deepen their project management.

4.4 Difficulties in Hospital Projects

When exploring project management in hospitals, different difficulties were identified in the literature. Evaluating the implementation of the palliative care program PalliSupport, Doorne et al. [22] identified rigid planning, stakeholder management and communication as challenges encountered. They also point out that the program was carried out with 5 regions simultaneously and point that it should have been carried out with only 1 at a time, to reduce complexity. One should also consider the time factors and financial investment in projects, depending on their complexity

[23]. Finally, interviewing project managers of a maternal and child health initiative, Saleem et al. [38] point out the lack of knowledge of medical professionals assigned to the function, political interference, and a bureaucratic structure as pain points in public health projects.

These findings are in line with project success criteria, according to Santos et al. [39], who identified the importance of the project manager, aspects of the organization, the scope of the project and the external environment. The authors also reinforce the need to study the criteria for public health projects, as they have a different nature from the others [39].

5 Conclusion

This research aimed to understand the best practices and main gains in hospital project management, which contributes to direct PM applications in other health contexts and to identify which benefits managers should expect. Furthermore, the authors analysed the available literature on the theme and noted that there is a predominance of the use of PM for hospital operations and processes, with great use of lean healthcare artifacts. Improved service quality and process efficiency are the points of greatest impact and results found in this type of work. The findings reinforce the wide variety of themes that permeate project management, as well as the interdependence of performance domains and PM areas. In a practical view, stand out the importance of structures for formalizing the adopted approaches and methods, such as the PMO. Furthermore, is important to prioritize the human aspects of the project, including both technical skills of the team and communication with professionals who did not participate directly. Finally, gains can be seen when using a gradual and iterative approach, mainly by reducing the complexity of projects.

As a suggestion for future research, we propose studying the topic for the health chain as a whole and the relationships between the types of health projects, their adopted practices, as well as their impact on operational and clinical outcomes in patient care. This work has limitations such as the use of only one database for analysis, having a comprehensive theme in relation to the search, leading to a certain heterogeneity of the articles.

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References

1. A. L. F. Alves, S. de C. Silva, and M. A. P. Nunes, "Project Management and PMO practices in hospitals: an integrative literature review," *Research, Society and Development*, vol. 11, no. 1, 2022, https://doi.org/10.33448/rsd-v10i4.24666.

2. M. T. Taner, B. Sezen, and J. Antony, "An overview of six sigma applications in healthcare industry," *Int J Health Care Qual Assur*, vol. 20, no. 4, pp. 329–340, 2007, https://doi.org/10.1108/09526860710754398.
3. K. M. Rosacker and K. M. Zuckweiler, "An Empirical Evaluation of Hospital Project Implementation Success," 2010.
4. D. C. Farias and F. O. de Araujo, "Gestão hospitalar no brasil: Revisão da literatura visando ao aprimoramento das práticas administrativas em hospitais," *Ciencia e Saude Coletiva*, vol. 22, no. 6. Associacao Brasileira de Pos - Graduacao em Saude Coletiva, pp. 1895–1904, Jun. 01, 2017. https://doi.org/10.1590/1413-81232017226.26432016.
5. R. M. Lima, J. Dinis-Carvalho, T. A. Souza, E. Vieira, and B. Gonçalves, "Implementation of lean in health care environments: an update of systematic reviews," *International Journal of Lean Six Sigma*, vol. 12, no. 2. Emerald Group Holdings Ltd., pp. 399–431, Mar. 20, 2021. https://doi.org/10.1108/IJLSS-07-2019-0074.
6. Project Management Institute, *The standard for project management and a guide to the project management body of knowledge (PMBOK guide)*, 7ª edition. Project Management Institute, 2021.
7. C. Santos, V. Santos, A. Tavares, and J. Varajão, "Project Management in Public Health: A Systematic Literature Review on Success Criteria and Factors," *Portuguese Journal of Public Health*, vol. 38, no. 1. S. Karger AG, pp. 37–48, Jul. 01, 2020. https://doi.org/10.1159/000509531.
8. J. Reiff and D. Schlegel, "Hybrid project management – a systematic literature review," *International Journal of Information Systems and Project Management*, vol. 10, no. 2. SciKA, pp. 45–63, 2022. https://doi.org/10.12821/ijispm100203.
9. I. Putera, "Redefining Health: Implication for Value-Based Healthcare Reform," *Cureus*, Mar. 2017, https://doi.org/10.7759/cureus.1067.
10. V. M. Dobin and B. Lazar, "Project Management and Quality in Healthcare: A Systematic Literature Review," *PM World Journal*, vol. 9, no. 9, 2020, [Online]. Available: www.pmworldlibrary.net
11. T. A. Souza, G. L. R. Vaccaro, R. M. Lima, and E. T. Lopes, "Application of Heijunka for Surgical Production Leveling," in *Springer Proceedings in Mathematics and Statistics*, 2022, vol. 400, pp. 275–288. https://doi.org/10.1007/978-3-031-14763-0_22.
12. M. Á. Castro Vida, J. E. Martínez De La Plata, J. A. Morales-Molina, J. J. Pérez Lázaro, and P. Acosta Robles, "Identification and prioritisation of risks in a hospital pharmacy using healthcare failure mode and effect analysis," *European Journal of Hospital Pharmacy*, vol. 26, no. 2, pp. 66–72, Mar. 2019, https://doi.org/10.1136/ejhpharm-2017-001242.
13. T. A. Souza, M. C. de Souza, R. M. Lima, L. v. Pimenta, and M. S. Oliveira, "Lean Healthcare Project Leader a framework based on functions and competencies," in *Springer Proceedings in Mathematics and Statistics*, 2019, pp. 261–272.
14. N. Grau *et al.*, "Risk Management in the Ambulatory Care Process in a Mutual Benefit Association Covering Work-Related Accidents and Diseases: Applying Modified Failure Mode and Effect Analysis (FMEA) Methodology," *J Patient Saf*, vol. 17, no. 8, pp. e1428–e1432, Dec. 2021, https://doi.org/10.1097/PTS.0000000000000542.
15. R. B. Briner and D. Denyer, "Systematic Review and Evidence Synthesis as a Practice and Scholarship Tool," in *The Oxford Handbook of Evidence-Based Management*, Oxford University Press, 2012. https://doi.org/10.1093/oxfordhb/9780199763986.013.0007.
16. M. Padalkar and S. Gopinath, "Six decades of project management research: Thematic trends and future opportunities," *International Journal of Project Management*, vol. 34, no. 7, pp. 1305–1321, Oct. 2016, https://doi.org/10.1016/j.ijproman.2016.06.006.
17. R. Dendere, M. Janda, and C. Sullivan, "Are we doing it right? We need to evaluate the current approaches for implementation of digital health systems," *Australian Health Review*, vol. 45, no. 6. CSIRO, pp. 778–781, Dec. 01, 2021. https://doi.org/10.1071/AH20289.

18. Archana S., S. R. Nilakantam, B. Hathur, and M. Dayananda, "The need and art of establishing skill and simulation centers to strengthen skill-based medical education: Learning insights and experience," *Ann Afr Med*, vol. 20, no. 4, pp. 247–254, 2021.
19. B. Spear, A. C. Kinart, B. Beauvais, and F. S. Kim, "Renovating Healthcare Facility Maintenance Planning: A Case Study From Walter Reed National Military Medical Center (WRNMMC)," *Health Environments Research and Design Journal*, vol. 14, no. 4, pp. 416–428, Oct. 2021, https://doi.org/10.1177/19375867211019749.
20. R. B. Hunter, F. K. Winston, P. Dehel, K. Oh, J. Nicklas, and H. Hartung, "SPRINTing to Innovation: Children's Hospital of Philadelphia's Strategic Approach to Discovering Its Untapped Innovation Potential," *Academic Medicine*, vol. 96, no. 4, pp. 534–539, Apr. 2021, https://doi.org/10.1097/ACM.0000000000003852.
21. D. Koike, Y. Nomura, M. Nagai, T. Matsunaga, and A. Yasuda, "Bundle interventions including nontechnical skills for surgeons can reduce operative time and improve patient safety," *International Journal for Quality in Health Care*, vol. 32, no. 8, pp. 522–530, Oct. 2020, https://doi.org/10.1093/intqhc/mzaa074.
22. I. van Doorne, V. M. W. van Schie, J. L. Parlevliet, D. L. Willems, M. van Rijn, and B. M. Buurman, "Challenges in the implementation and evaluation of a transmural palliative care pathway for acutely hospitalized older adults; lessons from the PalliSupport program: A qualitative process evaluation study," *Arch Gerontol Geriatr*, vol. 103, Nov. 2022, https://doi.org/10.1016/j.archger.2022.104782.
23. C. Varela-Rodríguez, A. García-Casanovas, B. Baselga-Penalva, and P. M. Ruiz-López, "Value-Based Healthcare Project Implementation in a Hierarchical Tertiary Hospital: Lessons Learned," *Front Public Health*, vol. 9, Feb. 2022, https://doi.org/10.3389/fpubh.2021.755166.
24. R. Gupta *et al.*, "Utilization of lean project management principles and health informatics to reduce operating room delays in a vascular surgery practice," *Am J Surg*, vol. 223, no. 1, pp. 176–181, Jan. 2022, https://doi.org/10.1016/j.amjsurg.2021.07.040.
25. A. Cherkaoui *et al.*, "Implementation of the WASPLab™ and first year achievements within a university hospital," *European Journal of Clinical Microbiology and Infectious Diseases*, vol. 39, no. 8, pp. 1527–1534, 2020, https://doi.org/10.1007/s10096-020-03872-1/Published.
26. L. A. Moon, G. Clancy, J. Welton, and E. Harper, "Nursing Value User Stories: A Value Measurement Method for Linking Nurse Contribution to Patient Outcomes," *CIN - Computers Informatics Nursing*, vol. 37, no. 3, pp. 161–170, Mar. 2019, https://doi.org/10.1097/CIN.0000000000000520.
27. S. Ahmed and A. F. Mohammed, "From process flows to benchmark in an accident and emergency hospital with PERT approach," *Kybernetes*, vol. 48, no. 3, pp. 520–545, Feb. 2019, https://doi.org/10.1108/K-02-2018-0088.
28. L. Li *et al.*, "Clinical Redesign: An Innovative Approach to Leading Change at an Academic Healthcare System," *Journal of Healthcare Management*, vol. 67, no. 1, pp. 13–24, Feb. 2022, https://doi.org/10.1097/JHM-D-20-00299.
29. C. Murphy, E. Mullen, K. Hogan, R. O'toole, and S. P. Teeling, "Streamlining an existing hip fracture patient pathway in an acute tertiary adult Irish hospital to improve patient experience and outcomes," *Int J Qual Health Care*, vol. 31, no. 1, pp. 45–51, Dec. 2019, https://doi.org/10.1093/intqhc/mzz093.
30. L. Giasson, "The Best of Both Models: Key Components of a Successful Hybrid Project Management Office Model in a Health Care Organization," *Health Care Manager*, vol. 38, no. 3, pp. 247–252, Jul. 2019, https://doi.org/10.1097/HCM.0000000000000272.
31. K. F. Woeltje *et al.*, "A Decade of Preventing Harm," *Jt Comm J Qual Patient Saf*, vol. 45, no. 7, pp. 480–486, Jul. 2019, https://doi.org/10.1016/j.jcjq.2019.04.007.
32. A. L. Mihaljevic *et al.*, "Heidelberger Interprofessionelle Ausbildungsstation (HIPSTA): a practice-and theory-guided approach to development and implementation of Germany's first interprofessional training ward," *GMS J Med Educ*, vol. 35, no. 3, 2018, [Online]. Available: http://www.tand-

33. J. R. Anderson *et al.*, "Translation to Practice: Accelerating the Cycle of Innovation to Impact," *Mayo Clinic Proceedings*, vol. 94, no. 3. Elsevier Ltd, pp. 490–499, Mar. 01, 2019. https://doi.org/10.1016/j.mayocp.2018.08.008.
34. I. B. Chung and C. Caldas, "Applicability of Blockchain-based Implementation for Risk Management in Healthcare Projects," *Blockchain Healthc Today*, vol. 5, no. Special Issue, Mar. 2022, https://doi.org/10.30953/bhty.v5.191.
35. A. Cardone and C. A. Grous, "Relocating Sterile Processing Activities to an Off-Site Facility: Cost, Design, and Project Management Considerations," *AORN J*, vol. 112, no. 1, pp. 30–38, Jul. 2020, https://doi.org/10.1002/aorn.13072.
36. J. H. Pitzen *et al.*, "Transforming the practice of medicine through team science," *Health Res Policy Syst*, vol. 18, no. 1, Sep. 2020, https://doi.org/10.1186/s12961-020-00619-4.
37. R. J. Scott, "A best-fit solution: Transforming an nhs library and knowledge service in readiness for a new hospital building without a traditional library space," *Journal of the Medical Library Association*, vol. 109, no. 3, pp. 483–489, Jul. 2021, https://doi.org/10.5195/jmla.2021.1167.
38. F. Saleem, I. Murtaza, S. Hyder, and M. I. Malik, "Public health and project management: Do projects deliver?," *Int J Environ Res Public Health*, vol. 17, no. 19, pp. 1–11, Oct. 2020, https://doi.org/10.3390/ijerph17197244.
39. C. Santos, V. Santos, A. Tavares, and J. Varajão, "Project Management Success in Health – The Need of Additional Research in Public Health Projects," *Procedia Technology*, vol. 16, pp. 1080–1085, 2014, https://doi.org/10.1016/j.protcy.2014.10.122.

Preparing Human Factors for Digital Transformation: A Framework for Innovations in Industrial Engineering Education

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Abstract The human factor in the face of Industry 4.0 is what particularizes this research. The paper aims to propose a framework for Industrial Engineering teaching to prepare engineers to work in digital transformation. This framework is based on an active methodology called Team Based Learning, and on the podcast's development as a product related to Digital Information and Communication Technologies. The investigation focused on a case study involving an Industrial Engineering undergraduate course during the emergency remote teaching period due to the covid-19 pandemic. The work was developed with a concept of continuous improvement based on the Plan-Do-Check-Act cycle in four academic semesters. The students elaborated team activities related to the use of digital technologies and they agreed that the framework provided team engagement and it will help them face the challenges encountered as an engineer in the Industry 4.0 environment. In this sense, the framework can support teachers and courses adapting engineering training to the digital transformation scenario. Despite having been elaborated throughout emergency remote teaching, the framework is applied to face-to-face, distance, or hybrid teaching.

Keywords Engineering education · Active learning · Industry 4.0

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1 Introduction

Industry 4.0 is based on the alignment of physical and digital technologies [1]. Adopting a network of sensors that communicate through processing systems and using different data analysis tools should provide numerous benefits to the industrial area. However, increasing management and competitiveness using Cyber-Physical Systems technologies will require organizational changes with various impacts on the workforce to engineers professionals.

New qualification requirements and tasks will arise [2, 3]. However, there is a gap in the literature about new technologies and their social aspects [4], despite the growing number of Industry 4.0 discussions in recent years [5].

This paper is configured within the digital transformation scenario and the demand to prepare the engineering workforce. Technological innovation modulates the integration of people, technology, and groups. However, the more traditional condition of engineering training certainly does not meet the demands of Industry 4.0. The point is that the training is individualizing, but what the Fourth Industrial Revolution also requires is multi-disciplinary teamwork [6]. So, how is it possible to optimize the training of engineers, preparing them for digital transformation, based on the use of Digital Information and Communication Technologies (DICT)? The paper aims to propose a framework for Industrial Engineering teaching to prepare engineers to work in digital transformation. This framework is based on an active methodology called Team Based Learning (TBL) and on the podcast's development as a product related to DTIC. The research focused on a case study developed during the remote teaching period due to the covid-19 pandemic in an Industrial Engineering face-to-face course at a higher education institution (HEI) in Brazil.

2 Industry 4.0 Challenges for Human Factors

Some studies indicate that the human factor can be considered the most crucial part of companies integrating Industry 4.0 tools to improve productivity and flexibility [7]. The advent of technology and Industry 4.0 significantly impact organizational and productive procedures, incorporating new elements or activities throughout these processes. This includes adopting Big Data to identify opportunities, improve innovative decision-making [8], and the emergence of new types of products, such as digital products and smart products [9].

Considering these new conditions, hard skills are not enough to work in Industry 4.0 context. The digital transformation scenario demands new different skills that combine IT and production knowledge [10]. For example, unlike physical products, digital products have an unfinished structure that can be modified, reprogrammed, and updated continuously [9]. Industry 4.0 requires multi-disciplinary teamwork [6] and the project of development of new products, in general, needs to bring together people from different functions and internal and external organization areas to work as a team [11]. So, more than thinking about the technological structures necessary for elaborating new projects in a digital context, it is necessary to think about the work teams' training [12]. Also, ideas are transformed into products through collective processes. Innovation is a process of creation that arises from social interaction, with communication and knowledge flowing through relevant roles [13].

There is a change in the productive environment, and the human factor training cannot remain the same. Because human factors play a fundamental role in production processes, the current demand is for engineers able to act in the Fourth Industrial Revolution [14]. However, in a culture where digital transformation requires multidisciplinary teamwork [6], many students have a background rooted in individualism. This teaching focused on the individual, in isolation — who will take tests, activities, and tasks alone, without exchanges with colleagues — it is in open disagreement with the demands of Industry 4.0 skills. It is essential to prepare Industrial Engineers, enabling more interdisciplinary training, which will qualify them for future professional work in different situations and contexts using new technologies.

Due to the search for a new profile of engineers, the idea of student-centered learning has been relevant in research on engineering education in the last decade [15]. In Brazil, the Ministry of Education presented new recommendations for this training, involving the adoption of active strategies that allow the improvement of skills such as "communicating effectively in written, oral and graphic forms", "being able to interact with different cultures, through work in face-to-face or distance teams, so that it facilitates collective construction" and "learning to learn" [16]. Ryan [17] says that it is possible to see active learning as an umbrella term that refers to various teaching models that focus on the accountability of learning for students. Active learning promotes the understanding and integrated development of skills in three domains: cognitive, affective, and psychomotor [17].

This need for changes in the training of engineers has been reflected in adopting some of that innovative teaching strategies. Discussions on Engineering Education, even in Brazil, highlight the use of methodologies such as Project Based Learning (PjBL) and Problem Based Learning (PBL) [18], which also seems to be a trend in the specific area of Industrial Engineering [19–22].

The framework proposed in this paper, consequently, has a strong emphasis on the fact that teamwork must be present in engineering classrooms so that the Industrial engineer has no difficulty adapting to the current corporate world and the future based on digital transformation.

3 Methods

The covid-19 pandemic brought numerous challenges to educational systems, especially those essentially structured in face-to-face actions. However, this period represented an opportunity to expand the views on learning processes and innovative practices more aligned with the new demands of social and technological advancement. This article is not restricted exclusively to the period of the pandemic but maintains propositions in learning functions obtained at the time. Especially because even with the end of health restrictions, the trend shows that the use of DICT remains relevant in education.

The research focuses on two human factors disciplines in an Industrial Engineering undergraduate. The authors planned and conducted the activities during the remote teaching period. From October/2020 to March/2022, several tasks were developed with eight classes involving 170 students, totaling four academic semesters [23].

To construct the framework, the proposal for the disciplines was developed with a design of continuous improvement based on the Plan-Do-Check-Act cycle (PDCA). Despite the great application in management, some studies demonstrate the possibility of adapting the scheme to educational contexts. Zuo [24] applied the principle of the PDCA cycle to improve the teaching quality monitoring system in applied universities, and Mergen et al. [25] proposed a teaching methodology based on PDCA for software engineering education. In the present study, the PDCA was used to structure the actions in four phases that gave rise to the teaching proposal.

The planning of disciplines (the “P” in the PDCA cycle) was carried out between March and September/2020. The first stage was to think about the organization of activities given the impossibility of physical contact. This condition met the need for non-individualizing training in preparation for the digital transformation circumstances. Also, it was aligned with the product development perspective, a professional activity characteristic of Industrial Engineering. At that time, it was verified that TBL was an appropriate pedagogical strategy for online contexts [26], which proposed teamwork. TBL establishes a sequence of steps in the learning process for students.

“Do” and “Check” stages (the “D” and the “C” in the PDCA cycle) were characterized by the development of students’ activities. During the “D”, teams created six podcasts. After each podcast, students evaluated the work that the other teams produced for the same theme that their group elaborated on. In the “C” phase, a “Peer Assessment” questionnaire was applied to students as another relevant learning opportunity. “Act” stage (the “A” in the PDCA cycle) was conducted by the professors based on the analysis of the data collected in the “Peer Assessment”. The “Peer Assessment” served as moments of reflection and discussion to improve the proposal and build a final model.

4 Proposal of Framework and Discussions

The main objective of this paper is to propose a framework for Industrial Engineering teaching to prepare human factors for digital transformation. This framework, indicated below, was based on TBL, and applied in undergraduate classes, within a conception of continuous improvement, based on the PDCA cycle. The proposal resembles the structure of the original TBL. However, it indicates more effective adaptations, especially concerning the use of podcast as a product related to DICT and for developing skills in teams.

4.1 PDCA Cycle

Figure 1 summarizes the stages of the PDCA cycle that served as the basis for building the framework. The activities carried out in each of the four phases are described below.

4.1.1 Plan: Planning of the Activities

The precepts of teamwork and product development perspective outlined the group of activities that composes the work presented here. Elaborated during a period of global crisis, the teaching-learning model was thought to be more resilient and applicable in online, hybrid, or face-to-face contexts. The TBL methodology was the base for the initial structuring of the reported activities.

Four essential elements fundamentally characterize TBL: the adequate formation of heterogeneous teams, the accountability of students for the elaboration of individual and collective tasks, frequent feedback, and the promotion of learning and team development [27]. The activities are the protagonist of TBL because, at this moment, practical situations or actual problems are proposed that lead to applying the concepts previously studied by the students. The teacher presents a situation for which teams need to come up with an answer. Each team will show their response simultaneously, communicating it orally and choosing an option in a set of possibilities determined by the teacher. Activities must be characterized by the "4S" to achieve maximum impact on learning [27]:

- Significant Problems: The proposed questions should be complex enough to involve all students and get them to use all available resources.

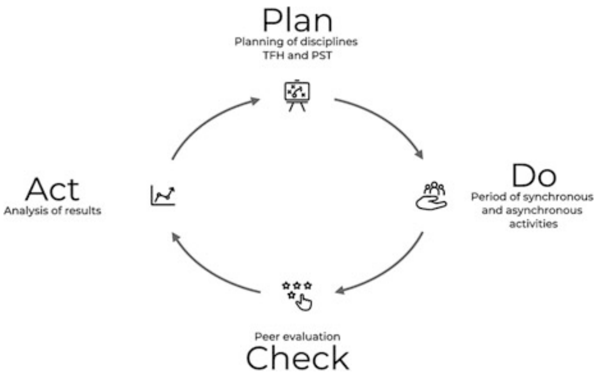

Fig. 1 PDCA cycle structuring teaching proposal

- Same Problem: All teams should receive the same problem simultaneously.
- Specific Choice: Teams should be presented with a list of possible correct answers, as multiple-choice questions focus the discussion on a limited set of topics and force teams to decide which option, they think is best.
- Simultaneous Report: The concurrency of responses prevents teams from modifying their choices by influencing the rest. Each team must commit to its response and defend it in the argumentation in case of divergence.

The last stage of TBL is peer assessment, an essential part of the strategy. Peer assessment allows them to perceive the individual contributions to the team's work, holds the student accountable, and makes him reflect on his actions and his colleagues [27–29].

The proposal aimed to make students elaborate podcast as digital products in a heterogeneous team acting remotely, seeking to represent a work process in the context of digital transformation.

The podcast can be understood as a digital product that, with the advancement of DICT, has become popular over the last few years. Podcasts have expanded the opportunities for the use of audio as a means of learning [30] since its emergence occurred amid technologies that facilitated production, distribution, and use [31]. Recording audio today is relatively uncomplicated. There is much software for audio recording, many of them open-source, available for Microsoft Windows, Linux, and MacOS.

To build their podcast, students would read scientific articles to elaborate a discuss with their team. The podcast development proposal included the basic elements expected in the generated product and established evaluation criteria. Each student would evaluate the results of the team's work, that is, the podcast developed, and these activities would be carried out asynchronously. However, synchronous activities were also proposed to monitor the groups, develop the works, and propose dynamics on the themes worked.

All the planning was made available to students on the first day of the synchronous meeting and was available throughout the semester, on Microsoft Teams.

4.1.2 Do: Development of Synchronous and Asynchronous Activities

The main activity carried out by the students was the development of the podcast. The proposal of the podcast included the basic elements expected in the final product generated, which would also be used as evaluation criteria, such as:

- Initial question – A question referenced by the word "you" as a required element to standardize the work of the teams. Example: "Do you know how ergology can be related to civil aviation?".
- Vignette – It was optional and could come before or after the initial question.
- Presentation of the article's title – It should be done in association with the original question as a required element. Students could use their imagination and build creative queries related to the topic of each of the articles.

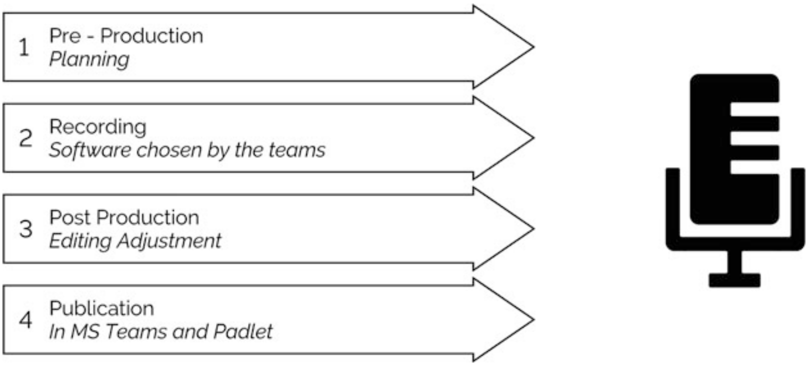

Fig. 2 Podcasts preparation process

- Presentation of the article's content – It must be summarized and carried out by at least three people from the team. At this point, students must answer the question presented at the beginning of the podcast. The team could be creative and relate the contents to real situations experienced, incorporating dialogues, background music, sounds, and effects, among others.
- Closing the podcast – It must make a complete reference to the article, and journal of publication, in addition to presenting the names of the members of the group.

Each podcast should be forwarded to teachers through Microsoft Teams and posted on Padlet (https://padlet.com). Similar to product development, the preparation of podcasts was structured as a process divided into macro steps, as shown in Fig. 2.

After delivering the podcast, each student evaluated the podcast developed by the other teams. This evaluation was performed by filling out a few questions in Microsoft Forms for each of the six podcasts produced.

4.1.3 Check: Peer Assessment

After developing six podcasts, a "Peer Assessment" was applied. The "Peer Assessment" was a questionnaire in Microsoft Forms to identify the students' perceptions in main aspects: the proposal and development of the activities of the discipline, the individual commitment to the performance of the activities, the involvement with the team, and how each team member contributed to the development of the activities.

The "Peer Assessment" questionnaire was composed mainly of closed questions, with a Likert scale of 05 points. The students were instructed to choose the option that best represented how they behaved about each item. The questionnaire presented five sections with 18 questions: five discursive questions and 13 objective questions, totaling 92 items.

4.1.4 Act: Results Analysis and Improvements Identification

The students' answers in the "Peer Assessment" were analyzed at the end of each semester in a preliminary way to identify possible needs for adjustments in the dynamics and work proposal so that the disciplines could be reapplied in the subsequent semester. It was from this analysis that some changes happened, such as the possibility for students to choose the articles of two podcast, which generated an extra negotiation activity within the teams; the publication of podcast in the Padlet application, improving the visualization of the generated products; adjustments in delivery times. The "Peer Assessment" served as a validation device of the proposed model ("Check") and promoted improvements in the proposal throughout the implementation semesters.

The authors performed a preliminary descriptive statistical analysis using the R language. Some categorical results about the satisfaction and perception of the validity of the work performed with the classes were observed. From the perspective of ninety-two percent of the students, the framework provided team engagement throughout the development of tasks. Ninety-four percent agreed that the framework adopted procedures different from purely expository lectures that are valid learning alternatives. Eighty-two percent of the students supported that the content and activities developed through the framework will help them face the challenges encountered as an engineer in Industry 4.0 context. Finally, eighty-nine asserted that the framework helped them become a more autonomous student.

4.2 Framework

Figure 3 represents the framework proposed. However, discussing aspects of this proposal is relevant, especially regarding the adaptations made in the TBL teaching strategy. These adaptations developed in the context of continuous improvement recommended since the methodology, aiming at a profile of engineers able to work in Industry 4.0.

The initial structuring of the reported activities was based on TBL, which was the starting point. The first stage of the TBL methodology is team formation, which was maintained in the framework with the same principles of TBL. The most significant changes, however, were made in the stages of "individual preparation", "guarantee of preparation," and "significant activities". They were grouped into a single stage in the authors' proposal, "Podcast Development from a scientific article," and then divided into seven sub-steps. In the present case study, using tests with closed answers was not justified to validate the student's preparation for group work (one of the stages of the original TBL). What was sought in the classes was to stimulate creativity, a condition that does not require preparation since being creative is a distinct characteristic of the conduct programmed beforehand. The activities of TBL can be summed up in podcast since they were significant activities around discipline

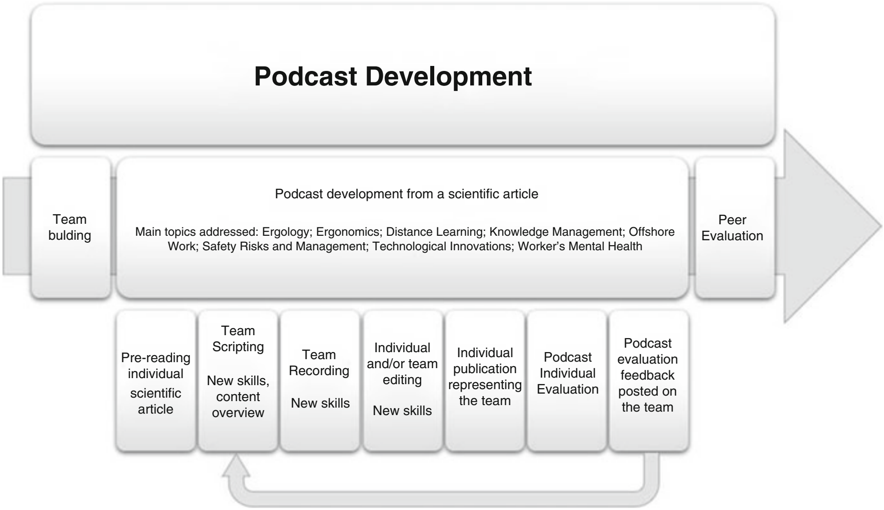

Fig. 3 The framework proposed is based on the TBL methodology

topics. The modifications made to the initial model of TBL and applied in the disciplines resulted from applying the PDCA cycle, resulting in a more optimized process. Such modifications are presented in diagram format, as shown in Fig. 3.

About TBL methodology, its "4S" [27] was resignified in a more expanded sense:

- Significant Problems in the articulation between teaching and research – discussions were held around current and relevant topics for the engineer's training. This element was not part of the original methodology of TBL.
- Same Problem on Human Factors – all students read the same text, always focusing on human factors at work, being led to reflect on the same issues, which also represents the dissemination of the research results.
- Specific Choice in DICT – the podcast is developed by the team, the "choice" for the proposal to develop a digital product. Such a focus on DTIC was not an initial proposal of the TBL. In this research, articulations were included using Microsoft Teams, Padlet, and WhatsApp, as well as other software for recording and editing podcast.
- Simultaneous Report for evaluation and dissemination – all teams met the same deadline for delivery, and each team/student only saw the production of the other teams "at the same time", with no influence on the delivery of the same podcast. Deliveries of works were carried out on Microsoft Teams, and a Padlet mural was created for each discipline.

The framework presented allowed broad learning to students, even during remote teaching, as a proposal more aligned with the professional demands of Industrial engineers in the era of Industry 4.0 with a focus on the development of the human factor. As predicted by the TBL methodology, working in heterogeneous teams was fundamental to fostering the development of negotiation and conflict management skills and collaborative creation from a multifunctional team perspective. Allied with this, the need to produce podcast simulated the work in product development teams, from creating a digital product in a non-face-to-face context. This condition can easily occur in the daily life of an Industrial engineer in the scenario of technological transformation, whether concerning the type of product produced or working conditions, both digital.

In addition to learning from the teams and the product elaborated, students could learn the content. They were presented in the articles on human factors that served as the basis for elaborating podcast. Using scientific articles as class material allowed students to have contact with current content relevant and applied within their training area. Also, unlike uses of a more transmissive education, the framework allowed students to take full advantage of the potential of the podcast as a way to build team learning.

From the themes worked, it was possible to lead the students to relate them to situations already experienced in their initial contacts with the field of Industrial Engineering and make them reflect on their future professional experiences. This reflection is also necessary to prepare future professionals to deal with the issues brought about by the advent of Industry 4.0 technologies, such as existing discussions on autonomous vehicles and accident liability [32]. Thus, the construction of the podcast required not only the reading of the texts but also the reconstruction of the content by moving the material from one means of dissemination to another, incorporating creativity, reflections, and the team members' experiences.

5 Conclusions

Given the new requirements for engineering training, this paper highlighted a series of relevant issues to propose a framework for Industrial Engineering teaching, to prepare human factors for digital transformation. The framework was based on TBL and podcast development within a conception of continuous improvement.

The choice to elaborate podcast allowed students' creativity and proved to be quite valid when investigated in the field of research. Among a vast scenario of active methodologies and DTIC, the production of team podcast based on TBL allowed making students active subjects in their learning process, based on the idea of preparing future engineers to work in the context of Industry 4.0.

A teaching proposal should always be flexible, consequently, the field of possibilities for further research is very broad. The authors intend to explore the data from the "Peer Assessment" form and take some hypothesis tests on the results in a continuous improvement.

The proposal also sought to work with students on emerging themes in the field of Industrial Engineering, including human factor themes that apply to telework contexts and remote practices so evidenced and discussed throughout the covid-19 pandemic. Such practices, even in the post-pandemic, tend to remain in discussions in the various sectors of society and the labor market due to the digital transformation experienced worldwide.

The transformation of educational environments, moreover, is essential to deal with generations of future engineers, helping them to develop a broad and systemic vision that will progressively impact how they deal with the current and future challenges of the market and society. The present work aimed to contribute to expanding discussions on training in Industrial Engineering, considering the importance of human factors in work.

Acknowledgments This study was partly financed by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001. The second author thanks the Brazilian Institute of Geography and Statistics (IBGE) for allowing her to take a temporary leave of absence to carry out the Sandwich Doctoral Program abroad (PDSE).

References

1. Bai, C., Dallasega, P., Orzes, G., Sarkis, J.: Industry 4.0 technologies assessment: A sustainability perspective. International Journal of Production Economics, 229. https://doi.org/10.1016/j.ijpe.2020.107776 (2020).
2. Burh, D.: Social Innovation Policy for Industry 4.0. Friedrich-Ebert-Stiftung, Division for Social and Economic Policies. Available in: http://library.fes.de/pdf-files/wiso/11479.pdf (2015).
3. Heideman Lassen, A., Waehrens, B.V.V.: Labour 4.0: developing competences for smart production. Journal of Global Operations and Strategic Sourcing, Vol. 14 No. 4, pp. 659–679. https://doi.org/10.1108/JGOSS-11-2019-0064 (2021).
4. Ligarski, M. J., Rozalowska, B., Kalinowski, K.: A study of the human factor in Industry 4.0 based on the automotive industry. Energies, 14, 6833 (2021).
5. Liao, Y., Deschamps, F., Loures, E. F. R., Ramos, L. F. P.: Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. International Journal of Production Research, https://doi.org/10.1080/00207543.2017.1308576 (2017).
6. Salah, B., Khan, S., Ramadan, M., Gjeldum, N.: Integrating the Concept of Industry 4.0 by Teaching Methodology in Industrial Engineering Curriculum. Processes, *8*(9), 1007 (2020).
7. Gallo, T., Cagnetti, C., Silvestri, C., Ruggieri, A.: Industry 4.0 tools in lean production: a systematic literature review. Proc. Comput. Sci. 180, 394–403 (2021).
8. Wang, Y., Zhang, H., Song, M.: Does Big Data-Embedded new product development influence project success? Research-Technology Management, 63(4), 35–42. https://doi.org/10.1080/08956308.2020.1762447 (2020).
9. Yoo, Y., Boland, R. J., Lyytinen, K., Majchrzak, A.: Organizing for Innovation in the Digitized World. Organization Science, 23(5), 1398–1408. https://doi.org/10.1287/orsc.1120.0771 (2012).
10. Santiteerakul, S., Sopadang, A., Sekhari, A.: Skill development for industrial engineer in Industry 4.0. Proceedings of IEEE 15th China-Europe International Symposium on Software Engineering Education (2019)
11. Keller, P., Lima, A.: Digital information product development: lessons from a small-sized German enterprise. INMR - Innovation & Management Review, 18(4), 434–454. https://doi.org/10.1108/INMR-03-2020-0033 (2021).
12. McDonough, E.F.: Investigation of factors contributing to the success of cross-functional teams. Journal of Product Innovation Management Volume 17, Issue 3, May, Pages 221–235. https://doi.org/10.1016/S0737-6782(00)00041-2 (2000).

13. Trott, P.: Gestão da inovação e desenvolvimento de novos produtos, 4 edição, Porto Alegre: Bookman (2012).
14. Gumaelius, L., Kolmos, A.: The future of engineering education: Where are we heading? SEFI 47th Annual Conference: Varietas Delectat, Proceedings of the Complexity is the New Normality, Budapest, Hungary, 16–20 September 2019; Nagy, B.V., Murphy, M., Järvinen, H.-M., Kálmán, A., Eds.; SEFI, European Association for Engineering Education: Brussels, Belgium, 2020; pp. 1663–1672 (2019).
15. Cuckierman, U.: Aprendizaje centrado en el estudiante: un enfoque imprescindible para la educación en ingeniería de Aseguramiento de la calidad y mejorade la educación en ingeniería: Experiencias en América Latina, Bogotá, ACOFI, pp. 27–39 (2018).
16. Brasil. Ministério da Educação: Diretrizes Curriculares Nacionais para os Cursos de Engenharia. Parecer CES 01/2019. Diário Oficial da União: seção 1, 109 (2019).
17. Ryan, M. F.: LIT Compendium of active learning strategies for student engagement. LIT Quality, Teaching & Learning. Retrieved June 13, 2022, from https://lit.ie/getmedia/73855786-7bc4-442a-bb72-bad82bb45f74/Compendium-of-Active-Learning-2021-2.pdf (2021).
18. Assumpção, G. D. S., Santos, C. M. D., Castro, A. D. C., Henriques, M. V., Santos, I. C. D.: Current trends in Production Engineering Education: Active learning strategies. IJCIEOM 2020 - International Joint Conference on Industrial Engineering and Operations Management, Online Platform. https://doi.org/10.14488/IJCIEOM2020_FULL_0011_37364 (2020).
19. Zancul, E. de S., Sousa-Zomer, T. T., Cauchick-Miguel, P. A.: Project-based learning approach: Improvements of an undergraduate course in new product development. Production, 27(spe). https://doi.org/10.1590/0103-6513.225216 (2017).
20. Tortorella, G., Cauchick-Miguel, P. A.: An initiative for integrating problem-based learning into a lean manufacturing course of an industrial engineering graduate program. Production, 27 (spe). https://doi.org/10.1590/0103-6513.224716 (2017).
21. Reis, A. C. B., Barbalho, S. C. M., Zanette, A. C. D.: A bibliometric and classification study of Project-based Learning in Engineering Education. Production, 27(spe). https://doi.org/10.1590/0103-6513.225816 (2017).
22. Uppvall, L., Blomkvist, P., Bergqvist, W.: Opening the black box of collaborative writing: Experiences from a teamwork-based course in industrial management. Production, 27(spe). https://doi.org/10.1590/0103-6513.222016 (2017).
23. Assumpção, G. S.; Santos, C. M.; Castro, A. C.: The Transition From the Conventional Classroom to Remote Teaching: How to Improve Online Practices. In: Susana Silva; Paula Peres; Candida Silva. (Org.). Developing Curriculum for Emergency Remote Learning Environments. 1ed.Pennsylvania: IGI Global, v. 1, p. 62–88 (2022).
24. Zuo, C.: Construction of teaching quality monitoring system in applied university under information technology environment. Proceedings of the 8th International Conference on Management, Education, and Information (MEICI 2018). https://doi.org/10.2991/meici-18.2018.222 (2018).
25. Mergen, S.; Kepler, F. N.; Silva, J. P. S.; Cera, M. C.: Using PDCA as a general framework for teaching and evaluating the learning of software engineering disciplines. Isys – Revista Brasileira de Sistemas de Informação, v. 7, n. 2 (2014).
26. Clark, M. et al.: Off to On: Best Practices for Online Team-Based Learning™. Center for Excellence in Learning and Teaching Publications (2018).
27. Michaelsen, L. K.; Sweet, M.: The Essential Elements of Team-Based Learning. New Directions for Teaching and Learning, n. 116 p 07–27 (2008).
28. Michaelsen, L. K., Davidson, N., Major, C. H.: Team-based learning practices and principles in comparison with cooperative learning and problem-based learning. Journal on Excellence in College Teaching, 25(3&4), 57–84 (2014).
29. Parmelee, D., Michaelsen, L. K.; Cook, S., Hudes, P. D.: Team-Based Learning: A practical guide: AMEE Guide n°65. Medical Teacher, 34:5, e275–e287. https://doi.org/10.3109/0142159X.2012.651179 (2012).

30. Edirisingha, P., Hawkridge, D., Fothergill, J.: A renaissance of audio: Podcasting approaches for learning on campus and beyond. European Journal of Open, Distance and E-Learning (2010).
31. Armstrong, G. R., Tucker, J. M., Massad, V. J.: Interviewing the experts: Student produced podcast. Journal of Information Technology Education: Innovations in Practice, v. 08 (2009).
32. Taeihagh, A., Lim, H. S. M.: Governing autonomous vehicles: emerging responses for safety, liability, privacy, cybersecurity, and industry risks. Transport Reviews, 39:1, 103–128. https://doi.org/10.1080/01441647.2018.1494640 (2019).

Multicriteria Decision for Electrified Vehicles Selection using Analytical Hierarchy Process Method

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Abstract Electrified vehicles (EVs) are a subject of common interest among environmentalists, policymakers, and companies worldwide. These vehicles can mitigate greenhouse gas emissions problems and the government is trying to boost the electric vehicle market through fiscal incentives and tax reduction. This paper proposes a multicriteria decision-making analysis for selecting electric, hybrid, and internal combustion engine vehicles currently available in Brazil. This study creates one decision model based on a set of technical, economic, and financial criteria to support the decision-making of potential electric car buyers. The most relevant criteria were the total cost of ownership safety, comfort, price, performance, and tax incentives. This study outcome will help consumers and manufacturers better understand the technical and financial criteria for selecting electrified vehicles.

Keywords Electrified vehicle · Electric vehicle · AHP · Decision making

1 Introduction

Making choices and deciding between different options is a daily act. Buying a vehicle, for example, is one of those choices made annually by millions of people worldwide. Throughout the year, the automotive industry renews itself through the launch of new vehicles, updates to current models, and incorporation of new technologies in the most diverse systems: braking, connectivity, and artificial intelligence, among others.

In propulsion systems, even though there have been several advances in efficiency and performance, combustion engines continue to be the most used way to move a vehicle. The transport sector accounts for 23% of emissions of gases harmful

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Table 1 Types of electrified vehicles available in Brazil

Types	Selected vehicles
Electric (BEV)	
Hybrid (HEV)	
Engine (ICE)	

to the ozone layer worldwide. In São Paulo city, the situation is even more serious, as automobiles are responsible for 72.6% of Greenhouse Gas (GHG) emissions [1].

Electrified vehicles (EVs) are a subject of common interest among environmentalists, policymakers, and companies worldwide. Adopting this technology can positively influence recurrent issues, such as environmental problems, energy security, and sustainability [2], so these changes occur. However, these vehicles need to be massively adopted.

Most countries have adopted aggressive targets to reduce greenhouse gas (GHG) emissions. Europe, for example, where transport represents the second largest source of GHG emissions, accounting for almost 25%, has committed to reducing its emissions by up to 40%, with the transport sector playing a key role in these reductions [3, 4].

It is worth mentioning that, at this moment, there are several technologies in the market for electric vehicles (EV), such as vehicles with range extension technologies (REX). Hybrids (HEV) feature a combustion engine operating with an electric motor. These are often considered transitional technologies and do not connect to the electrical grid since they do not use charger cables in their regeneration. Hybridization occurs through Series or Parallel and has some levels: Micro, Mild, and Full. These levels occur by changing the alternator, electric motor, and battery proportions compared to the electric motor.

The focus of this study will be battery electric vehicles, from the Battery Electric Vehicles (BEV) – which have only the electric motor, or internal combustion vehicles, from the Internal Combustion Engine (ICE) – which have only the engine combustion, as shown in Table 1.

2 Background

2.1 Electrification Technologies

The efficiency of electrified vehicles is noted as being on another level compared to traditional internal combustion vehicles, with levels around 60% against approximately 18% of internal combustion vehicles. This difference mainly considers the losses that exist, internally or externally, in a combustion motorization system, which are much greater than in an electrified motor, even if we believe the losses through charging systems, battery efficiency, losses in the inverters, and the transmission.

In electrified vehicles, energy comes from batteries recharged through the electrical network, which are independent of fossil fuels and have no exhaust, as they do not release polluting gases.

In addition to the environmental and efficiency benefits, there is also performance, as torque transfer occurs almost instantaneously between the engine and the axles, providing excellent acceleration. By comparison, the Tesla Model S reaches the mark of 1.9 seconds from 0 to 100 km/h, while a Ferrari 488 takes 3 seconds to get the same speed.

There are different types of electric motors. Direct Current (DC) motors used to be considered the most appropriate technology for electric vehicles. They are the least complex and expensive due to their simpler control electronics. However, they require regular maintenance because of the presence of commutators and brushes that are in contact and are prone to wear. This feature makes the technology unsuitable for the widespread adoption of engines in BEV vehicles. Alternating Current (AC) motors are cheaper. Therefore, they require complicated and expensive power electronics, including an inverter as a power source – the batteries – which provide DC current. Thus, the total cost of AC motors becomes higher. Its advantages are a higher power density, which is very important in an automotive application, as it allows the use of smaller and lighter engines and greater efficiency, maximizing the range of battery charge capacity, which is still a major barrier to the adoption of these vehicles [5].

Three main AC motors are normally considered for use in BEV: induction switched reluctance and permanent magnet brushless motors. Induction motors are low-cost, reliable, and maintenance-free compared to DC motors. A specific control system is needed, but many improvements have been made in recent years. Switched reluctance motors are considered high-potential motors. Its construction is simple, the manufacturing cost is low, and the torque-speed characteristic is an interesting case about using the VEB. However, its control and design are difficult, and acoustic noise issues have yet to be resolved. Finally, with the improvement of permanent magnet materials, PM motors have also become very attractive. They offer high efficiency, high power density, and reliability. However, its cost remains high due to permanent magnetic materials.

It includes the motor topology, drive operation, and control strategies, which are crucial to maximizing efficiency [6, 7]. Among the challenges of electrified vehicles, we also have the relationship of energy storage due to the price of batteries, durability, and charging time [8]. As for batteries, the type that has been widely used is the Lithium-Ion (Li-Ion), presenting a high energy density due to the electrochemical properties of Lithium being high and its mass being low and exhibiting high efficiency and durability, as opposed to its cost, which is around US$ 700/KWh. BEV vehicles have an average of 20–25 KWh [9].

Even though electric motors are a tried and tested technology, their application in automotive powertrains brings new restrictions regarding weight, robustness, and reliability. Possible future improvements of current electric motors include reducing the cost of high-temperature permanent magnets, developing controllers for safer operation of subsystems, and decreasing the number of sensors in the motor [6].

2.2 Financial Incentives

Public incentive policies actively impact the development and adoption of electric mobility technologies. Leveraging electric vehicles begins with establishing goals and objectives, followed by adopting a vehicle emissions standard. An EV deployment plan often includes procurement programs to stimulate demand for electric vehicles and allow for an initial deployment of publicly accessible charging infrastructure.

Tax incentives are especially important given that purchase prices for EVs, as is often the case with newer technologies, are higher than equivalent combustion vehicles (ICE). To reduce this difference, they are often associated with regulatory measures that increase the value proposition of EVs because, even with the benefits related to emissions, world governments need to add economic advantages, whether for end consumers or automakers.

In Table 2, we can cite incentives aimed at consumers with lower financing rates, tax reductions, or direct post-purchase subsidies. It is also possible to mention some practices that already exist worldwide. Hybrid and electric vehicles: public policy

Table 2 Table captions should be placed above the tables

Country	Financial incentives
Germany	Exemption from licensing fees
Spain	Subsidies of up to 25% on the price of the vehicle, before taxes, in the amount of up to €6000
France	€450 million in discounts granted to consumers who buy electrified vehicles, with 90% of this amount coming from taxes on inefficient vehicles and 10% from direct subsidies.
China	Vehicle purchase subsidies of up to 元60,000 (about US$10,000)
India	Subsidy of 100,000 (about US$ 2000) or 20% of the vehicle price, whichever is less. Tax incentives for pure electric and plug-in hybrids.

suggestions for the segment using financing by BNDES [10]. From the automakers' point of view, CO_2 reduction targets linked directly to tax deductions and subsidies guarantee the investment and production of electrified vehicles.

Policies to support the deployment of charging infrastructure include minimum requirements to ensure the availability of chargers in new or renovated buildings and parking lots and the deployment of publicly accessible chargers in cities and on-road networks. The adoption of standards facilitates the interoperability of various types of charging infrastructure [11]. The United States has an adoption credit of US $7500, in addition to state and local incentives, which vary according to each location, being an important factor in the adoption of BEVs [12].

In Brazil, the government has been starting to adopt incentive measures. However, these incentives have yet to come to fruition, as electric vehicles have been taxed at 25%; and hybrid vehicles at 13% of IPI. Only in São Paulo are EVs exempt from rotation, which becomes a huge obstacle to adopting this product. "Price tag shock" still affects the purchase of high-value products [13], although many experts argue that costs for these products may be diluted in the long term [14, 15].

In markets where break-even is easier to achieve, it is common for automakers to invest in consumer education as a cheaper way to encourage the purchase of (BEV). Total Operating Cost (TCO) estimators have become a tool that aims to better inform consumers about how the US Department of Energy already presents a calculator for this purpose [16]. Incentives for the Brazilian market, Rota 2030 (a tax incentive program for automakers that includes Hybrid and Electric vehicles) provides for a change in the IPI rates, aiming to increase the competitiveness of these products, thus increasing their penetration in Rota 2030 Program [17].

3 Materials and Methods

Choosing a vehicle is a complex task involving several quantitative or qualitative variables, such as power, load capacity, safety, comfort, autonomy, offroad capability, vehicle safety, size, and previous experiences with the brand. Each customer assigns a different importance to each characteristic, according to its use for that product. This is easily noticeable when analyzing the number of types of vehicles to meet the most different services and preferences [18].

As it involves several options and criteria, both quantitative and qualitative, choosing a vehicle is a problem that fits the Analytic Hierarchy Process (AHP) method. This makes it possible to be analyzed, based on the priorities explained below, which is the most logical choice within the options and criteria [19].

These comparisons will be performed based on the multicriteria method of support and decision called the Analytic Hierarchy Process. Saaty developed this method in 1977 to propose a technique that was representative of the decision-making process of human beings, aiming to achieve better choices based on hierarchy, peer comparisons, judgment scales, allocation of weights for criteria, and selection of the best alternative from a finite set of variants by calculating its functional utility [20].

The method's execution steps divide the general problem into smaller hierarchical levels while maintaining the participation of these points in the overall decision, facilitating understanding and evaluation. When trying to solve a complex problem, it is easier to be divided into smaller ones than to solve them individually, as they converge in solving the initial problem. We can find a visual example of the hierarchical structure of the AHP method. The weights assigned to the criteria are defined using a direct comparison between them, in which each criterion is compared with the others using the Saaty scale [21].

After extensive research and professional experience in the subject, these values were given by the author, in addition to the support of executives in the automotive sector who provided their opinions as experts in evaluating these criteria. The decision model incorporates the following points:

- Objective: the problem that the decision-maker wants to solve. In this case, the choice or not of an electric vehicle.
- Criteria: are the parameters considered to evaluate the problem and classify alternatives; and
- Sub-criteria: are the points chosen within the criteria to quantify them.

3.1 Definitions of Criteria and Alternatives

For the analysis, we will study only vehicles sold officially in Brazil until the end of 2019, excluding unofficially imported vehicles. For this, we will compare three kinds of vehicles: ICEs, BEV, and HEV, forming the comparison pairs. Vehicles of similar categories that deliver identical sizes and powers were considered. Among the comparisons, recharge values for the common electrical network were chosen because it is the reality of the residents of the Federal University of Bahia.

Within the scenarios mentioned above, the possibilities of 10,000, 20,000, and 30,000 km driven annually in a three-year cycle were considered, generating three scenarios: 30,000, 60,000, and 90,000 km for the total cycle.

It is worth mentioning that the number of electrified vehicles in the Brazilian market is quite modest compared to combustion vehicles, which ends up limiting the user's choice options interested in this type of product since they are almost entirely located in a price range above R$100,000.00. And since we are talking about Brazil, whose market is mostly B vehicles, with approximately 46% of all registrations in the country, in 2022 being between small hatchbacks and small sedans, the absence of electrified vehicles in these categories greatly affects their participation in the market our market. The criteria used to analyze were purchase price, performance, safety, comfort, and operating costs.

3.1.1 Purchase Price

Most consumers search for a car with a predefined budget, which begins with a value and then looks for options that fit that budget. Therefore, even considering the total cost of owning a vehicle, the value of the acquisition price was also accepted. Since as previously mentioned, this aspect is one of the factors that most need to be worked on so that the consumer can understand the possible added value in the long-term ownership of an electric vehicle.

3.1.2 Performance

A large part of buying a vehicle's emotional aspect is power-related. Each person may have a different perception of this issue for various reasons, whether in terms of the vehicle's acoustic insulation or how it responds to acceleration. To approach this criterion more rationally and increase the robustness of the data, making it more quantitative, we will use as data the values of Torque (kgf/m) and Power (CV) available in the technical sheet of each vehicle in the proper automaker's website.

3.1.3 Safety

Another issue often on the covers of automotive magazines is the safety levels each vehicle presents, delivered by the NCAP or New Car Assessment Program, in English. It offers consumers independent and transparent information on the safety levels of different vehicle models on the market. NCAP uses internationally recognized test methods and rates the protection provided by vehicles for adult and child occupants from 0 to 5 stars. These values are available for consultation online. To assign them, we will use the peer ranking of this study.

3.1.4 Comfort

The definition of comfort is quite subjective: "Act or effect of Comforting oneself." Each consumer has their purpose of comfort, which can vary greatly between them. To mitigate these differences, we will consider criteria that value physical comfort and, for the most part, are linked to vehicle characteristics, such as wheelbase (mm), length (mm), and width (mm). These data were obtained from the technical data sheets of the products, also available on the automakers' website.

3.1.5 Operating Costs

The operating costs were calculated to summarize the current acquisition costs, future expenses, and vehicle sales after a predetermined window, thus giving a more realistic view. The importance of this step is necessary, as EVS cars have a way of convincing the consumer that the value is amortized over time due to lower costs and maintenance expenses. Given that for many consumers, the list price is a limiting value in the decision-making process for a vehicle.

To raise the values, we assume some assumptions listed below. This place already has tax incentives for electric vehicles. This step will analyze the sensitivity of the decision when the fiscal incentives are applied.

Considering a 3-year vehicle cycle, we will calculate the operating cost of each year since the first period, starting with: Operating Cost = devaluation + consumption cost + taxes + insurance + maintenance. After these calculations are performed, we have the values presented in Table 3.

4 Results and Discussion

After filling in the values given by specialists, the criteria weight table was analyzed for the consistency of the assigned weights. The Consistency Index is obtained through the eigenvalues resulting from the normalization of the data. The analysis's value was 0.028, demonstrating that 2.8% of the evaluations need to be more consistent with the established acceptable, which must be below 5%.

Analyzing the criteria and weights attributed to them, after analysis and normalization of the values, the criteria of cost of ownership and acquisition price present weights of 0.411 and 0.402, respectively, which demonstrates the great relevance of these criteria for the user, presenting more than 80% of the total, as can see in Fig. 1a.

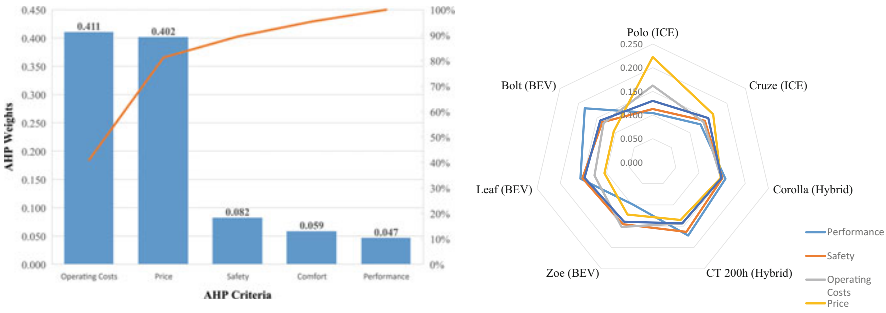
The next step was to compare the chosen options, presented in Table 3, for each evaluation criterion, generating a matrix with normalized values for each item. The Fig. 1b shows the relative weight of the vehicles for each attribute, making it possible to individually analyze what stands out the most within the considered options.

Based on the metrics presented in the Evaluation Criteria section, the values normalized and multiplied by the prioritization weights of the attribute were added for each vehicle. Thus, we obtained the ranking of the best choices within the analyzed conditions, generating the following matrices. From these matrices, we can conclude that the colors in red represent the vehicles that were worse in the given criterion, and vehicles in green represent the best within the criteria in which they are inserted (see in Table 4).

Considering the criteria that most impact the analysis about the cost of ownership and acquisition price, the electric vehicles (BEV): Leaf, Bolt, and Zoe were in the last positions, surprising with the high value that these vehicles are represented. This

Table 3 Criteria to analyze the electrified vehicles

Brand	Model	Technology	Price	Perform	Safety	Comfort	Operating costs
Volkswagen	Polo	ICE	$16,493.01	116	17	8.7	$15,912.12
Chevrolet	Cruze	ICE	$22,552.89	150	34	10	$18,880.43
Toyota	Corolla	Hybrid	$24,948,10	173	38	9.9	$17,506.78
Lexus	CT200h	Hybrid	$27,145.71	181	37	9.6	$18,034.03
Renault	Zoe	BEV	$29,920.16	92	34	9.3	$17,038.68
Nissan	Leaf	BEV	$35,127.74	149	40	9.8	$20,515.32
Chevrolet	Bolt	BEV	$34,127.74	203	32	9.4	$19,496.55



(a) (b)

Fig. 1 Pareto plot for criteria's weights (**a**) and Radar plot (**b**) for criteria's weights by electrified vehicles

Table 4 Comparative analysis among the electrified vehicles

Criteria	Weights	Cruze	Zoe	Polo	Bolt	Corolla	CT 200 h	Leaf
Peformance	0.04676	0.129	0.099	0.104	0.183	0.157	0.172	0.156
Safety	0.08235	0.140	0.145	0.113	0.136	0.150	0.163	0.152
Operations costs	0.41054	0.137	0.152	0.162	0.132	0.148	0.143	0.126
Price	0.40169	0.163	0.123	0.223	0.105	0.147	0.135	0.105
Comfort	0.05864	0.150	0.139	0.130	0.141	0.149	0.143	0.147
Results		**0.148**	**0.136**	**0.178**	**0.125**	**0.148**	**0.143**	**0.122**

directly interferes with the ownership cost since the complete cycle devaluation was considered. It is worth highlighting that the Cost of Ownership for BEV vehicles has its worst number in scenario 1, representing the lowest number of kilometers driven. The advantage of not needing gasoline has little influence on costs.

It is noted that the BEV vehicles improve in the overall result regarding the greater number of kilometers, as seen in scenario 3, in which Bolt went from 0.120 to 0.125, Zoe from 0.131 to 0.136, and Leaf from 0.117 to 0.122, with all other criteria, remained stable, changing only the cost of ownership values.

Combustion vehicles (ICE) had the worst results, due to the increase in the running cycle, given that all other parameters remained unchanged, with Cruze going from 0.152 to 0.148 and Polo from 0.186 to 0.178. This result had a direct impact on fuel costs. Due to this degradation, the Cruze (ICE) was overtaken by the Corolla Hybrid for 3 years of operation. It is possible to observe that, while Electric vehicles (Bolt, Zoe, and Leaf) improve their grades and Combustion vehicles (Cruze and Polo) worsen their grades, Hybrids (Corolla and CT 200 h) have practically stable results for the 3 years, as their costs end up being balanced due to the high-efficiency averages (km/l) about traditional combustion vehicles. However, it gets less evolution when compared to electric ones.

5 Conclusion

After filling in the values given by specialists, the criteria weight table was analyzed for the consistency of the assigned weights. The Consistency Index is obtained through the eigenvalues resulting from the normalization of the data. The analysis's value was 0.028, demonstrating that 2.8% of the evaluations need to be more consistent with the established acceptable, which must be below 5%.

Analyzing the criteria and weights attributed to them, after analysis and normalization of the values, the criteria of cost of ownership and acquisition price present weights of 0.411 and 0.402, respectively, which demonstrates the great relevance of these criteria for the user, presenting more than 80% of the total.

This study observed that electrified and electric vehicles are quite equal and, in some cases, even better than combustion vehicles. However, the price of these products is a factor that weighs negatively on the comparisons made.

The VW Polo obtained the best placements in the three scenarios but is classified as an entry vehicle, unlike the other test vehicles in different categories, such as Medium Hatch. The Polo has more sophisticated equipment levels, showing that hybrid vehicles become interesting options for the Brazilian consumer. The Cruze is practically tied to the Corolla Hybrid for 3 years of analyzed operation.

The discussion of incentives that begins this article is necessary, as it is clear, after carrying out the analysis, that the price of the vehicle, due to its impact on the two main criteria, makes electric vehicles less attractive than combustion vehicles. However, actions that reduce costs for the end customer, such as exemption from Government taxes or even fees for manufacturers to reduce the amount paid by the buyer, are initiatives of great importance that enable the delivery of the most competitive products to the consumer. Brazilian consumer.

One of the limitations of this study is the number of vehicles analyzed, given that in a real purchase situation, the consumer may have access to many options, not just those captured in this article. In addition, each consumer has very specific preferences for choosing their vehicle. Therefore, a more ecological consumer profile should have been considered, which would, in theory, give more value to electric vehicles.

References

1. IEMA. Inventory of atmospheric emissions from road passenger transport in São Paulo. 2017. Available at: http://emissoes. energyeambiente.org.br. Last accessed 4 July 2019.
2. Mock, P., Yang, Z. Driving electrification: A global comparison of fiscal incentive policy for electric vehicles. In: ICCT, the International Council on Clean Transportation, 2014.
3. Rezvani, Z.; Jansson, J.; Bodin, J. Advances in consumer electric vehicle adoption research: A review and research agenda. *Transportation Research Part D: Transport and Environment*, 34 (1), 122–136, (2015). https://doi.org/10.1016/j.trd.2014.10.010

4. Gumz, J., Fettermann, DC., Sant'Anna, AMO., Tortorella, GL. Social influence as a major factor in smart meters' acceptance: findings from Brazil. *Results in Engineering*, 15, 100510, (2022). https://doi.org/10.1016/j.rineng.2022.100510
5. Garcia, D.A., Martinez, J.L.R. Model-based design validation and optimization of drive systems in electric, hybrid, plug-in hybrid and fuel cell vehicles. *Energy*, 254(9), 123719, 2022. https://doi.org/10.1016/j.energy.2022.123719
6. Emadi, A., Lee, Y. J., Rajashekara, K. Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles. *IEEE Transactions on Industrial Electronics*, 55(6), 2237–2245, 2008. https://doi.org/10.1109/TIE.2008.922768
7. Acosta, SM., Amoroso, AL., Sant'Anna, AMO., Canciglieri Junior, O. Relevance vector machine with tuning based on self-adaptive differential evolution approach for predictive modeling of a chemical process. *Applied Mathematical Modeling*, 95:125–142, 2021. https://doi.org/10.1016/j.apm.2021.01.057
8. Hota, A.R., Juvvanapudi, M., Bajpai, P. Issues and solution approaches in PHEV integration to the smart grid. *Renewable and Sustainable Energy Reviews*, 30, 217–229, (2014). https://doi.org/10.1016/j.rser.2013.10.008
9. Deberitz, J. *Lithium: production and application of a fascinating and versatile element*. Verlag Moderne Industry, 2006.
10. BRAZIL, BC. Quotations of all currencies to PTAX closing. 2019. Available at: https://www.bcb.gov.br/estabilidadefinanceira/cotacoestodas. Last accessed 4 July 2019.
11. IEA. Global EV Outlook 2019. 2019. Available at: https://www.iea.org/publications/reports/globalevoutlook2019/. Last accessed 4 July 2019.
12. Jenn, A., Springel, K., Gopal, A.R. Effectiveness of electric vehicle incentives in the United States. *Energy Policy*, 119, 349–356, (2018). https://doi.org/10.1016/j.enpol.2018.04.065
13. Deloitte. New Market, New Entrants, New Challenges, Battery Electric Vehicles. 2019. https://www2.deloitte.com/content/dam/Deloitte/uk/Documents/manufacturing/deloitte-uk-battery-electric-vehicles.pdf. Last accessed 4 July 2019.
14. Allcott, H.; Wozny, N. Gasoline prices, fuel economy, and the energy paradox. *Review of Economics and Statistics*, MIT Press, 96 (5), 779–795, 2014
15. Wohlgemuth, M., Fries, CE., Sant'Anna, AMO. Giglio, R. Fettermann DC. Assessment of the technical efficiency of Brazilian logistic operators using data envelopment analysis and one inflated beta regression, *Annals of Operations Research,* 286:703–717, 2020. https://doi.org/10.1007/s10479-018-3105-7
16. ENERGY, D. Office of Science User Facilities. 2019. Available at: https://www.energy.gov/science/science-innovation/office-science-user-facilities. Last accessed 4 July 2019.
17. ANFAVEA. National association of motor vehicle manufacturers. 2020. Available at: https://anfavea.com.br/site/. Last accessed 2 January 2022.
18. Murugan, M., Marisamynathan, S. Elucidating the Indian customers requirements for electric vehicle adoption: An integrated analytical hierarchy process – Quality function deployment approach. *Case Studies on Transport Policy*, 10, 1045–1057, (2022). https://doi.org/10.1016/j.cstp.2022.03.017
19. Fabianek, P., Will, C., Wolff, S., Madlener, R. Green and regional? A multi-criteria assessment framework for the provision of green electricity for electric vehicles in Germany. Transportation Research Part D, 87 102504, (2020). https://doi.org/10.1016/j.trd.2020.102504
20. Saaty, T.L. Time-dependent decision-making; dynamic priorities in the AHP/ANP: Generalizing from points to functions and from real to complex variables. *Mathematical and Computer Modeling*, 46(7–8), 860–891, (2007).
21. Canciglieri, O., Sant'Anna, A.M.O., Machado, L.C. Multi-attribute method for prioritization of sustainable prototyping technologies. *Clean Technologies and Environmental Policy*, 17, 1355–1363, 2020. https://doi.org/10.1007/s10098-015-0962-5

BIM Critical Factors-Based Framework Towards Digitalization of Construction in the Public Sector

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Abstract In recent years, Building Information Modeling (BIM) has emerged as a relevant methodology for the digitalization of the construction industry, presenting a close relationship with digital transformation in the public sector and its relevance in building new frameworks for service delivery and creating new forms of relationships between stakeholders. There is evidence that some countries, such as the UK and the US, have developed critical success factors (CSFs) to implement BIM successfully. Nowadays, there is also an increase in the subject in developing countries, especially regarding studying CSFs for their proper implementation. With Decree 10.306/2020, the Brazilian government established the use of BIM in the direct or indirect execution of engineering works and services in the country. In this vein, this paper proposes a framework based on CSFs for BIM implementation in the public sector. A qualitative-quantitative approach was used, with a combination of a scoping review, interviews with experts in BIM in public works, and the application of fuzzy multicriteria methods to assess the level of importance of CSFs.

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In this sense, this research contributes to identifying an appropriate procedure for selecting critical factors that should be prioritized for the success of BIM in the public sector. Furthermore, it aims to provide a pathway toward the digitization of construction in the public sector through the multi-perspective CSFs to BIM.

Keywords Critical success factors · Public sector · Digitalization framework

1 Introduction

Building Information Modelling (BIM) is a working methodology that integrates all project parts throughout the construction life cycle, extracting real information and transforming it into digital information to create a product that optimizes the work [1]. In recent years, BIM has emerged as an innovative concept for the field of public works operating in the construction industry. BIM offers a new paradigm for designing, building, operating, and maintaining a facility. It is a systematic approach to the life cycle of infrastructure and is one of the latest technologies that are revolutionizing the architecture, engineering, and construction (AEC) industry worldwide. Although BIM has been considered the primary methodology of digital planning in construction and can be used to establish common communication standards between project participants, there is an absence of a standardized data schema in BIM and a protocol for defining responsibility for information use [2]. Implementing BIM also brings certain risks for construction projects, as BIM is supplemented with information from various disciplines, faster and more accurately, affecting evaluation.

Kassem and Succar [3] have established clear definitions for implementing this methodology, such as the successful adoption of BIM tools and workflows within a single organization. On the other hand, BIM diffusion is the adoption rate of BIM tools and workflows in markets [4]. studied the implementation of BIM in an architectural firm and found several significant factors in the implementation process [5]. termed these factors as critical success factors (CSFs), constituting essential elements for successfully implementing a new system. From this perspective [6], reported that CSFs, first proposed by [7], have been widely adopted by researchers as a top-down approach to examining technological change [8]. also, point out that the CSFs are an effective way to identify a few manageable but vital factors from a large number of factors.

The evolution of digital transformation in the construction industry, as far as public works are concerned, has recently been driven by CSFs for BIM implementation. However, considering resource scarcity and criticality, the evaluation of priority factors can be supported by multicriteria decision-making methods (MCDM). These methods offer several advantages, such as handling different types of information, rules and regulations, stakeholder requirements, specialized skills, and construction-related data [9]. On the other hand, the question is how to deal with the uncertainties and vagueness inherent in the decision-making process. The fuzzy MCDM approach allows both objective and subjective criteria to be considered and is suitable for combining various evaluations and linguistic weights to determine the best selection alternatives. The fuzzy sets theory presents some solutions to the problem of ranking alternatives by aligning factors, or indicators, that complement each other [10].

To address current gaps in empirical studies on digitization in construction, and identify the CSFs for BIM implementation in the public sector supported by MCDM methods, it was defined as the objective of this work to answer the following research question: (i) What are the CSFs for BIM implementation in public works? This study aims to provide a BIM CSFs-based framework for the digitalization of construction in the public sector. The proposal of a multi-perspective framework to define a path with the use of construction digitization can help project participants make informed decisions and can minimize the gap between the digital world (e.g., 3D model, simulation model, etc.) and the real one (position or condition of materials, equipment).

2 Background

2.1 Critical Success Factors for BIM

Public administration is moving from digitizing single administrative forms to redesigning entire processes and services to transform its operations digitally [11]. The public sector is vital in leading the industry toward BIM adoption. In recent years, BIM implementations have continued to increase sharply as more and more government agencies and non-profit organizations from various countries worldwide have implemented BIM in their projects and provided different BIM standards and solutions. In the public sector context, digital transformation is considered the application of IT solutions to improve the accessibility and efficiency of public service organizations [11]. Scholars argue that digital transformation in the public sector is an important and essential endeavor for the effectiveness of public administration as well as the promotion of democratic values and mechanisms [12]. According to [11], the goal of exploring the CSFs that influence digital transformation in the public sector stems from the idea that public organizations satisfy the interests of multiple stakeholders while navigating complex decision-making processes; these analyze the various challenges of digital technology and transformation in the public sector and identify several factors that are well configured to materialize the benefits of digital transformation in the construction sector.

The successful implementation of BIM requires the consideration of integrated factors during use. From this context, 42 CSFs were detected for BIM implementation in public works. For example, in the list of CSFs, factors include support for BIM use by senior and middle management, individual and group motivation in the organization to adopt BIM, cooperation in simultaneous access of works, presence of qualified BIM personnel, integration of project documentation/proposal, BIM training programs, and risk mitigation with BIM-ready projects where leadership, training, and other aspects are involved. With the growing acceptance of BIM to improve traditional practices, industry interest has shifted from applying BIM to determining how to adopt BIM in organizations successfully. CSFs is a concept proposed by [7], representing a limited number of areas where satisfactory results ensure successful competitive performance for an organization. BIM is inevitable because of its current need for the industry and various social bodies. Significantly, the public sector recognizes the benefits that BIM can bring. The authors warn that while BIM does not address all concerns, it can provide opportunities for construction sectors, especially in public works, to take a step in the right direction for a more sustainable future.

2.2 MCDM Methods for CSFs Assessment

MCDM is a powerful approach widely used to deal with unstructured problems that contain multiple and potentially conflicting objectives [13]. Several MCDM techniques have been developed and are used in various fields of engineering as well as management. MCDM can support decision-makers in evaluating alternatives and have an impact on increasing the dynamism of the requirements for decision-making. The applied potential means that this methodology can become a powerful tool to help you select your criteria and priorities in a wide range of infrastructure 'building problems'.

In this research, hybrid MCDM methods such as Fuzzy Analytic Hierarchy Process (FAHP) [14] were used to obtain the weights based on the experts' experience in evaluating CSFs for BIM implementation in public works and fuzzy *'VlseKriterijumska Optimizacija I Kompromisno Resenje'* (FVIKOR) [15], meaning multicriteria optimization and compromise solution, was used to rank all CSFs evaluated. Regarding the models for the selection of CSFs in BIM application, researchers and practitioners have adopted different techniques [16]. applies AHP-VIKOR with an integrated approach for BIM evaluation applications based on Rough theory to transform the preferences of experts, similar is the case of [17], which conducted a comprehensive study on the evaluation of the financial performance of construction companies by integrating entropy and fuzzy VIKOR models, [18] where construction projects are evaluated by combining Fuzzy AHP and Fuzzy VIKOR multicriteria decision making methods to evaluate and prioritize five construction projects in the area of road construction in Isfahan, Iran.

The literature reviewed applied FAHP as a standalone or hybrid approach for MCDM as part of their solutions. The VIKOR approach [19], specifically refers to the Lp metric [20] and has been viewed as one of the best methods within MCDM for solving discrete decision problems with non-measurable and conflicting criteria. FVIKOR method can be used to deal with qualitative situations and are very effective in dealing with non-commensurable criteria. In this study, the FAHP and FVIKOR methods were chosen for selecting CSFs for BIM implementation, which will be integrated into the proposed framework. Moreover, with the proposed hybrid fuzzy group-MCDM technique, this framework will have a holistic approach to properly classify CSFs.

3 Research Methodology

3.1 Research Steps

This section describes the steps of research, which presents a mixed approach with qualitative-quantitative methods. The exploratory study analyzed the most relevant CSFs that influence the adoption of BIM in public works. Although recent studies on BIM implementation have adopted this approach [21], there is a lack of studies in the context of public works. The presented methodology has four steps: (i) literature review, where the most prominent articles were selected considering their contribution to the research (quality-checks), remaining, finally, 32 articles; (ii) interviews, involving experts from academia and practice, to assess the CSFs with a 7 point Likert scale; (iii) application of the hybrid MCDM method, which were used to produce final scores for the different alternatives (CSFs) for implementing BIM in public works; (iv) CSF-based framework proposal. The details of the review data collection and interviews will be covered in Sect. 3.2, while the details of the MCDM methods will be in Sect. 3.3, and the framework will be discussed in Sect. 4.

3.2 Data Collection

In the first step, the results of the 32 articles obtained were considered to identify the CSFs for BIM implementation and the most suitable MCDM methods to be used. In the second step, a questionnaire with 42 CSFs was built and applied to a sample of seven academics and five construction industry experts to assess the CSFs. The reliability of the measurement instruments was determined by Cronbach's alpha coefficient, using SPSS version 20 software. A Cronbach's alpha of 0.958 was obtained, which shows high internal reliability and is considered acceptable. The questionnaire is available on google forms: (https://docs.google.com/forms/d/1UWTRUV8EdEqf9kTzjMBBMhdGU_yowlRmgZ_WMiuLbZ8/edit). In the third step, the CSFs were analyzed to give weight to the experts using the fuzzy AHP. For this research, the accumulated experience in working with BIM was taken into consideration, assigning the following weights: 1 for respondents with up to 0 years of experience, 2 for professionals with less than 5 years of experience, 3 for those with experience between 5 and 10 years, and 4 for those with more than 10 years of experience. Most experts claim to have less than 5 years of experience, equivalent to 60%, and the rest have between 5 and 10 years of experience, equal to 40%, working with BIM. Then, in the fourth step, the FVIKOR method was applied to rank all the CSFs.

3.3 Data Analysis

Concerning MCDM analysis, the FAHP method was applied in Microsoft Excel, while the FVIKOR method was applied through the R programming language, using the FVIKOR function available in the R package "MCDM". Unlike the classical AHP [20], in which the nine-point Saaty scale does not take into account the uncertainty associated with the decision-makers perception, the FAHP, according to [22], uses five triangular fuzzy numbers (TFN) $\left(\tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}\right)$ with the corresponding membership functions to determine the weights of the evaluation criteria [23]. The computational procedure of the method is described in five steps:

1. Compare the performance score. TFN indicate the relative strength of each pair of elements in the same hierarchy.
2. Construct the fuzzy comparison matrix. The fuzzy judgment matrix $\tilde{A}$ is constructed using triangular fuzzy numbers according to Eq. 1:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix} \tag{1}$$

3. Solve for the fuzzy eigenvalue. A fuzzy eigenvalue, $\tilde{\lambda}$, is a fuzzy number solution to Eq. 2:

$$\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x} \tag{2}$$

Where $\tilde{\lambda}_{max}$ is the largest eigenvalue of $\tilde{A}$ and $\tilde{x}$ is non-zero and of dimension $n \times 1$, fuzzy vector containing fuzzy number $\tilde{x}_i$. To perform fuzzy multiplications and additions using interval and cut-off arithmetic α, the equation $\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x}$ is equivalent to Eqs. 3 and 4:

$$\left[a^{\alpha}_{i1l}x^{\alpha}_{1l}, a^{\alpha}_{i1u}x^{\alpha}_{1u}\right] \oplus \cdots \oplus \left[a^{\alpha}_{inl}x^{\alpha}_{nl}, a^{\alpha}_{inu}x^{\alpha}_{nu}\right] = \left[\lambda x^{\alpha}_{il}, \lambda x^{\alpha}_{iu}\right] \tag{3}$$

where:

$$\begin{gathered} \tilde{A} = \left[\tilde{a}_{ij}\right], \tilde{x}^{t} = (\tilde{x}_{1,\cdots,}\tilde{x}_{n}), \\ \tilde{a}^{\alpha}_{ij} = \left[a^{\alpha}_{ijl}, a^{\alpha}_{iju}\right], \tilde{x}^{\alpha}_{i} = \left[x^{\alpha}_{il}, x^{\alpha}_{iu}\right], \tilde{\lambda}^{\alpha} = \left[\lambda^{\alpha}_{l}, \lambda^{\alpha}_{u}\right] \end{gathered} \tag{4}$$

for $0 < \alpha \leq 1$ e tudo i, j, where $i = 1, 2, \cdots, n$; $j = 1, 2, \cdots, n$.

The cut-off α is known to incorporate the confidence of the experts or decision maker(s) about their preference. The degree of satisfaction for the judgment matrix $\tilde{A}$ is estimated by the optimism index μ. A higher value of the index μ

indicates a higher degree of optimism. The optimism index is a convex linear combination defined by Eq. 5 [24].

$$\tilde{a}_{ij}^{\alpha} = \mu a_{iju}^{\alpha} + (1-\mu) a_{ijl}^{\propto}, \qquad \forall \mu \in [0,1] \tag{5}$$

When α is fixed, the following matrix can be obtained after setting the optimism index, μ, to estimate the degree of satisfaction, as indicated in Eq. 6, where the eigenvector is calculated by fixing the value μ and identifying the maximum eigenvalue.

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12}^{\alpha} & \cdots & \tilde{a}_{1n}^{\alpha} \\ \tilde{a}_{21}^{\alpha} & 1 & \cdots & \tilde{a}_{2n}^{\alpha} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{a}_{n1}^{\alpha} & \tilde{a}_{n2}^{\alpha} & \cdots & 1 \end{bmatrix} \tag{6}$$

4. Calculate the consistency ratio (CR), in which it must be less than or equal to 0.10 for an acceptable comparison, and is calculated according to Eq. 7:

$$CR = CI/RI, \quad \text{where } CI = (\lambda_{max} - n)/(n-1) \tag{7}$$

5. Priority Aggregation. The final step in deriving criteria weights is to aggregate the local priorities obtained at different levels of the decision hierarchy into overall composite priorities.

The fuzzy VIKOR method was developed to solve problems in a fuzzy environment, where both criteria and weights can be fuzzy sets [25]. A seven-point TFN scale is used to deal with imprecise numerical quantities, one of their main advantages is their ability to obtain a solution with the highest utility trade-off.

As presented in the previous section, the respondents were grouped into levels of experience. Table 1 presents the triangular fuzzy scale for the levels mentioned.

Extending the method to FVIKOR can help in situations with uncertain conditions [26]. The FVIKOR method is described in nine steps:

Table 1 Fuzzy scale of experience levels

Experience level	Triangular fuzzy scale		
Level 1 (N1)	0.00	0.00	0.50
Level 2 (N2)	0.00	0.50	0.75
Level 3 (N3)	0.50	0.75	1.00
Level 4 (N4)	0.75	1.00	1.00

1. Determine the ideal $\tilde{f}_i^* = \left(l_i^*,\ m_i^*, r_i^*\right)$ and the nadir $\tilde{f}_i^0 = \left(l_i^0,\ m_i^0, r_i^0\right)$ values of all criterion functions, $i = 1, 2, \ldots$, n as indicated in the Eqs. 8 and 9:

$$\tilde{f}_i^* = \underset{j}{\mathrm{MAX}} \tilde{f}_{ij}, \quad \tilde{f}_i^0 = \underset{j}{\mathrm{MIN}} \tilde{f}_{ij} \quad \text{for} \quad i \in I^b \tag{8}$$

$$\tilde{f}_i^* = \underset{j}{\mathrm{MIN}} \tilde{f}_{ij}, \quad \tilde{f}_i^0 = \underset{j}{\mathrm{MAX}} \tilde{f}_{ij} \quad \text{for} \quad i \in I^c \tag{9}$$

2. Compute the normalized fuzzy difference $\tilde{d}_{ij}$, $j =$ 1,..,J $i = 1, 2, \ldots, n$, as indicated by Eqs. 10 and 11:

$$\tilde{d}_{ij} = \frac{\left(\tilde{f}_i^* \ominus \tilde{f}_{ij}\right)}{\left(r_i^* - l_i^0\right)} \text{ for } i \in I^b \tag{10}$$

$$\tilde{d}_{ij} = \frac{\left(\tilde{f}_{ij} \ominus \tilde{f}_i^*\right)}{\left(r_i^0 - l_i^*\right)} \text{ for } i \in I^c \tag{11}$$

3. Compute $\tilde{S}_j = \left(S_j^l, S_j^m, S_j^r\right)$ and $\tilde{R}_i^* = \left(R_j^l, R_j^m, R_j^r\right)$, $j = 1, 2, \ldots, J$ by the relations, according to Eqs. 12 and 13:

$$\tilde{S}_j = \sum_{i=1}^{n} \otimes \left(\underset{\mathrm{j}}{\tilde{\mathrm{w}}} \otimes \underset{ij}{\tilde{\mathrm{d}}}\right) \tag{12}$$

$$\tilde{R}_j = \underset{i}{\mathrm{MAX}} \left(\tilde{w}_j \otimes \underset{ij}{\tilde{\mathrm{d}}}\right) \tag{13}$$

where $\tilde{S}$ is a fuzzy weighted sum, $\tilde{R}$ is a fuzzy operator MAX (To express an imprecise value, as "about m"("approximately m"), the TFN $\tilde{N} = (l, m, r)$ is used, associated with the membership triangular function defined as follows: $\mu_{\tilde{N}}(x) = \left\{ \begin{array}{ll} \frac{(x-l)}{(m-l)}, & x \ll m \\ \frac{(r-x)}{(r-m)}, & x \gg m \\ 0, & x \notin [l, r] \end{array} \right\}$ The membership function $\mu(x)$ denotes the degree of truth that the fuzzy value is equal to x within the real interval $[l, r]$. The fuzzy number $\tilde{N}$ has the core m with $\mu(m) = 1$ and the support $[l, r]$), $\tilde{w}_j$ are the weights of criteria, expressing the DM's preference as the relative importance of the criteria.

4. Compute the values $\tilde{Q}_j = \left(\tilde{Q}_j^l, \tilde{Q}_j^m, \tilde{Q}_j^r\right)$, $j = 1, 2, \ldots, J$ by the relation, as indicated in Eq. 14:

$$\tilde{Q}_j = \frac{v\left(\tilde{S}_j \ominus \tilde{S}^*\right)}{\left(S^{or} - S^{*l}\right)} \oplus \frac{(1-v)\left(\tilde{R}_j - \tilde{R}^*\right)}{\left(R^{or} - R^{*l}\right)} \tag{14}$$

where: $\tilde{S}^* = \underset{j}{\text{MIN}} \tilde{S}_j$, $S^{or} = max_j S_j^r$, $\tilde{R}^* = \underset{j}{\text{MIN}} \tilde{R}_j$, $R^{or} = max_j R_j^r$, and v is introduced as a weight for the strategy of "the majority of criteria" (or "the maximum group utility"), whereas $1 - v$ is the weight of the individual regret. These strategies could be compromised by $v = 0.5$, and here v is modified as $v = (n + 1)/2n$ (from $v + 0.5(n - 1)/n = 1$) since the criterion (1 from n) related to R is included in S, too. The best values of S and R are denoted by $\tilde{S}^*$ and $\tilde{R}^*$ respectively.

5. "Core" ranking, rank the alternatives by sorting the core values Q_j^m, $j = 1, 2, \ldots,$ J in decreasing order. The obtained ordering is denoted by $\{A\}_{Q^m}$.
6. Fuzzy ranking

   The jth ranking position in $\{A\}_{Q^m}$ of an alternative $A^{(i)}$, $j = 1, 2, \ldots, J$ is confirmed if $\underset{k \epsilon J^i}{\text{MIN}} \tilde{Q}^{(k)} = \tilde{Q}^{(j)}$ where $J^j = \{j, j + 1, \ldots, J\}$ and $\tilde{Q}^k$ is the fuzzy merit of the alternative A^k at the kth position in $\{A\}_{Q^m}$. Confirmed ordering represents "exact"

   Fuzzy ranking $\{A\}_{\tilde{Q}}$, although the set $\{A\}_{\tilde{Q}}$ could not be complete ordering (it may be partially ranking).
7. Defuzzification of $\tilde{S}_j, \tilde{R}_j, \tilde{Q}_j, j = 1, 2, .., J$ by the relations, as indicated in Eq. 15.

$$Crisp\left(\tilde{N}\right) = \frac{(2m + l + r)}{4} \tag{15}$$

   Here the defuzzification method "2nd weighted mean" is applied to convert a fuzzy number into the crisp score
8. Rank the alternatives, sorting by the crisp values S, R, and Q in decreasing order. The results are three ranking lists $\{A\}_S$, $\{A\}_R$, $\{A\}_Q$.
9. Propose as a compromise solution the alternative ($A^{(1)}$) which is the best ranked by the measure $Q(in\ \{A\}_Q)$ if the following two conditions are satisfied:

   C1:"Acceptable Advantage": $Adv \geq DQ$, where: $Adv = \frac{\left[Q\left(A^{(2)}\right) - Q\left(A^{(1)}\right)\right]}{\left[Q\left(A^{(J)}\right) - Q\left(A^{(1)}\right)\right]}$ is the advantage rate of the alternative $A^{(1)}$ ranked first, $A^{(2)}$ is the alternative with the second position in $\{A\}_Q$, and the threshold $DQ = \frac{1}{(J-1)}$.

   C2: "Acceptable Stability in decision making": The alternative A^1 must also be the best ranked by S or/and R. If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

   - Alternatives $A^{(1)}$ and $A^{(2)}$ if only the condition C2 is not satisfied, or
   - Alternatives $A^{(1)}$, $A^{(2)}$,..., $A^{(M)}$ if the condition C1 is not satisfied; $A^{(M)}$ is determined by the relation $Q(A^M) - Q(A^1) <$ DQ for maximum M (the positions of these alternatives are "in closeness").

4 Results and Discussion

This section presents the obtained results, the weights of the experts, the rank of CSFs for BIM implementation in public works, and the proposed framework. First, the experts with the highest importance were ranked considering pairwise comparisons using the nine-point scale of Saaty. The results of the FAHP indicated that the expert 'E5' is the most important followed by the 'E3' (see Table 2). As this is a group MCDM problem, from a multi-decision perspective, where each expert represents a criterion of the decision matrix. The experience of the experts (criteria) provided the weights for the criteria using FAHP, and then, the performance (level of importance) of each CSF for BIM implementation regarding each criterion was used to apply FVIKOR and obtain the rank of CSFs. Median was used to analyze the most important CSFs.

4.1 Weight Allocation with FAHP

A comparison was made between the experts regarding the level of experience (N1, N2, N3, and N4) shown in Table 1. In this step, the geometric mean of the fuzzy comparison value ($\tilde{r}_1$) was calculated, also obtaining the Power Inverter (P-1) and increasing rank (INCR), as shown in Table 2.

We proceeded to calculate the fuzzy weights for each expert, and the order of importance of the experts considered the pairwise comparisons using a preference scale, which will contribute to the selection of CSFs for BIM implementation in public works.

Table 2 Fuzzy weights and ranking of experts

Fuzzy geometric mean				Weight fuzzy					
CRI	r_i			Wi			Mi	Normalized weight (Ni)	Rank
E1	0.000	0.869	0.960	0.000	0.096	0.138	0.076	0.135	5
E2	0.869	1.060	1.000	0.076	0.118	0.144	0.112	0.200	4
E3	0.921	1.042	1.150	0.081	0.116	0.166	0.124	0.221	2
E4	0.960	1.000	1.131	0.084	0.111	0.163	0.122	0.217	3
E5	1.000	1.000	1.179	0.088	0.111	0.170	0.127	0.226	1
Total	3.750	4.971	5.420						
P (−1)	0.267	0.201	0.185						
INCR	0.088	0.111	0.144						

Table 3 Ranking of CSFs with FVIKOR

	Alternatives	S	R	Q	Ranking
CSF2	Ease of learning in BIM-based programs	0.09	0.05	0.03	**3**
CSF5	Availability of performance, usability, and financial information at the management stage with BIM	0.08	0.05	0.02	**1**
CSF8	Inclusion of BIM in the competitive environment of the industry	0.09	0.06	0.06	**5**
CSF11	Availability of return on investment	0.09	0.05	0.03	**4**
CSF14	Knowledge and demands of clients about BIM technology	0.12	0.06	0.08	**8**
CSF20	Having the necessary information and technological infrastructure for BIM applications within the institution	0.08	0.05	0.02	**2**
...	...	...	...	...	...

4.2 Ranking with FVIKOR and Framework Proposal

The hybrid FMCDM approach provided the rankings that made it possible to select the CSFs for the implementation of BIM in public works, according to the preference of the group of decision-makers. The results of the FVIKOR analysis are presented in Table 3.

Both FVIKOR conditions "Acceptable advantage condition" and "Acceptable stability in decision making" were fulfilled, and the alternative CSF5 has one of the best rankings for S and/or R. Consequently, the final ranking was CSF5 $\succ$ CSF20 $\succ$ CSF2 $\succ$ CSF11 $\succ$ CSF8, identified as the five most important CSFs for BIM implementation in public works. The ranking also allows knowing which are the main factors within each perspective (local) and in general (global), which in practice represents the level of importance of good practices for the digitization of construction in the public sector. Moreover, for the selection of factors according to their influence on the BIM perspective, we used the median based on the "Q" measure of the CSFs as threshold. Thus, from the 42 CSFs, just 21 remained (with a median bellow 20.8). The results represent the CSF with the highest order of importance, with CSF31 being the lowest and CSF5 the most critical. In addition, a framework was developed according to the BIM CSFs benchmarks (best alternatives), grouping the factors in order of importance, in which the most important CSFs were identified according to six BIM perspectives [27] (see Fig. 1). The analysis of the BIM perspectives according to the CSFs could reveal that there are many perspectives. For example, processes and operation (e.g. CSF5), Information and Technology (e.g. CSF20); Culture and People (e.g. CSF2); Finance (e.g. CSF11); Supply Chain (e.g. CSF8), and Legal (e.g. CSF29) [28, 29].

Moreover, the dynamic capabilities view (DCV), a source of "variation" for technological innovation and adaptation among firms [30], can bridge CSFs to respond to the dynamic conditions of construction digitization in the public sector by combining knowledge readily to effectively coordinate or reallocate internal and

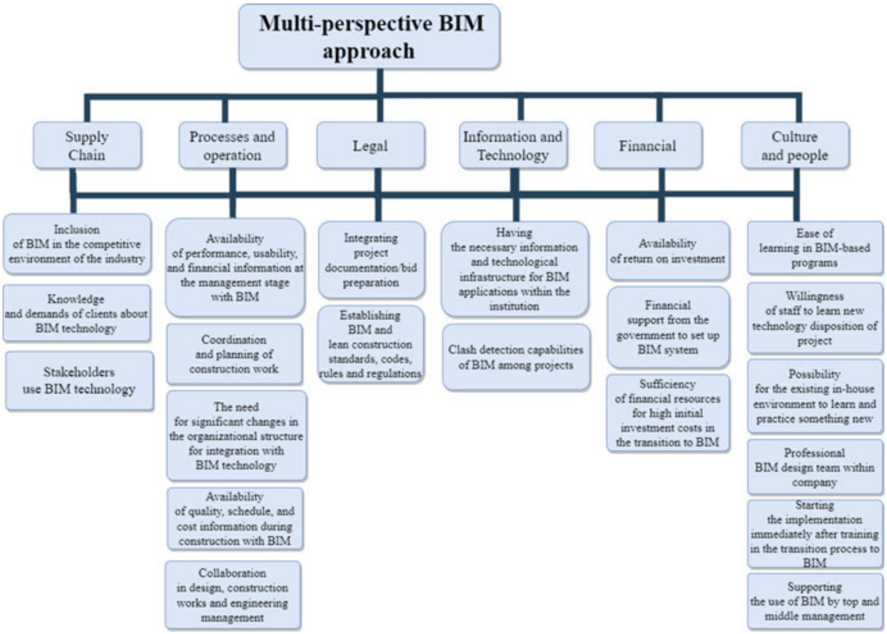

Fig. 1 Multi-perspective framework for implementing BIM in public works

external resources to improve the skills that are needed according to BIM strategies. Strong dynamic capabilities help an organization to be innovative, successful, and resilient, particularly in the presence of technological and political turbulence and deep uncertainty [31].

5 Conclusions

The identification and selection of CSFs have been considered necessary for using appropriate digital methods and are drivers for successful BIM implementation. Therefore, this research reviewed a significant number of articles to identify CSFs for BIM implementation. The FAHP and FVIKOR methods, both robust with fuzzy logic, were used to eliminate uncertainty in the results. This study provides a list of priority CSFs that require significant attention in BIM implementation in public works. The result provides more information on selecting CSFs for BIM implementation in public works based on best practices. The proposed framework can be more effective and efficient than conventional approaches as it reveals the best alternatives among CSFs for BIM implementation in public works.

This study evaluates the importance of the identified factors, which from the perspective of DCV can add more value to construction digitalization. So that despite the identification of multiple BIM capabilities for construction digitalization, the research also focuses on prioritizing the most important ones. It is shown that the integration of FMCDM can be used as an evaluation tool to prioritize the success factors in the early stage of construction digitization. FAHP-FVIKOR combination can help the decision maker to build a solid evaluation basis. BIM methodology is developing rapidly, but it's effective use and practical application are not without limitations. A future study is suggested to apply the research with a larger sample and test the framework with different public sector companies.

References

1. Eastman, C.M., Eastman, C., Teicholz, P., Sacks, R., Liston, K.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. John Wiley & Sons (2011)
2. Chen, Q., García de Soto, B., Adey, B.T.: Construction automation: Research areas, industry concerns and suggestions for advancement. Automation in Construction. 94, 22–38 (2018)
3. Kassem, M., Succar, B.: Macro BIM adoption: Comparative market analysis. Automation in Construction. 81, 286–299 (2017)
4. Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C., O'Reilly, K.: Technology adoption in the BIM implementation for lean architectural practice. Automation in Construction. 20, 189–195 (2011)
5. Morlhon, R., Pellerin, R., Bourgault, M.: Defining building information modeling implementation activities based on capability maturity evaluation: A theoretical model. International Journal of Information Systems and Project Management. 3, 51–65 (2015). https://doi.org/10.12821/ijispm030103
6. Park, J.-W., Kim, S.-C., Lee, S.-S., Song, H.-Y.: Suggesting Solutions when Applying Building Information Modeling (BIM) to the Korean Construction Industry through Case Studies. Journal of the Korea Institute of Building Construction. 9, 93–102 (2009)
7. Rockart, J.F.: Chief executives define their own data needs. Harv Bus Rev. 57, 81–93 (1979)
8. Lu, W., Shen, L., Yam, M.C.: Critical Success Factors for Competitiveness of Contractors: China Study. J. Constr. Eng. Manage. 134, 972–982 (2008)
9. Belay, S., Goedert, J., Woldesenbet, A., Rokooei, S.: Enhancing BIM implementation in the Ethiopian public construction sector: An empirical study. Cogent Engineering. 8, 1886476 (2021)
10. Ullah, K., Witt, E., Lill, I., Banaitienė, N., Statulevičius, M.: Readiness assessment for BIM-based building permit processes using Fuzzy-COPRAS. Journal of Civil Engineering and Management. 28, 620–633 (2022)
11. Jonathan, G.M.: Digital Transformation in the Public Sector: Identifying Critical Success Factors. In: Themistocleous, M. and Papadaki, M. (eds.) Information Systems. pp. 223–235. Springer International Publishing, Cham (2020)
12. Gil-García, J.R., Pardo, T.A.: E-government success factors: Mapping practical tools to theoretical foundations. Government Information Quarterly. 22, 187–216 (2005)
13. Lee, S.M., Eom, H.B.: Multiple-criteria decision support systems: The powerful tool for attacking complex, unstructured decisions. Systems Practice. 3, 51–65 (1990)
14. Xu, Z., Liao, H.: Intuitionistic Fuzzy Analytic Hierarchy Process. IEEE Transactions on Fuzzy Systems. 22, 749–761 (2014)
15. Liao, H., Xu, Z.: A VIKOR-based method for hesitant fuzzy multi-criteria decision making. Fuzzy Optim Decis Making. 12, 373–392 (2013)

16. Aminrad, A., Miehosseini, M., Ehsanifar, M., Zeighami, E.: An Integrated Approach for Evaluation Applications of Building Information Modeling Based on Rough Number. Journal of System Management. 0, (2022)
17. Lam, W.S., Lam, W.H., Jaaman, S.H., Liew, K.F.: Performance Evaluation of Construction Companies Using Integrated Entropy–Fuzzy VIKOR Model. Entropy. 23, 320 (2021)
18. Hatefi, S.M., Heidari, A.: Evaluating construction projects based on the risk factors by using an integrated fuzzy AHP and fuzzy VIKOR model. Journal of Structural and Construction Engineering. 5, 156–175 (2019)
19. Opricovic, S.: Multicriteria optimization of civil engineering systems, (1998)
20. Pamučar, D., Stević, Ž., Sremac, S.: A New Model for Determining Weight Coefficients of Criteria in MCDM Models: Full Consistency Method (FUCOM). Symmetry. 10, 393 (2018)
21. Ikram, M., Zhang, Q., Sroufe, R.: Developing integrated management systems using an AHP-Fuzzy VIKOR approach. Business Strategy and the Environment. 29, 2265–2283 (2020)
22. Ayağ, Z.: A fuzzy AHP-based simulation approach to concept evaluation in a NPD environment. IIE Transactions. 37, 827–842 (2005)
23. Machado, E., Scavarda, L.F., Caiado, R.G.G., Thomé, A.M.T.: Barriers and Enablers for the Integration of Industry 4.0 and Sustainability in Supply Chains of MSMEs. Sustainability. 13, 11664 (2021)
24. Lee, C.W., Kwak, N.K.: Information resource planning for a health-care system using an AHP-based goal programming method. Journal of the Operational Research Society. 50, 1191–1198 (1999)
25. de Paula Vidal, G.H., Caiado, R.G.G., Scavarda, L.F., Ivson, P., Garza-Reyes, J.A.: Decision support framework for inventory management combining fuzzy multicriteria methods, genetic algorithm, and artificial neural network. Computers & Industrial Engineering. 174, 108777 (2022)
26. Opricovic, S.: Fuzzy VIKOR with an application to water resources planning. Expert Systems with Applications. 38, 12983–12990 (2011)
27. Blampain, F., Bricogne, M., Eynard, B., Bricogne, C., Pinon, S.: Digital solution for planning and management of construction site operations: a proposal of BIM-based software architecture and methodology. (2022)
28. Lins, M.G., Zotes, L.P., Caiado, R.: Critical factors for lean and innovation in services: from a systematic review to an empirical investigation. Total Quality Management & Business Excellence. 32, 606–631 (2021)
29. Nascimento, D.L. de M., Goncalvez Quelhas, O.L., Gusmão Caiado, R.G., Tortorella, G.L., Garza-Reyes, J.A., Rocha-Lona, L.: A lean six sigma framework for continuous and incremental improvement in the oil and gas sector. International Journal of Lean Six Sigma. 11, 577–595 (2019)
30. Vogel, R., Güttel, W.H.: The Dynamic Capability View in Strategic Management: A Bibliometric Review. International Journal of Management Reviews. 15, 426–446 (2013)
31. Teece, D., Leih, S.: Uncertainty, Innovation, and Dynamic Capabilities: An Introduction. California Management Review. 58, 5–12 (2016)

Evaluation of the Implementation of Recycling, Reuse, Remanufacturing, and Reduction in the Reverse Chain of Brazilian WEEE: Survey in Electronics Companies

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Abstract Due to territorial expansion, national requirements for electronics manufacturers and importers to dispose of waste electrical and electronic equipment (WEEE) have resulted in considerable difficulties in establishing a WEEE reverse chain in Brazil. Adding to the complexity is the need to implement a circular economy (CE) in this reverse chain, an important aspect of a company's external competitiveness. In this context, this study aims to evaluate the reverse chain flow of WEEE for CE and its action of recycling, reuse, remanufacturing and waste reduction of WEEE in Brazil by means of Friedman test and Simes-Hochberg multiple comparisons. It was concluded that, in addition to immediately addressing complex problems, the initial manager's strategy was to take recycling and remanufacturing actions due to short-term currency revaluation.

Keywords Circular economy · WEEE · Reverse chain · Reverse logistic

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1 Introduction

Growth in the production and obsolescence of electronic equipment has resulted in a 3–5% annual increase in waste electrical and electronic equipment (WEEE) [1]. WEEE are important not only because of the scarcity and value of the materials they contain, but also because they contain materials that can negatively impact the environment if not disposed of properly and lose additional resources through waste recycling [2]. From a socio-economic point of view, the disposal of WEEE represents an economic opportunity due to the raw materials contained in this type of waste, such as plastics, iron, aluminum, steel, gold, silver, bronze, copper, platinum and palladium [3].

In Brazil, Federal Law 12.305/2010 establishes the National Solid Waste Policy (PNRS) to manage the WEEE recycling logistics system, which defines the shared responsibilities of the participants in the WEEE recycling chain. It refers, therefore, to reverse logistics as a tool for economic and social development, covering actions, procedures and means aimed at collecting and returning solid waste for reuse in the production cycle or in environmentally appropriate destinations [4]. Reverse logistics can be understood as the process of efficiently and cost-effectively planning, implementing and controlling the flow of raw materials, work-in-process, finished product and related information from the point of consumption to the point of origin with the purpose of recovering the amount spent on manufacturing or disposing of this product properly [5].

The shortage of reverse chain of WEEE based on circular economy concepts is another relevant aspect. The circular economy is an economic model based on the reduction, reuse, recovery and recycling of raw materials for a better use of natural resources, handling them in a closed circuit [6]. Thus, Shittu [1] point out in their research that few companies consider reverse logistics of WEEE as a necessary step to obtain CE for resource efficiency, as the main reason for this initiative is to close the life cycle in the reverse chain of WEEE until the end of shelf life of products [6].

In this context, the objective of this study is to evaluate, through the Friedman Test and Simes-Hochberg multiple comparisons, the actions adopted for reverse logistics for recycling, reuse, remanufacturing and reduction of WEEE in Brazil, promoting CE.

2 Systematic Literature Review and Hypothesis Development

2.1 *WEEE Reverse Logistics/Chain Promoted Recycling, Reuse, Reduction and Remanufacturing*

Recycling, reuse, reduction and remanufacturing actions are validated in the content analysis of WEEE logistics/reverse chain items.

Reverse logistics leads to CE as ***recycling*** is implemented, leading to the recovery of materials and precious metals in closed loops [7, 8] in industrial symbiosis [9], this facilitates compliance with environmental legislation [10–12] as well as consumer participation in the recycling and return of WEEE reverse chains [6]. Notably, the legalization of the formal sector in relation to the informal sector is made possible by legislation and tax incentives [13], as the informality of the recycling sector negatively contributes to the reverse chain from an economic point of view, despite mitigating hazardous substances [14]. The increase in operating capacity and the improvement in working conditions and safety has integrated the formal and informal sectors of recycling through the development of the extended manufacturer responsibility project [15]. However, the increased need for recycling is generated by the adoption of EEE collection centers, which requires investment in technologies, but also an increase in economic gain [16]. The location of recycling centers, collection routes and disposal of end-of-life WEEE should also be evaluated in order to recover secondary raw material, save energy and mitigate environmental impacts [17]. Thus, synergy between recovery centers and manufacturers is necessary so that the WEEE collection, recovery and dismantling processes generate CE with revenue [18], examples such as plastic recycling and recovery [19, 20] and recycling of laptop waste, in addition to mitigating environmental impacts, promote CE [21]. It should be noted that an economically viable solution is outsourcing transport to reverse logistics operators [22].

WEEE ***reuse*** was also implemented in the adoption of reverse logistics/chain resulting in CE, so for the products to be reintroduced in the market, it is recommended to cover CE principles in the generation and production of EEE and WEEE management with clear definitions of standards of reuse [1], including aspects of waste, qualification, cost, available labor, technological adequacy for reuse, aiming to reduce hazardous substances [8] in the reuse of WEEE from cell phones in the production of by-products [14], involving the reuse of secondary plastic from WEEE in CE [19, 20] the reuse of laptop components [21], and recycling and recovery of precious metals [16]. It should be noted that the reuse of WEEE is encouraged by the informal market, contributing not only to extending the useful life of the products, but also to the financial support of its collectors [13].

In other studies, CE was the result of the adoption of reverse logistics/chain due to the implementation of WEEE ***remanufacturing***, in which CE coverage is recommended in the generation, production and management of WEEE, assuming the remanufacturing of products for reintroduction in the market [1], with the purpose of marketing remanufactured EEE [8, 14, 16], for example the business strategy for the practice of remanufacturing for laptops [21]. The circularity of the material is optimized through remanufacturing, which is also responsible for using waste to produce new EEE [18]. On the other hand, the high cost of using materials recovered from WEEE causes a lack of incentives for remanufacturing [11].

In addition, other studies have shown that CE has ***reduced*** material usage because of adopting reverse/chain logistics. Thus, reducing the use of materials [23] allowed products and WEEE to be used for as long as possible through actions such as: (i) adopting a transport strategy, (ii) circular product design, and (iii) consumer participation. The use of recycled materials has also helped to reduce the consumption of virgin raw materials [16, 17], for example plastic recycling and recovery [19, 20]. Circularity and reduction in the use of materials is also promoted by the adoption of industrial symbiosis [9], this occurs when recycling and remanufacturing are used, as the use of remanufactured products reduces the consumption of new or virgin materials [14, 21].

In this context, research has shown that CE was implemented through recycling, reuse, remanufacturing and reduction of materials as a result of the adoption of logistics/reverse chain. Thus, the circularity of waste in a closed cycle becomes the objective of the EC from the perspective of the reverse chain of WEEE, proposing the maximum reuse of waste in production and/or sale to the secondary market. Thus, the fourth hypothesis is suggested:

H1: WEEE reverse logistics/chain promotes CE by generating: H1a: reduction of material consumption; H1b: waste reuse; H1c: waste recycling and H1d: remanufacturing of EEE products.

3 Research Methodology

A cross-sectional survey was used to identify the best reverse chain management system for WEEE. A descriptive and exploratory approach was adopted to collect data, which were searched only once [24, 25].

Quantitative and qualitative research methods can work together to provide a better understanding of a phenomenon. This is what Yin [26] suggests can be done by using both approaches together.

Access to documented data, such as "PNRS" and "Sectorial Agreement for the Implementation of the Brazilian System of Reverse Logistics for Electrical and Electronic Products", describes the objectives of the study as exploratory, using a qualitative and documental approach to try to provide insights into a subject that is still little known. Understood and containing many hypotheses with an overview of a specific topic of interest [27, 28].

G*Power 3.1.9.7 was used to assess the sample size using statistical software. The methods recommended by Cohen [29] were implemented in the statistical software G*Power when analyzing the relationship between a sample's mean and internal variances. This is referred to as the f test, and it demonstrates whether there is a significant difference between the sample means. G*Power determines the size of the effect by using three parameters: 0.02, 0.15 and 0.35. These correspond to small, medium, and large effects, respectively [29]. In the present study, the value of 0.35 was adopted for the effect size (f^2). The minimum Survey sample size of 84 responses was determined using G*Power software.

Experts in the researched field first tested the hypothesis with a pilot study according to Forza [24]. Ten representatives of EEE manufacturers and importers (managers and supervisors of corporate sustainability areas) who participated in the negotiation of the reverse chain management of WEEE in São Paulo, Brazil, and who know the participants (manufacturers, managers, recyclers) in depth, were interviewed, in addition to committing to comply with the "Sectorial Agreement for the Implementation of the WEEE Reverse Logistics System". This step was personally accompanied by the authors to contextualize the study and remove doubts.

In the next step, the researchers sent a questionnaire to a larger group of people. This eliminates any survey responses that are unrelated to the study [24]. The Google Forms platform allowed the collection of responses to questionnaires from 91 experts sent by email.

After receiving the answers to the questionnaires, the data were collected, processed, and submitted to statistical tests. A Friedman test followed by a Simes-Hochberg multiple comparison test was used to assess each actor's level of importance in reverse chain management to promote a circular economy The Friedman Test, as suggested by Siegel and Castellan [30] and outlines in further detail by them, is a non-parametric measurement intended for use in the creation of test modules for testing data measured as ordinal variables. It should cover three or more groups of analyses. To confirm the rejection of the null hypothesis by the Friedman test, a separate test is needed that compares several groups and finds significant differences between their results. This is necessary to identify which groups have statistically different means and are not rejected. A Simes-Hochberg multiple comparison test is used to assess differences between two groups. This test examines "two by two" the results of each group, looking for significant differences between the tested groups [31]. The Action Stat 3.7 software was used to perform statistical evaluations.

4 Results

The supposed results of Question 1 concern the reverse chain of WEEE management with the objective of promoting CE in Brazil, seeking to assess the extent to which the "4Rs" of CE are applied in practice. A Likert scale from 1 (not important) to 7 (extremely import) was used to determine importance for each R (Reduce, Reuse, Remanufacture, and Recycle). The descriptive analysis of Fig. 1 shows that the "Degree of Importance" for R, the most representative answer, is recycling. Next comes remanufacturing, followed by reuse and reduction. These data show that reuse and reduce with little expressive values.

In the non-parametric statistical analysis referring to H1 (Fig. 2), the "P-value $= 2.00656 \times 10^{-58}$". When examining the Friedman test results, the P-value is less than 0.05 and indicates that the null internal hypothesis should be rejected. Therefore, the results of this test indicate that there are statistically significant differences between at least two groups of elements among the 4R's of the CE with 95% confidence.

Then, the "Simes-Hochberg Test" was used, which evaluated the assumption of the null hypothesis that the means of the results of each group are equal. This was

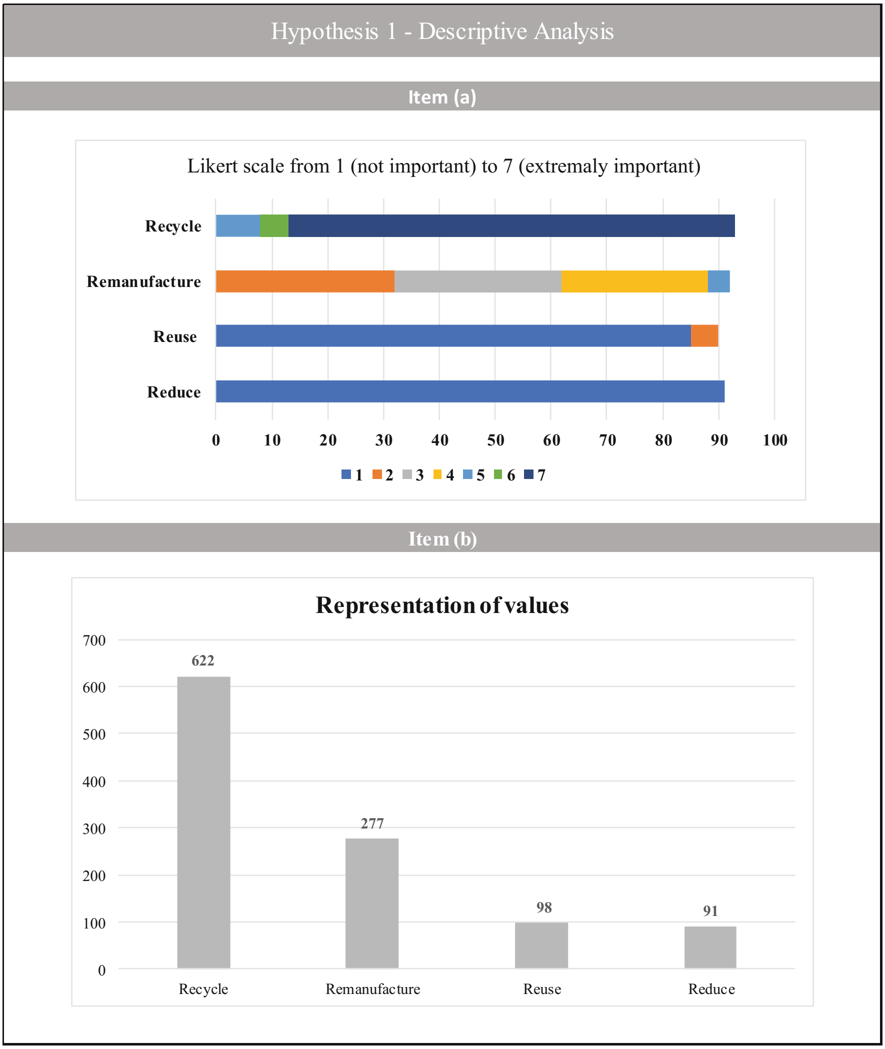

Fig. 1 Descriptive analysis of Hypothesis 1 (Reduce, Reuse, Remanufacture, Recycle)

done with multiple comparisons, evaluating the differences between each pair of values (with no statistically significant difference).

The existence of statistically represented differences between all combinations ("Recycle and Reduce", "Recycle and Remanufacture", "Recycle and Reuse", "Remanufacture and Reduce", "Remanufacture and Reuse") was confirmed by the "Simes-Hochberg" test when the null hypothesis was rejected for each combination according to the results "P-value" less than 0.05. However, for the combination (Reuse and Reduce), the "P-value"result was above 0.05. Thus, the multiple comparisons test proves that "there are no statistically significant differences" between

Hypothesis 1: Non-parametric Statistical Analysis

Step 1: Friedman Test

Methods: Friedman rank sum test by Action Stat 3.7

Friedman Test	
Elements	**Results**
Friedman chi-square	155.4457831
Degrees of freedom	2
P-value	1.78945E-34

Multiple Comparison Table - FWER (Simes-Hochberg)				
Players compared	**Observed diference**	**Results**	**P-value**	**P-value adjusted**
Manager - Manufacturer	391	8.969116732	1.50156E-08	3.00312E-08
Manufacturer - Recycler	47	2.297872882	0.054245504	0.054245504
Manager - Recycler	438	11.266989610	3.28626E-14	9.85878E-14

Grouping Table		
Players	**Sum (rank)**	**Groups**
Manager	614	A
Manufacturer	223	B
Recycler	176	C

Step 2: Conceptual Structure

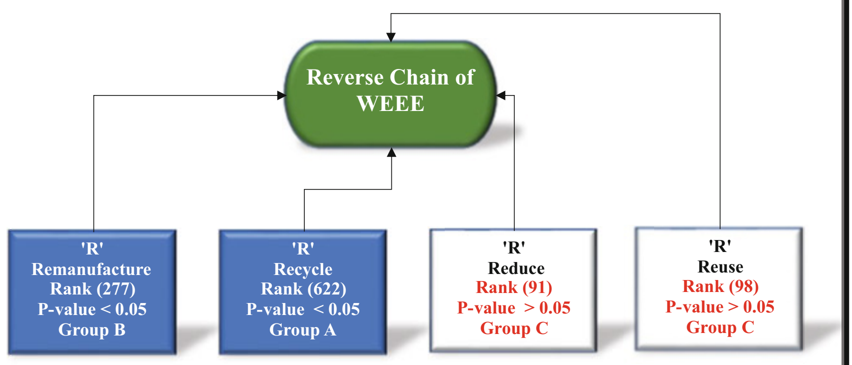

Fig. 2 ‘Non-parametric’ statistical analysis of Hypothesis 1

these elements. When sorting all analyzed elements, the grouping table (Fig. 2) displays their ordered ranking with higher weights going to Recycle, Remanufacture, Reuse, and Reduce.

The greater presence of R (Recycle) in this study for the reverse chain of WEEE points to an emphasis on the importance of recycling electronic waste, encouraging the reuse of secondary raw materials. Recycled materials reduce the consumption of virgin raw materials, in addition to avoiding the extraction of raw materials from nature. This is CE’s biggest contribution to the environment.

When considering the operation and implementation of "R" (Remanufacturing) in the reverse chain of WEEE in Brazil, recovery of components, manufacturing of modules and new electronic products are rarely practiced. On the other hand, in terms of implementing the reverse WEEE chain in Brazil, there are no practices related to "R" (Reduce) and "R" (Reuse).

This discovery reveals that the creation of new products with lower ecological and energy costs through strategic planning can be carried out using materials labeled as electronic waste, which are part of the 'R' (Reduce). This information also does not apply to the 'R' (Reuse) of the reverse chain of Brazilian WEEE, as practical strategies are still employed to extend the useful life of a product in terms of operational use and within functional standards.

Thus, recycling is a more representative action in relation to reuse, as it involves the use of recycled secondary materials in the recycling of WEEE. By using recycled secondary materials instead of natural raw materials, this reduces the need to extract virgin raw materials from nature, as well as contributing to CE. It was also observed that remanufacturing involves the recovery and reuse of parts, modules, and the creation of new products through secondary reuse processes. This allows components to contribute to CE through product improvement and prevention of inappropriate disposal of WEEE in the environment. On the other hand, in the reverse chain of Brazilian WEEE, reduction and reuse is not applied in terms of EEE design for less consumption or use of materials, in addition to extending the useful life of obsolete EEE. However, some users are privileged with the application of the R's (Reduce and Reuse) converging with the electronics production chain, but not with the reverse WEEE chain. Although several scientific journals have articles detailing reuse [8], remanufacturing [14, 18, 32] and recycling practices [10, 12, 33], as part of the '4Rs' of CE, there is no research evaluating the practical applications of the '4Rs' of CE (Remanufacture, Recycle, Reduce and Reuse) in the reverse chain of WEEE. Furthermore, this finding corroborates the results of Bressanelli et al. [34], which explains which strategies need to be implemented in the reverse WEEE chain; including running CE and implementing all 4R methods to maximize product value before end of life.

5 Conclusion

This study brings important contributions to the theory and practice of electronic waste management. When evaluating the application of the 4R's of the Circular Economy (CE) in the reverse chain of Waste Electrical and Electronic Equipment (WEEE), the study identified that, despite the adoption of recycling and remanufacturing, reduction and reuse actions were not observed.

A possible explanation for this result is that, by opting to carry out reduction and reuse actions, the manufacturer itself waives the need to hire a waste manager with a focus on recycling and remanufacturing as central objectives. However, the study points out that it is important for organizations to be aware of actions to reuse and reduce material consumption, even when outsourcing WEEE management to a waste management company.

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In summary, this study highlights the importance of adopting EC's 4R's in electronic waste management, and guides organizations to consider not only recycling and remanufacturing, but also reduction and reuse actions in the reverse WEEE chain. With this, it is expected that the management of electronic waste can be more efficient, sustainable and in line with the principles of the Circular Economy.

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References

1. Shittu et al. Global E-waste management: Can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and future challenges. Waste Management, 120, 549–563, (2021).
2. Forti et al. The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential, (2020).
3. ABDI – Agência Brasileira de Desenvolvimento Industrial. Logística reversa de equipamentos eletroeletrônicos – análise de viabilidade técnica e econômica. Brasília, novembro de 2013. Available online: http://www.resol.com.br/textos/dwnl_1362058667.pdf, last accessed 2022/10/25.
4. BRASIL. Política Nacional de Resíduos Sólidos - PNRS. Lei n. 12.305, de 02 de agosto de 2010. Diário Oficial da República Federativa do Brasil, Poder Executivo, Brasília. Distrito Federal. Available online: http://www.planalto.gov.br/ccivil_03/Ato2007-2010/2010/Lei/L12305.htm, last accessed 2022/10/25.
5. Rogers, D. S., & Tibben-Lembke, R. S. Going backwards: reverse logistics trends and practices. The University of Nevada, Reno. Center for Logistics Management, Reverse Logistics Council, 2-33, (1998).
6. Isernia et al. The reverse supply chain of the e-waste management processes in a circular economy framework: Evidence from Italy. Sustainability, 11(8), 2430, (2019).
7. Matarazzo et al. Mass balance as green economic and sustainable management in WEEE sector. Energy Procedia, 157, 1377–1384, (2019).
8. Brito et al. Reverse remanufacturing of electrical and electronic equipment and the circular economy. Revista de Gestão, (2022).
9. Marconi et al. An approach to favor industrial symbiosis: The case of waste electrical and electronic equipment. Procedia Manufacturing, 21, 502–509, (2018).

10. Hagelüken et al. The EU circular economy and its relevance to metal recycling. Recycling, 1(2), 242–253, (2016).
11. Levänen et al. Modelling the interplay between institutions and circular economy business models: A case study of battery recycling in Finland and Chile. Ecological Economics, 154, 373–382, (2018).
12. Bridgens et al. Closing the loop on E-waste: A multidisciplinary perspective. Journal of Industrial Ecology, 23(1), 169–181, (2019).
13. Tong et al. Towards an inclusive circular economy: Quantifying the spatial flows of e-waste through the informal sector in China. Resources, Conservation and Recycling, 135, 163–171, (2018).
14. Cordova-Pizarro et al. Circular economy in the electronic products sector: Material flow analysis and economic impact of cellphone e-waste in Mexico. Sustainability, 11(5), 1361, (2019).
15. Sengupta et al. Circular economy and household e-waste management in India: Integration of formal and informal sectors. Minerals Engineering, 184, 107661, (2022).
16. Parajuly, K., & Wenzel, H. Product family approach in e-waste management: a conceptual framework for circular economy. Sustainability, 9(5), 768, (2017).
17. Ottoni et al. A circular approach to the e-waste valorization through urban mining in Rio de Janeiro, Brazil. Journal of Cleaner Production, 261, 120990, (2020).
18. Alves, D. S., & Farina, M. C. Disposal and reuse of the information technology waste: A case study in a Brazilian university. European Business Review, (2018).
19. Wagner et al. Towards a more circular economy for WEEE plastics–Part A: Development of innovative recycling strategies. Waste Management, 100, 269–277, (2019).
20. Wagner et al. Towards a more circular economy for WEEE plastics–Part B: Assessment of the technical feasibility of recycling strategies. Waste Management, 96, 206–214, (2019).
21. André et al. Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse. Waste Management, 88, 268–279, (2019).
22. Sabtu et al. Multi-criteria decision making for reverse logistic contractor selection in e-waste recycling industry using polytomous rasch model. Jurnal Teknologi, 77(27), (2015).
23. Shevchenko et al. Towards a smart E-waste system utilizing supply chain participants and interactive online maps. Recycling, 6(1), 8, (2021).
24. Forza, C. Survey research in operation management: a process-based perspective. International Journal of Operation & Production Management, (22), pp. 152–194, (2002).
25. Kumar, A., & Dixit, G. A novel hybrid MCDM framework for WEEE recycling partner evaluation on the basis of green competencies. Journal of Cleaner Production, 241, 118017, (2019).
26. Yin, R. K. Case study research: Design and methods. (5), Sage, (2009).
27. Denzin, N. K., & Lincoln, Y. S. The Sage handbook of qualitative research. Sage, (2011).
28. Martins, G. A., & Theóphilo, C. R. Scientific research methodology for applied social sciences. Atlas, (2009).
29. Cohen, J. Statistical Power Analysis for the Behavioral Sciences. (2). New York: Psychology Press, (1988).
30. Siegel, S. C., & Castellan, J. N. J. Nonparametric statistics for the behavioural sciences. New York, McGraw-Hill, (1988).
31. Demsar, J. Statistical comparisons of classifiers over multiple data sets. Journal of Machine Learning Research, (7) pp-1–30, (2006).
32. Agrawal et al. Reverse supply chain issues in Indian electronics industry: a case study. Journal of Remanufacturing, 8(3), 115–129, (2018).
33. Souza et al. Sustainability assessment and prioritisation of e-waste management options in Brazil. Waste management, 57, 46–56, (2016).
34. Bressanelli et al. Circular Economy in the WEEE industry: a systematic literature review and a research agenda. Sustainable Production and Consumption, (23), pp. 174–188, (2020).

Artificial Intelligence in Supply Chain Management: A Systematic Literature Review and Guidelines for Future Research

Bárbara Ferreira and João Reis

Abstract Artificial intelligence (AI) has been considered an important enabler of supply chains (SC), as it helps to monitor SC competitiveness and management. Thus, AI has been gaining notability in management. However, no academic manuscript offers a detailed study of specific artificial intelligence techniques. Indeed, several existing reviews in this field provide considerable insight, but are often too general. To address this issue, we conducted a systematic literature review that aims to provide solid and relevant foundation, targeting the artificial intelligence techniques that are most prevalent in supply chain management. This research identified the main artificial intelligence technics in the field of supply chain management, namely, artificial neural networks, fuzzy logic and genetic algorithm, although other topics have emerged as well, such as sustainability, environment, big data, and automatization. We recognize that AI plays an important role in SCM and how beneficial it is to use it while being considered risky at the same time. Additionally, we disclose how beneficial AI techniques are, since when used together they allow using fewer resources to obtain optimal results in SCM. Future research should examine how the application of artificial intelligence techniques may differ across organizations of different sizes.

Keywords Artificial intelligence · Supply chain management · Systematic literature review · Fuzzy logic · Genetic algorithms · Artificial neural networks

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1 Introduction

Artificial intelligence has been gaining notoriety in all industries [1] and its impact on supply chain management has become a topic of discussion [2]. AI has the potential to add business capabilities, increase data sharing, reduce costs and increase quality of service in supply chain management (SCM) [3]. It is also predicted that, with the growth of artificial intelligence, many companies will radically change their planning, scheduling, optimization, and transportation [4]. It is common to find similar studies that demonstrate the importance of artificial intelligence in SCM. In this regard, a study carried out by Naz et al. [5] provides useful information on the most prevalent AI technics in SCM, although it has not analyzed these technics in dept. Another recent study related to this article was developed by Toorajipour et al. [6], where a systematic literature review on the contributions of AI in SCM was carried out. Although interesting results have been found by the cited authors, such as the most prevalent AI technics applied to the SCM, such as fuzzy logic (FL), genetic algorithms (GA), and artificial neural networks (ANN). However, to our knowledge, no study presents a systematic literature review that can identify research gaps and assess current knowledge in the field of AI from a holistic perspective. In this regard, this article intends to fill the gap in the literature, which is to find the main AI technics that can improve the responsiveness of SCM workflow [7]. At the same time, we also intend to study the benefits of several combined AI techniques [8]. Therefore, this article answers the following research question: How did the ANNs, FL, and GA affect the supply chain the most? Although it is known that these three AI techniques are the most prevalent in SCM, we could also recognize that it may be beneficial to use the three together, as they allow the use of fewer resources to obtain optimal results. In this regard, we suggest further investigation into how the application of AI techniques may differ in organizations of different sizes.

The remaining sections of this article are structured as follows: section two presents a description of the methods used to carry out this article, namely the PRISMA statement (Preferred Reporting Items for Systematic Review and Meta-Analysis Protocol) and the content analysis technique. In the third section, the results of the analysis are presented. The fourth section presents a discussion of the results that allow for future guidelines and, finally, the fifth section ends with theoretical and managerial conclusions.

2 Materials and Methods

2.1 Search Strategy

Elsevier Scopus was the database selected to carry out this review, considering the fact that it is one of the largest databases with a large number of high-quality, peer-reviewed scientific articles [9], as it is also the database selected by researchers who have articles published in this field [5, 6, 10, 11]. This search performed on article title, abstract and keywords, to identify peer-reviewed systematic reviews in English. The search terms used included "artificial intelligence "AND "supply chain management". Scopus was able to identify a total of 914 manuscripts on August 17th, 2022. A limit was added for the year of publication and the scope ranged from 2018 to mid-2022, as there was an exponential growth of articles in this area during this period of time. Since our objective is not to write a technical article focused on engineering and computer science, but rather an analysis from a managerial point of view, we selected the areas of Business, Management and Accounting. We observed that the main countries that published articles with these search terms were the United Kingdom, the United States and India, as they are considered the most productive and influential in the area of AI research in SCM, however our article does not distinguish in context.

2.2 PRISMA Protocol

The objective of this article is to carry out a systematic literature review to obtain an exhaustive search of published manuscripts. In that regard, we used the PRISMA statement tool, which we thought was the most appropriate because it allows a targeted and transparent search [12]. We used only a single database, for several reasons: (1) it is agreed that Scopus is one of the world's largest abstract and citation databases of peer-reviewed research literature; the use of only one database also allows presenting the results in a more transparent way, allowing reliability and reproducibility by other researchers [13, 14]; (2) when compared to other databases (e.g., Web of Science), the use of Scopus is justified by researchers who conducted similar studies [15] and who argued that AI re-search is more representative in this database due to the larger number of documents that can be captured there; and (3) compared to academic search engines (e.g. Google Scholar), Scopus captures fewer documents. However, as we prioritized studies with blind peer re-view, we had to exclude them from this research.

Figure 1 shows that a total of 893 manuscripts were identified. The review process was based on filters in order to restrict the search to the best quality articles. We started by excluding journals that were not written in the English language, as English is increasingly becoming a universal language in scientific research. Then we decided to narrow the review to articles and journals in order to select only reliable manuscripts, as journal articles have better quality content than others, such as book chapters and conference proceedings, in a total of 309 manuscripts. This systematic literature review also includes the manuscripts published from 2018 to 2022, as it was possible to perceive an exponential growth in the publication of articles during this period. Finally, a new filter was applied to obtain only articles related to Business, Administration and Accounting, as we intend to obtain an analysis from a managerial point of view, with a total of 59 reviews. During the eligibility phase, after carefully reading all selected manuscripts, it was possible to exclude articles to which we could not have granted access (n = 34). Considering that articles other than those obtained through the Scopus search were not included, we ended the search with 34 reviews.

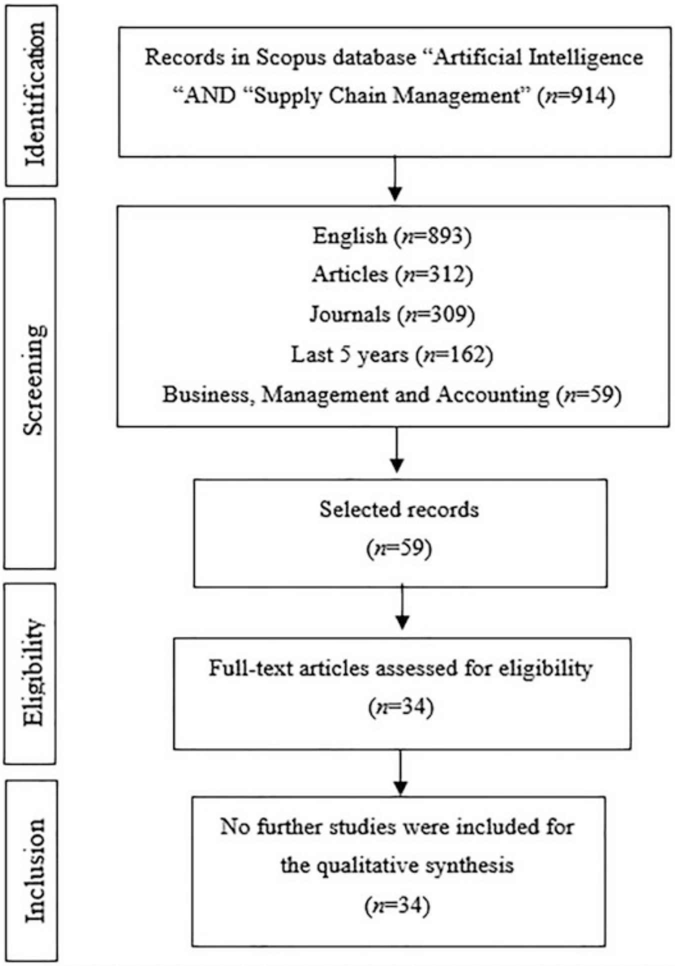

Fig. 1 PRISMA protocol

3 Results

3.1 Sustainability

In supply chain management and artificial intelligence literature, sustainability is a general concern advocated by Ouyang and Li [16], Zhang et al. [17], Thuermer [18], and Dirican [19].

In the literature, it is quite evident that the influence of AI on sustainable SCM is still at an early stage [20]. It is argued that to achieve sustainability in supply chain management, it is important to make use of tools such as AI, robotics, big data, digitization and the Internet of things [21]. AI has revolutionized the way we do business [22] and has made the supply chain management process more transparent, which is an important criterion regarding sustainability [21]. For an organization to be more sustainable [23], all three dimensions of sustainability need to be aligned (economic, environmental, and social). In this line of thought, it is stated that the strength of the supply chain mainly depends on an effective articulation between suppliers, customers, and the three aforementioned pillars of sustainability, however, this articulation is more effective in the use of artificial intelligence [24]. A case of success is the Henkel Ibérica factory, which started to use AI to achieve sustainability in its company, prescribing actions to ensure flawless operations on the production line, using historical data [25].

Ouyang and Li [16] support the idea that AI technologies are not necessary when it comes to achieving sustainability in supply chain management, as existing resources are sufficient. On the other hand, we have Thuermer [18], and Dirican [19], who argue that artificial intelligence is crucial to achieving sustainability in supply chain management. It is also emphasized that the role of AI increases an organization's ability to better process information [20]. Thus, when AI is incorporated into supply chain networks, the information circulating in these systems works in pull mode, allowing organizations to improve operations and provide just-in-time deliveries [26].

Moreover, Berg et al. [27] stressed that the goal of supply chain management is to comprehend under what conditions their products or services are designed, produced, and used to maximize sustainability performance and circularity. With this in mind, making informed decisions means that product sustainability and circularity performance need to be evaluated at a case-specific level. In this way, the use of IoT, big data, AI, and blockchain offers great potential to increase sustainability and circularity of products and resources [27].

In short, it was possible to ascertain that artificial intelligence is an important topic when it comes to achieving sustainability in SCM. Thus, the SCM needs to be aligned with the main pillars of sustainability to get good use of AI. In addition, the literature also mentions that the use of AI increases the sustainability and circularity of products and resources.

3.1.1 Environment

The environment is another topic associated with artificial intelligence and supply chain management, being discussed mainly by Lee and Choi [28] and Zhang et al. [29] It is also an important pillar of sustainability as it plays a crucial role in implementing sustainable practices in the supply chain [30].

Due to globalization, large distances between two connections have increased, bringing with them unsustainable issues, resulting in the environmental impact on SCM [31]. The environmental impact represented by the supply chain, such as producing, sourcing, and distributing has been the main concern [28]. Therefore, the need to adopt eco-friendly systems is urgent [31]. Big data analytics and AI can play a key role in the SCM environment, as with economic development, industrial modernization and better energy structures it is possible to balance the impact [32]. Furthermore, environmental awareness is growing rapidly with the proliferation of information and communication technology (ICT) and social media, another challenge that organizations face in a competitive business environment [29].

Environmental management can also offer financial benefits to organizations in or-der to increase the competitiveness of their work. In this regard, SC strategies can also be implemented through artificial intelligence [29]. For instance, a mathematical models using a fuzzy particle swarm optimization were designed to offer a solution for better SCM, considering environmental challenges associated with the manufacturing and industrial sector [33, 34]. Accenture leverages this model, providing the flexibility to plan at the city level and the ability to aggregate the data globally. It enables users to make decisions based on data and insights and considers the many factors needed to effectively manage a real estate portfolio of global size. Data is consolidated from multiple systems and provided in near real-time [35].

Suppliers can also play a very important role in enforcing green supply chain prac-tices [30, 36]. On the other hand, is also considered risky to adopt practices related to the environmental impact of their SC, as they face changes in decision parameters, information uncertainty and changes in decision boundaries [37]. However, technological progress can play an important role in economic development, upgrading industrial structure and adjusting energy structure, while decreasing risks [31].

That said, it is safe to say that while globalization is a supply chain issue when it comes to environment, AI has the ability to lessen the risks that come with it and create better options.

3.2 Artificial Intelligence Techniques

We identified three AI techniques applied to SCM, namely ANN, genetic algorithms and fuzzy logic. Mainly supported by Eleonora et al. [38] Amine et al. [39] and Toorajipour et al. [6].

Eleonora et al. [38] starts by defining the concept of ANN, stating that is a mathematical tool inspired by biological neural networks that provide, for a given problem, solutions similar to those formulated by the human mind. Similar to the following concept, they also stated that ANNs are typically based on mathematical regression to correlate input and output flows to and from process units. Such models predominantly depend on a large number of experimental data [40]. It is shown that ANN models can provide more accurate predictions taking into consideration other AI techniques [38, 41, 42]. Therefore, ANN is a technique mainly used in SCM, applied to marketing, sales forecasting and customer segmentation [43]. As the McKinsey case study illustrates, using ANN in auto-motive marketing to reach customers at the right moment with a tailored, individual message. Also through programmatic advertising, with AI at its very core, automotive players can allow AI to determine which customers to reach, with which messages, at what time and through which channels [44]. The use of ANNs for demand forecasting problems is not new and has been proposed in different contexts [38]. Thus, if other tools are integrated with artificial neural networks, it is possible to obtain a more effective fore-cast.

When it comes to genetic algorithms (GA) the most consensual concept is a computational algorithm inspired by Darwinian evolutionary theory, which can be called in short as "survival of the fittest" [45]. GA allows parameter optimization and can also be extended to multi-objective optimizations (MOO) [46]. Fuzzy Logic allows dealing with uncertainty, unpredictability, hard-to-formulate systems and information fuzziness [47]. Being defined as an approach that perfectly addresses qualitative information and resembles the way humans make inferences and decisions [48], representing the frontier between AI and non-AI techniques [49].

Overall, the most prevalent AI techniques in SCM offer the possibility to gain human capabilities such as thinking like humans, acting like humans, reasoning and acting rationally. Based on these characteristics, AI techniques can be grouped into four categories, namely, human thinking (HTT), human acting (HAT), rational thinking (RTT) and rational acting (RAT) techniques [28, 50], also giving the possibility to have better forecasting in SCM.

3.3 Big Data

Gualandris and Kalchschmidt [51] stress that Big Data is a complex and large data set that goes beyond traditional systems that have the ability to process, monitor, and visualize, and has been gaining much notability due to the rapid dissemination of information technology [52]. Due to the increase size of data, in today's highly competitive market, big data is crucial to help with changes such as the IT revolution, customer awareness and globalization. In this way, supply chain experts seek to find a way to manage a large amount of data in order to achieve an integrated, efficient, effective and agile supply chain system [53]. Keeping this in mind, big data analytics (BDA) in conjunction with artificial intelligence was defined as the best solution, allowing companies to extract useful information from the huge amount of data and use this information to manage supply chain problems [53, 54]. It was also recently noted that the use of BDA-AI can significantly reduce carbon intensity, making use of two models of hybrid metaheuristic algorithms [55, 56].

Business analytics and big data play an important role while enhancing a company's information processing [53]. In a recent study, a theoretical framework was developed and tested in supply chain finance and studied the effect of big data on analytics capability, reaching the conclusion that big data analytics has a positive effect on the integration of supply chain finance [57]. As BDA-AI is useful to process unstructured data in order to reveal thoughtful insight. BDA-AI has the ability to analyze dynamic energy consumption and carbon emission data in real-time and support the optimization of the manufacturing process with the aim of saving energy and reducing emissions [58, 59].

Regarding the decision-making procedures of companies, the importance of big data has increased due of technological progress across the industry [60]. However, research on the influence of big data on the environmental dimension of the SC is still in its early stages [53]. As in such a volatile market, despite the growing popularity of emerging technologies, such as big data analytics and artificial intelligence, there is ambiguity about how the adoption of business analytics affects firm performance [61–64]. It is still considered a risky adoption and leaves stakeholders vulnerable to greater losses.

In this way, the adoption of BDA-AI refers to the use of big data analytics powered by artificial intelligence to extract more meaningful information with which companies can improve their decision-making skills. Enabling better management to fight the market competitiveness. However, scholars still consider the adoption of BDA-AI a risky move.

3.4 Automatization

The idea of automatically learning and developing trading strategies on automated supply chain procurement platforms gained interest. Given the inherent suitability of software agents for these tasks, most follow-up work on automation in SCM uses agent-based systems, which began with the proposal of various frameworks detailing agent roles and activities [65–68].

Automation in the supply chain took its first steps with the now ubiquitous electronic procurement (e-Procurement) [69, 70], allowing an increase in accuracy and speed of procurement, and enabling the reduction of costs with bureaucracy and administration. In this regard, some studies reveal that a large percentage of managers may lose their jobs to automation. While opposing arguments claim that it is better to invest in automation as it is becoming an important factor for profit margins as well as allowing for potential expansion in the customer base as more relationships can be easily managed without the need to invest more in capital human, making it an attractive option. With automation, we will start to have a human being whose behavior is imitated by an intelligent agent [65–68].

Automation in the supply chain can be divided in three different capabilities, namely “process automation”, “operational automation” and “tactical automation”. Being described that such capabilities are not defined by the “level” of intelligence, but by the “complexity” of the process that the automation activity is being applied [71]. Process automation is meant for supply chain data entry with robotic process automation and recognition in e-procurement, while operational automation is for coordinating production schedules and co-optimizing inventory levels. Finally, tactical automation concerns the handling of various business-to-business (B2B) processes [71].

It is claimed that only three studies made use of multi-agent-based automation approaches [72]. Proposed by Ying and Dayong [72] a framework for 3 PL (Third Party Logistics) for the formation of ad hoc virtual private logistics teams, an

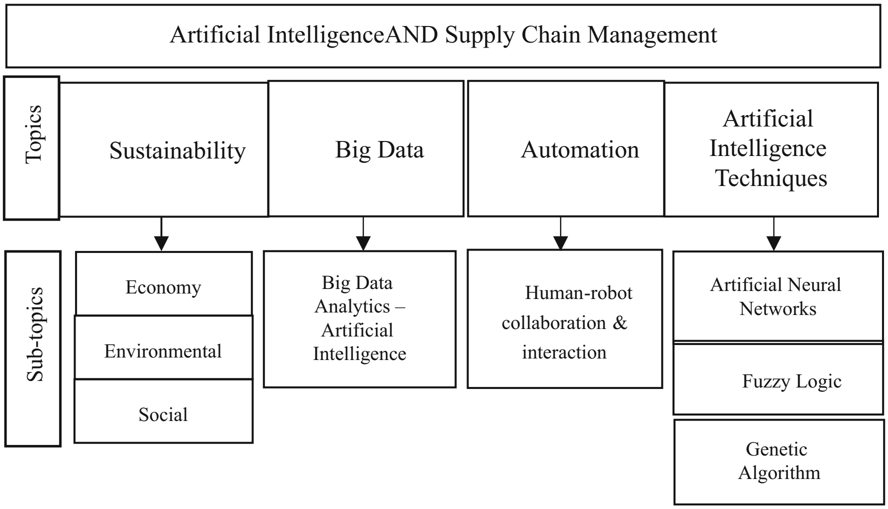

Fig. 2 Emerging topics of supply chain management

automated route planning system was built for cases where transportation and production schedules are closely connected and goods are distributed immediately after production. This system was applied to a German newspaper, resulting in a system that was able to handle fluctuations in production schedules better than the existing centrally planned system. It is argued that automation plays a key role in the supply chain, although it is proclaimed that it can lead to job losses. Within recent research it is stated that human-robot interaction and human-robot collaboration can be of paramount importance in some areas of the SCM [15, 73]. To provide a comprehensive overview of the results, we present a summary of this section in Fig. 2.

The article aimed to provide a solid foundation on the AI techniques that are most prevalent in SCM. However, the results highlighted the existence of other relevant topics and subtopics that are displayed in Fig. 2. Based on the results of the systematic review, we, therefore, argue that AI plays an important role in SCM, in particular, within the pillars of sustainability, in the context of big data analytics, and in relation to interactions and collaborations between humans and robots. These results can offer useful paths (topics and subtopics) that allow researchers to justify and carry out research in the field of AI and SCM.

4 Discussion

Four important themes emerged from the literature within artificial intelligence and supply chain management, namely, sustainability allied with the environment, artificial intelligence techniques, big data, and automatization.

Considering the first topic, we can acknowledge that, although the influence of AI in sustainable SCM is still incipient, it already plays a pivotal role in improving the organization's management. In this regard, one should keep in mind that all three dimensions of sustainability are relevant and must should need to be aligned – economic, environmental and social. That said, in order to maximize sustainability and circularity performance, the use of AI can offer options that were previously unavailable in the market, such as route optimization. On the other hand, the environment also strongly contributes to achieving the sustainability goals, in this regard the previous argument, e.g., route optimization through AI, also allows mitigating the effects of globalization. Thus, AI is one of the technologies capable of mitigating risks, as it is able to make use of techniques such as fuzzy particle swarm optimization, helping to optimize a problem by improving an existing solution.

As far as artificial intelligence techniques are concerned, we have identified "ANN", "genetic algorithms" and "fuzzy logic" as the most relevant techniques when it comes to SCM. Regarding the ANN, they have the ability to predict and provide accurate results, therefore, it is easier to predict the number of sales and solve problems in sales forecasting, which leads to a more sustainable SCM. However, when it comes to solving complicated problems, genetic algorithms have better utility as they work with a larger number and variables and can also be extended to multiple objective optimizations. In addition to the above, fuzzy logic is a great technique when working with qualitative information, as it is able to approach it perfectly. For instance, it is capable of reassembling a human mind, as it works very well under uncertainty and unpredictability. In this way, these techniques together open the possibility of reducing human effort. As when grouped into four categories, namely human thinking (HTT), human acting (HAT), rational thinking (RTT) and rational acting (RAT) techniques, they have great performance forecasting in SCM. There-fore, ANNs, FL, and GA are considered important techniques, since they make available the use of fewer resources to obtain great results in supply chain management.

Due to the increasing size of data in SCM, big data analytics has proven to be crucial in helping with changes such as IT revolution, customer awareness and globalization. The use of big data analytics (BDA) in conjunction with artificial intelligence was defined as the best solution, allowing companies to extract actionable insights from large amounts of data and use that information to SCM issues. Although BDA is still considered a risky adoption, it is taken as the best way to combat market competitiveness. As a last topic, we present automatization, which can be divided into three different capabilities, namely: "process automation", "operational automation", and "tactical automation". These capabilities are considered very important due to the increase in accuracy and speed of acquisitions, in addition to enabling the reduction of costs with bureaucracy and administration.

5 Conclusions

5.1 *Theoretical and Managerial Contributions*

The main theoretical contributions of this research are the increase of new perspectives on the use of AI in SCM that had not been previously explored. Although other similar studies can be found in the literature, this research is original since it covers an analysis of the most prevalent AI techniques in SCM, providing a more comprehensive knowledge than the existing literature. With the help of the PRISMA statement we were able to refine our search and bring to light the most relevant topics in SCM. In this regard, we have found that sustainability, environment, big data and automation play important roles in how the supply chain is managed and in market competitiveness.

From a managerial perspective, the great challenge that organizations face today are the rapidly changing environments (VUCA) and globalization. We suggest that managers consider the use of big data analytics, which allows them to manage a large amount of data more efficiently, by combining data with AI techniques. In our understanding, it may be relevant that managers are also entrepreneurs so that they can explore new dynamics and obtain competitive advantages. Although it is claimed that automation can lead to operational and tactical level employees (managers) losing their jobs, it is possible to achieve great results by having human capital working alongside automation [15, 73]. Thus, organizations can benefit from more accurate results, speed of acquisition and reduction of bureaucracy and administration costs.

5.2 *Research Limitations and Suggestions for Future Research*

The limitations of this research are essentially related to the methods. Systematic re-views present a snapshot of a given reality [74] at a given point in time. Therefore, while scientific databases are constantly being updated with new peer-reviewed research, they become outdated [75]. By restricting the search to certain keywords and applying filters that allowed selecting the most important articles, we may also have run the risk of excluding relevant manuscripts. Although we are aware of the above limitations, we believe in the value of this systematic review, as it presents in a few pages the state of the art of AI in SCM. As for future research, we suggest examining how the application of AI techniques might differ across organizations of different sizes. To this end, empirical studies can be carried out in a real context, in order to explore the application of AI in e.g., sales forecasting and customer experience design. It can also be analyzed how an organization achieves sustainability in SCM via AI, depending on the degree of maturity of these technologies in the organization. Finally, we suggest that an investigation be carried out to explore the risks of using AI technologies in SCM [61–64].

References

1. Dubey, R., Gunasekaran, A., Childe, S. J., Bryde, D. J., Giannakis, M., Foropon, C., Rameshwar, D., Hazen, B. T. Big data analytics and artificial intelligence pathway to operational performance under the effects of entrepreneurial orientation and environmental dynamism: A study of manufacturing organisations. International Journal of Production Economics, 226, 107599 (2020).
2. The Economist, https://www.economist.com/special-report/2018/03/28/how-ai-is-spreading-throughout-the-supply-chain, last accessed 2022/11/10.
3. Brandon-Jones, A., & Kauppi, K. Examining the antecedents of the technology acceptance model within e-procurement. International Journal of Operations & Production Management, 38 (1), 22–42 (2018).
4. Khalifa, N., Abd Elghany, M., & Abd Elghany, M. Exploratory research on digitalization transformation practices within supply chain management context in developing countries specifically Egypt in the MENA region. Cogent Business & Management, 28(1), 1965459 (2021).
5. Naz, F., Agrawal, R., Kumar, A., Gunasekaran, A., Majumdar, A., & Luthra, S. Reviewing the applications of artificial intelligence in sustainable supply chains: Exploring research propositions for future directions. *Business Strategy and the Environment*, (2022).
6. Toorajipour, R., Sohrabpour, V., Nazarpour, A., Oghazi, P., & Fischl, M. Artificial intelligence in supply chain management: A systematic literature review. Journal of Business Research, 122, 502–517 (2021).
7. Lee, C. K., Ho, W., Ho, G. T., & Lau, H. C. Design and development of logistics workflow systems for demand management with RFID. Expert systems with applications, 38(5), 5428–5437 (2011).
8. Madhavaram, S., & McDonald, R. E. Knowledge-based sales management strategy and the grafting metaphor: Implications for theory and practice. Industrial Marketing Management Selling and Sales Management, 39, 1078–1087 (2010).
9. Vinodh, S., Antony, J., Agrawal, R., & Douglas, J. A. Integration of continuous improvement strategies with Industry 4.0: a systematic review and agenda for further research. The TQM Journal, 33 (2), 441–472 (2020).
10. Maitre, E., Sena, G. R., Chemli, Z., Chevalier, M., Dousset, B., Gitto, J. P., & Teste, O. The investigation of an event-based approach to improve commodities supply chain management. Brazilian Journal of Operations & Production Management, 19(2), 1–19 (2022).
11. Kannan, D. Role of multiple stakeholders and the critical success factor theory for the sustainable supplier selection process. International Journal of Production Economics, 195, 391–418 (2018).
12. Tranfield, D., Denyer, & D., Smart, P. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. British Journal of Management, 14(3), 207–222 (2003). https://doi.org/10.1111/1467-8551.00375
13. Cook, D. J., Mulrow, C. D., & Haynes, R. B. Systematic reviews: synthesis of best evidence for clinical decisions. Annals of internal medicine, 126(5), 376–380 (1997).
14. Moher, D., Cook, D. J., Eastwood, S., Olkin, I., Rennie, D., Stroup, D. F., & Quorom Group. Improving the quality of reports of meta-analyses of randomised controlled trials: the QUOROM statement. The Lancet, 354(9193), 1896–1900 (1999).
15. Reis, J., Santo, P.E., Melão, N. Influence of artificial intelligence on public employment and its impact on politics: a systematic literature review. Brazilian Journal of Operations & Production Management, 18, 1–22 (2021).
16. Ouyang, Yanfeng, and Xiaopeng Li. "The Bullwhip Effect in Supply Chain Networks." European Journal of Operational Research, 201 (3): 799–810 (2010). https://doi.org/10.1016/j.ejor.2009.03.051.

17. Zhang, Y., Ren, S., Liu, Y., & Si, S. A big data analytics architecture for cleaner manufacturing and maintenance processes of complex products. Journal of Cleaner Production, 142, 626–641 (2017). https://doi.org/10.1016/j.jclepro.2016.07.123
18. Thuermer, Karen E. "Machine Learning is Coming: Artificial Intelligence Capabilities Will Help Food Companies Make Up-to-the-minute Decisions That Can Reduce Supply Chain Disruptions. (Sector Reports: Software & Technology)." Food Logistics, 11 (182): 68 (2016).
19. Dirican, Cüneyt. "The Impacts of Robotics, Artificial Intelligence on Business and Economics." Procedia - Social and Behavioral Sciences, 195: 564–573 (2015).
20. Benzidia, S., Makaoui, N., & Bentahar, O. The impact of big data analytics and AI on green supply chain process integration and hospital environmental performance. Technological Forecasting and Social Change, 165, 120557 (2021). https://doi.org/10.1016/j.techfore.2020.120557
21. Sanders, N. R., Boone, T., Ganeshan, R., & Wood, J. D. Sustainable supply chains in the age of AI and digitization: research challenges and opportunities. Journal of Business Logistics, 40(3), 229–240 (2019). https://doi.org/10.1111/jbl.12224
22. Schneider, S., & Leyer, M. Me or information technology? Adoption of AI in the delegation of personal strategic decisions. Managerial and Decision Economics, 40(3), 223–231 (2019). https://doi.org/10.1002/mde.2982
23. Elkington, J. Cannibals with forks: the triple bottom line of 21st-century business. Stony Creek, CT: New Society, (1998).
24. Büyüközkan, G., & ÇifÇi, G. A novel fuzzy multi-criteria decision framework for sustainable supplier selection with incomplete information. Computers in Industry, 62(2), 164–174 (2011). https://doi.org/10.1016/j.compind.2010.10.009
25. Henkel, https://www.henkel.com/sustainability, last accessed 2022/12/08.
26. Femi Olan, Shaofeng Liu, Jana Suklan, Uchitha Jayawickrama & Emmanuel Ogiemwonyi Arakpogun: The role of Artificial Intelligence networks in sustainable supply chain finance for food and drink industry, International Journal of Production Research, (2021). https://doi.org/10.1080/00207543.2021.1915510
27. Berg, H., Le Blévennec, K., Kristoffersen, E., Strée, B., Witomski, A., Stein, N., Bastein, T., Ramesohl, S., & Vrancken, K. Digital circular economy: a cornerstone of a sustainable European industry transformation [White paper]. European Circular Economy Research Alliance, (2020).
28. Lee, J.-Y., & Choi, S. Supply chain investment and contracting for carbon emissions reduction: A social planner's perspective. International Journal of Production Economics, 231, 107873 (2021). https://doi.org/10.1016/j.ijpe.2020.107873
29. Zhang, Q., Gao, B., & Luqman, A. Linking green supply chain management practices with competitiveness during covid 19: The role of big data analytics. Technology in Society, 70, 102021 (2022).
30. Govindan, K., Jafarian, A., Khodaverdi, R., & Devika, K. Two-echelon multiple-vehicle location–routing problem with time windows for optimization of sustainable supply chain network of perishable food. International Journal of Production Economics, 152, 9–28 (2014). https://doi.org/10.1016/j.ijpe.2013.12.028
31. Elhedhli, S., & Merrick, R. Green supply chain network design to reduce carbon emissions. Transportation Research Part D: Transport and Environment, 17(5), 370–379 (2012). https://doi.org/10.1016/j.trd.2012.02.002
32. Li, M., & Wang, Q. Will technology advances alleviate climate change? Dual effects of technology change on aggregate carbon dioxide emissions. Energy for Sustainable Development, 41, 61–68 (2017). https://doi.org/10.1016/j.esd.2017.08.004
33. Mathivathanan, D., Kannan, D., & Haq, A. N. Sustainable supply chain management practices in Indian automotive industry: A multi-stakeholder view. Resources, Conservation and Recycling,128, 284–305 (2018).

34. Che, Z. H. Using fuzzy analytic hierarchy process and particle swarm optimisation for balanced and defective supply chain problems considering WEEE/RoHS directives. International Journal of Production Research, 48(11), 3355–3381 (2010). https://doi.org/10.1080/00207540802702080
35. Accenture, https://www.accenture.com/pt-pt/case-studies/about/sap-real-estate, last accessed 2022/12/08.
36. Kannan, D., de Sousa Jabbour, A. B. L., & Jabbour, C. J. C. Selecting green suppliers based on GSCM practices: Using fuzzy TOPSIS applied to a Brazilian electronics company. European Journal of Operational Research, 233(2), 432–447 (2014). https://doi.org/10.1016/j.ejor.2013.07.023
37. Matos, S., & Hall, J. Integrating sustainable development in the supply chain: The case of life cycle assessment in oil and gas and agricultural biotechnology. Journal of Operations Management, 25(6), 1083–1102 (2007). https://doi.org/10.1016/j.jom.2007.01.013
38. Bottani E., Centobelli P., Gallo M., Kaviani A. M., Jain V., Murino T. "Modelling wholesale distribution operations: an artificial intelligence framework", Industrial Management & Data Systems, (2019). https://doi.org/10.1108/IMDS-04-2018-0164
39. Belhadi A., Kamble S., Fosso S., Wamba & Maciel M. Queiroz: Building supply-chain resilience: an artificial intelligence-based technique and decision-making framework, International Journal of Production Research, (2021). https://doi.org/10.1080/00207543.2021.1950935
40. Yang, H., & Chen, H. Biomass gasification for synthetic liquid fuel production. In R. Luque, & J. G. Speight (Eds.), Gasification for Synthetic Fuel Production, Woodhead Publishing Series in Energy, 11 pp. 241–275 (2015). Woodhead Publishing. https://doi.org/10.1016/B978-0-85709-802-3.00011-4.
41. Benkachcha, S., Benhra, J., & El Hassani, H. Demand forecasting in supply chain: comparing multiple linear regression and artificial neural networks approaches. International Review on Modelling and Simulations, 7(2), 279–286 (2014).
42. Yeganeh, B., Motlagh, M. S. P., Rashidi, Y., & Kamalan, H. Prediction of CO concentrations based on a hybrid Partial Least Square and Support Vector Machine model. Atmospheric Environment, 55, 357–365 (2012).
43. Kasabov, N. Chapter 6 - Evolving and Spiking Connectionist Systems for Brain- Inspired Artificial Intelligence. In R. Kozma, C. Alippi, Y. Choe, & F. C. Morabito (Eds.), Artificial Intelligence in the Age of Neural Networks and Brain Computing, pp. 111–138. Academic (2019). https://doi.org/10.1016/B978-0-12-815480-9.00006-2.
44. McKinsey, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/winning-tomorrows-car-buyers-using-artificial-intelligence-in-marketing-and-sales, last accessed 2022/12/08.
45. Darwin, C. On the Origin of Species London John Murray, (1859).
46. Streichert, Felix. "Introduction to Evolutionary Algorithms." Paper to Be Presented Apr 4, (2002).
47. Solgi, Y., and S. Ganjefar. "Variable Structure Fuzzy Wavelet Neural Network Controller for Complex Nonlinear Systems." Applied Soft Computing, 64: 674–685 (2018).
48. Keramitsoglou, I., Cartalis, C., & Kiranoudis, C. T. Automatic identification of oil spills on satellite images. Environmental Modelling & Software, 21, 640–652 (2006). https://doi.org/10.1016/j.envsoft.2004.11.010
49. Bundy, A. (Ed.). Artificial Intelligence Techniques: A Comprehensive Catalogue (4th ed.). Berlin Heidelberg: Springer, (1997).
50. Russell, S., and P. Norvig. *Artificial Intelligence: A Modern Approach*. Upper Saddle River, NJ: Prentice-Hall, 28 (2010).
51. Gualandris, J., & Kalchschmidt, M. Developing environmental and social performance: the role of suppliers' sustainability and buyer–supplier trust. International Journal of Production Research, 54(8), 2470–2486 (2016).

52. Papadopoulos, T., & Gunasekaran, A. Big data analytics in logistics and supply chain management. Computers & Operations Research, 98, 251–253 (2018). https://doi.org/10.1016/j.cor.2018.05.015
53. Benzidia, S., Makaoui, N., & Bentahar, O. The impact of big data analytics and artificial intelligence on green supply chain process integration and hospital environmental performance. Technological Forecasting and Social Change, 165, 120557 (2021).
54. Maheshwari, S., Gautam, P., & Jaggi, C. K. Role of Big Data Analytics in supply chain management: current trends and future perspectives. International Journal of Production Research, 59(6), 1875–1900 (2021).
55. Goodarzian, F., Kumar, V., & Abraham, A. Hybrid meta-heuristic algorithms for a supply chain network considering different carbon emission regulations using big data characteristics. Soft Computing, 25(11), 7527–7557 (2021). https://doi.org/10.1007/s00500-021-05711-7
56. Liu, J., Liu, L., Qian, Y., & Song, S. The effect of AI on carbon intensity: Evidence from China's industrial sector. Socio-Economic Planning Sciences, 101002 (2021). In Press. https://doi.org/10.1016/j.seps.2020.101002
57. Yu, W., Wong, C. Y., Chavez, R., & Jacobs, M. A. Integrating big data analytics into supply chain finance: The roles of information processing and data-driven culture. International Journal of Production Economics, 236, 108135 (2021). https://doi.org/10.1016/j.ijpe.2021.108135
58. Singh, S. K., & El-Kassar, A. N. Role of big data analytics in developing sustainable capabilities. Journal of cleaner production, 213, 1264–1273 (2019).
59. Ikram, M., Zhang, Q., & Sroufe, R. Future of quality management system (ISO 9001) certification: novel grey forecasting approach. Total Quality Management & Business Excellence, 32(15–16), 1666–1693 (2021).
60. Chen, H., Chiang, R. H., & Storey, V. C. Business intelligence and analytics: From big data to big impact. MIS Quarterly, 36(4), 1165–1188 (2012). https://doi.org/10.2307/41703503
61. Akter, S., Wamba, S. F., Gunasekaran, A., Dubey, R., & Childe, S. J. How to improve firm performance using big data analytics capability and business strategy alignment? International Journal of Production Economics, 182, 113–131 (2016).
62. Wamba, S. F., Dubey, R., Gunasekaran, A., & Akter, S. The performance effects of big data analytics and supply chain ambi-dexterity: The moderating effect of environmental dynamism. International Journal of Production Economics, 222, 107498 (2022).
63. Ramanathan, R., Philpott, E., Duan, Y., & Cao, G. Adoption of business analytics and impact on performance: a qualitative study in retail. Production Planning & Control, 28(11–12), 985–998 (2017).
64. Aydiner, A. S., Tatoglu, E., Bayraktar, E., Zaim, S., & Delen, D. Business analytics and firm performance: The mediating role of business process performance. Journal of business research, 96, 228–237 (2019).
65. Glushko, R. J., Tenenbaum, J. M., & Meltzer, B. An XML Framework for Agent-based E-commerce. Communications of the ACM, 42(3), 106-ff (1999).
66. Julka, N., Karimi, I., & Srinivasan, R. Agent-based supply chain management—2: a refinery application. Computers & chemical engineering, 26(12), 1771–1781 (2002).
67. Xue, X., Li, X., Shen, Q., & Wang, Y. An agent-based framework for supply chain coordination in construction. Automation in construction, 14(3), 413–430 (2005).
68. Jiao, J. R., You, X., & Kumar, A. An agent-based framework for collaborative negotiation in the global manufacturing supply chain network. Robotics and Computer-Integrated Manufacturing, 22(3), 239–255 (2006).
69. Neef, D. E-Procurement: From strategy to implementation. FT press, (2001).
70. Brandon-Jones, A., & Carey, S. The impact of user-perceived e-procurement quality on system and contract compliance. International Journal of Operations & Production Management, (2011).
71. Xu, L., Mak, S., & Brintrup, A. Will bots take over the supply chain? Revisiting agent-based supply chain automation. International Journal of Production Economics, 241, 108279 (2021).

72. Ying, W., & Dayong, S. Multi-agent framework for third party logistics in E-commerce. Expert Systems with Applications, 29(2), 431–436 (2005).
73. Galin, R. R., Meshcheryakov, R. V. Human-robot interaction efficiency and human-robot collaboration. In Robotics: Indus-try 4.0 Issues & New Intelligent Control Paradigms (pp. 55–63), Springer, Cham (2020).
74. Reis, J., Marques, P.A., Marques, P.C. Where are smart cities heading? A meta-review and guidelines for future research. Applied Sciences 12(16), 8328 (2022).
75. Reis, J. Politics, power, and influence: Defense industries in the post-cold war. Social Sciences, 10(1), 10 (2021).

Analysis of the ANEEL Consumer Satisfaction Index Through the Application of Item Response Theory

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Abstract This research aims to measure the ANEEL Consumer Satisfaction Index (IASC) of CELESC electricity distributor through the application of the Item Response Theory. The IASC is an indicator that allows evaluates the satisfaction of the residential consumer with the services provided by the electricity distributor with the intention of stimulating continuous improvement. The data set of the satisfaction survey fulfilled out by ANEEL in 2020 is quantitative and was obtained through secondary sources. It was possible to test the validity and internal consistency of the items and through the Item Response Theory (IRT) an interpretable scale was built to measure the level of consumer satisfaction. It was possible to calculate and explain the information curves of the items and the test, as well as demonstrate the gain that can be obtained with its application to measure the level of consumer satisfaction. The satisfaction level scale was created in five categories: "very dissatisfied, dissatisfied, neither dissatisfied/nor satisfied, satisfied and very satisfied. The results showed that 1.05% of consumers are very dissatisfied, 15.85% are dissatisfied, 55.75% are neither dissatisfied/nor satisfied with the company; 26.31% are satisfied, and 1.05% are very satisfied with the energy distributor. The created scale allows the energy distributor to monitor the measured indicators and evaluate the evolution of consumer satisfaction. In addition, managers to develop strategies to improve the level of consumer satisfaction can use the model created, to achieve continual improvement in service delivery of the Electricity Distributor.

Keywords Consumer satisfaction · ANEEL consumer satisfaction index · Item response theory

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1 Introduction

Today's society depends more and more on energy to satisfy increasing levels of quality of life, social and material well-being. Electricity is an essential element for the performance of human activities, and its use is present in most activities from work to leisure. It is an economic sector whose efficiency affects other sectors of the economy, in addition, of course, to human life itself.

The Brazilian electricity sector has been undergoing structural transformations since the mid-1990s. The model adopted in the restructuring of the sector is market oriented and is characterized by the deverticalization of the power companies through the separation of generation, transmission, distribution and commercialization activities, in addition to incentives for competition. The National Electrical Energy Agency (ANEEL) was created to regulate the Brazilian electrical sector, through Law 9427/1996 and Decree 2335/1997, with the objective of regulating and supervising electrical energy activities, linked to control of the quality of electricity supplied to end consumers [1, 2].

The quality of the service provided by electricity distributors encompasses the continuity of services, in terms of duration and frequency of electricity supply, and response times for emergency events [3]. Consumer satisfaction is one of the main objectives of organizations, and tends to be measured by technical performance, such as the availability of electricity [4].

According to Marchetti and Prado [5], the recognition of this basic principle of management has made it increasingly important to monitor consumer satisfaction. Consumer satisfaction, as well as the connection between consumer satisfaction and the quality of the service provided, are important indicators for the survival and profitability of the organization and have been the object of study in the marketing literature, by research institutes, government agencies and companies that intend to implement total quality management programs, given its great importance for the company [6, 7].

According to Santos Neto, Reis [4], electricity service providers should develop tools capable of measuring and supporting the quality management of their services, as well as the perceived quality and satisfaction of their consumers. Therefore, measuring and evaluating the quality offered by service providers is important both for research purposes and for companies that intend to improve their services. Regarding the quality and management of services in the electricity sector, it is observed that this sector has attracted significant research attention in recent years.

Santos Santos Neto, Reis [4] used partial least squares structural equation modeling (SEM–MQP) and covariance-based structural equation modeling (SEM–BC) to compare the results of the models to indicate the modeling that best fits the problem of measuring satisfaction of residential electricity consumers. The authors concluded that the comparative analyzes of convergent validity, discriminant validity and reliability of the constructs for the measurement models demonstrated that MEE–MQP and MEE–BC are complementary and not competing, so that one method cannot be considered superior to the other.

Ishizaki, Piai [8] propose a multiple linear regression model to evaluate the impact of distribution indicators on the ANEEL Consumer Satisfaction Index. The authors point out that, of the variables tested, only the continuity indicator does not have statistical significance with the model, requiring actions focused on improving the duration and equivalent frequency of interruption per consumer unit, since they have a greater impact on consumer satisfaction residential electricity.

In another study area, Duarte, e Silva [9] explored a conceptual model to measure consumer perceptions about the convenience of online shopping. The research had a sample of 250 young Portuguese people and Confirmatory Factor Analysis (CFA) and a covariance-based Structural Equation Model (CB-SEM) were used to validate the measurement model and test the relationships in the model. The authors identified which dimensions of online convenience stores affect consumers' intention to use online shopping, and demonstrated that the possession, transaction and evaluation constructs are the dimensions that most influence online shopping. The authors state that frequent monitoring of these consumers' perceptions and expectations is a prerequisite for achieving continuous improvement in the provision of online shopping services.

ANEEL developed the ANEEL Index of Consumer Satisfaction (IASC) with the goals of evaluating user satisfaction with its distributors and creating a sectorial index that would allow monitoring over time, encouraging the organization's commitment to best practices in management, with the quality of the distribution system, consumer satisfaction, with its financial results and socio-environmental sustainability, but, above all, with the most important thing of all, the commitment to people's lives.

The measurement and analysis of the IASC of an electricity distributor is used to improve the services provided by it, but also the company's own management. Constructing such a measurement is a complex task due to the latent nature of the measurement. ANEEL uses to generate the Satisfaction indices, the averages obtained in the Global Satisfaction, Global Disconformity, and Distance to an Ideal Company indicators, weighted by their respective weights, and calculated by the PLS (Partial Least Squares) method.

The Item Response Theory (IRT) is a statistical tool that allows the creation of an interpretable scale, where items and respondents are positioned. Thus, managers can interpret the scale values and, consequently, understand what it means to achieve a certain level of satisfaction.

They can also visualize the main characteristics of the satisfaction level and can define the necessary actions to improve the satisfaction of their customers. In this context, the objective of this article is to use the Item Response Theory to measure the ANEEL index of satisfaction of the residential consumer of Centrais Elétricas de Santa Catarina S.A. (CELESC). This measurement is based exclusively on the results of the Satisfaction survey carried out by ANEEL in 2020. This article is structured as follows: ANEEL Consumer Satisfaction Index, Item Response Theory, Materials and Methods, Results and Discussion and Conclusions.

2 Theoretical Framework

2.1 ANEEL Consumer Satisfaction Index

ANEEL established the IASC to compare companies of different sizes, characteristics and regions. The IASC questions the degree of satisfaction of the Brazilian residential consumer with the electricity distribution companies; assists in the supervision of the quality of service; allows a comparison between the concessionaires; and ANEEL discloses such information to the population [10].

Held annually by ANEEL since 2000, the IASC encourages the continuous improvement of services provided by electricity distributors. With the objective of enhancing the best practices of companies, in 2002 ANEEL instituted the IASC Award, to highlight the most efficient distributors in the consumer's perception. The best evaluated companies each year receive a certificate and a quality seal from the Agency, which can be used in institutional promotional material [11]. This award is an important indicator of quality in the Brazilian electricity sector and impacts the maximum price and profit margins of the companies. The IASC is intended to emulate competition, promote efficiency and drive quality improvements over time in a monopolistic market and ensure that the consumer is a significant part of the companies' strategic objectives.

The IASC was created according to its international counterpart, ACSI – American Customer Satisfaction Index [12], where the constructs Perceived Quality and Value precede the constructs of Satisfaction, Confidence and Fidelity, as shown in Fig. 1.

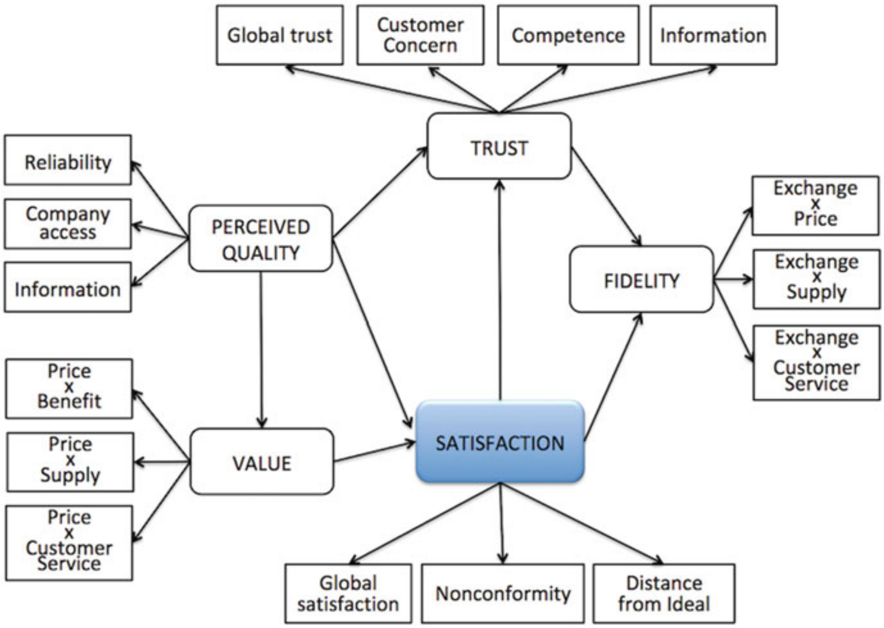


Fig. 1 ANEEL model of consumer satisfaction [13]

The constructs measure consumer perception as from different observable variables, which are the attributes (questions) of the research. The construct Perceived Quality is a latent variable, measured from the dimensions: (i) customer information, (ii) access to the company and (iii) service reliability. These dimensions are measured based on several items, considered the most important in the perception of consumers, chosen from discussions with sectorial agents and focus groups. The Value Construct evaluates the consumer's perception in the economic dimension in relation to the benefits that energy brings, the quality of supply and customer service. The Satisfaction construct measures customer satisfaction with the company based on three dimensions: (i) overall satisfaction, (ii) distance to the ideal company, and (iii) global non-compliance. The Confidence construct measures the level of Confidence that consumers have with their electricity supplier, and Fidelity evaluates the possibility of changing suppliers based on the value of tariffs, supplies and/or services provided by the company [13].

2.2 Item Response Theory

Item Response Theory (IRT), also known as latent trait theory, is a set of mathematical models used to measure latent traits that cannot be observed directly, but rather through a set of items designed for this purpose [14, 15]. It allows creating a measurement scale in which items and respondents can be positioned together, facilitating the understanding of the scale [16, 17].

For Reise, Ainsworth [18], IRT is a set of mathematical and statistical models that are used to: (i) analyze items and scales; (ii) create and administer measures; (iii) measure individuals or organizations of "latent trait" construct of interest. IRT seeks to mathematically represent the probability of a person giving a given response to the item as a function of the level of the "latent trait" and the item's parameters [14, 16].

Due to its ability to evaluate and improve instruments, IRT has been used in the development of performance measures in various research areas, such as education [19], marketing [20, 21], services [22], environmental management [15, 17, 23–25], ergonomics [26, 27], sustainability [28], psychology [29], satisfaction [30], nutrition [31, 32] and many others.

The item response models developed differ in the mathematical form of the item characteristic function and/or in the number of parameters specified in the model. The main difference between these models corresponds to the assumption regarding the relationship between the option selection of a response and the level of the latent trait. Among the models for items with dichotomous responses or items corrected as right or wrong, the Two-Parameter Logistic Model estimates the difficulty parameter (b) and the slope or discrimination parameter (a).

The need for psychometric tests, which present levels of responses that are not considered only dichotomous, motivated the development of models for IRT that address such needs, such as the Graduated Response Model (GRM) [33], the Partial Credit Model [34], among others. The GRM proposed by Samejima [33] is suitable for analyzing data on a satisfaction scale, as the selection of response options is composed of items with polytomous and ordered responses. Thus, a specific response category depends both on the discrimination parameter (a) common to all item categories and on the distance from adjacent difficulty categories. Necessarily, there must be an ordering between the levels of difficulty of the categories of a given item, according to the classification of their scores.

3 Materials and Methods

The approach of the present study is quantitative. The methodology involves a research instrument that measures the performance of companies based on the perception of residential electricity consumers. The IASC is the result of an opinion poll that was carried out by the company Qualitest Ciência e Tecnologia Ltda. at ANEEL's request in the period from November 24, 2020 to February 06, 2021 in 21 cities in the State of Santa Catarina, Brazil (Arabutã, Balneário Camboriú, Blumenau, Camboriú, Chapecó, Concórdia, Cordilheira Alta, Florianópolis, Herval d' Oeste, Indaial, Itapoá, Jardinópolis, Joinville, Lages, Lebon Régis, Mondaí, Palhoça, São Miguel do Oeste, Serra Alta, Tubarão, Videira) with residential consumers of the electricity distributor CELESC.

The instrument asks residential consumers about their perception of the electricity supplier "CELESC distributor" based on a model composed of five dimensions: Perceived Quality, Perceived Value, Satisfaction, Confidence in the Supplier and Fidelity. The description of the IASC questionnaire data can be seen in Table 1.

Each dimension is evaluated in the questionnaire through a group of questions asked to each respondent, who expressed their opinion using response categories from 0 to 10. The description of the scales is presented in Table 2.

The IASC survey presents response categories from 0 to 10. In this survey, the response categories were grouped as shown in the last row of Table 2. Five hundred and seventy-four consumers answered the questionnaire. This instrument is an important indicator of the quality of services provided by concessionaires, it helps ANEEL to supervise and regulate the electricity market, as well as monitor the performance of concessionaires.

The survey database can be found at https://antigo.aneel.gov.br/pesquisas-iasc. Statistical analyzes were performed in relation to the dimensionality of the instrument. To test the validity and consistency of the items, Samejima's Graded Response Model of Item Response Theory was used. Initially, the Parallel Analysis with a polychoric correlation matrix and the Full Information Factor Analysis [35] were used to verify the dimensionality of the instrument, that is, to verify the number of factors involved [19]. In this research, this type of analysis is chosen because it is more appropriate to treat a set of items using ordinal response categories [36]. These analyzes were performed using R Software [37], Psych packages [38] and Mirt (multidimensional item response theory) [39].

Table 1 Description of IASC questionnaire data

Constructs	Indicators	Item	Description of the items used in the study
Perceived quality	Customer information	V24	Ease to understand all electricity bill information
		V90	Disclosure of important information by the distributor about risks associated with the use of energy
		V21	Serving all consumers without discrimination
		V16	Security that the amount charged on the electricity bill is correct
	Company access	V11	Ease of contact with the company
		V14	Efficiency in resolving customer issues and requests
		V10	Compliance with the deadline given for the performance of the services
		V12	Kindness and politeness of the company's employees
		V17	Ease of access to electricity bill receipt and payment stations
	Reliability in services	V8	Constant power supply, i.e. no power outages
		V9	Power supply without voltage variation, i.e. without alternating bright light and dim light
		V13	Advance notice of power outages, in the event of non-payment
		V18	Agility of electric power return when there is an interruption
		V20	Early warnings of power outages for maintenance
Perceived value	Evaluates the consumer's perception of the economic dimension in relation to the facilities that energy brings, the quality of supply	V91	Considering the quality of the electricity supply, such as, for example, not missing or varying electricity, speed and punctuality in network repairs, advance notice, etc., how do you evaluate the price paid?
		V92	Considering the Price, how do you evaluate the quality of electrical energy?
Satisfaction	Evaluates the consumer's perception of the economic dimension in relation to the facilities that energy brings, the quality of supply and customer service	V7	Evaluating the quality of services provided by CELESC distributor, you are "dissatisfied"; "Neither dissatisfied nor satisfied"; or "satisfied?
		V25	The quality of services provided is "worse than expected"; "as expected, as expected"; or "better than expected"?

(continued)

Table 1 (continued)

Constructs	Indicators	Item	Description of the items used in the study
		V32	Thinking about the quality of services, in general, would you say that it is “far from ideal”; “neither far nor close to ideal”; or “close to ideal”?
Confidence	Evaluate the suppliers	V37	Is the distributor reliable?
		V38	Am I convinced that the distributor is concerned with the interests of its customers?
Fidelity	Evaluate the possibility of changing suppliers	V94	What is the chance of recommending the company to relatives and friends?
		V93	What is the chance of changing electricity supply company?

Table 2 Measuring scales evaluated in the IASC questionnaire

Perception of scales		Scale categories		
Perceived quality		Worse than expected	As expected/same as expected	Better than expected
Perceived value		Expensive	Not expensive/not cheap	Cheap
		Bad	Not bad/not good	Good
Satisfaction	Global	Dissatisfied	Neither dissatisfied/nor satisfied	Satisfied
	Distance to the ideal company	Far from the ideal	Not far/not close	Close to the ideal
	Global non-compliance	Worse than expected	As expected/same as expected	Better than expected
Confidence		I disagree	I don’t disagree/I don’t agree	I agree
Fidelity		Would not exchange	It depends	Would exchange
Survey score from 0 to 10		Very dissatisfied = 1, 2 e Dissatisfied = 3, 4	Neither dissatisfied/Nor satisfied = 5, 6	Satisfied = 7, 8 e Very Satisfied = 9, 10
		(NA) Does not know how to assess (NA) Did not answer		

In Samejima’s Gradual Response Model [33, 40, 41] it is assumed that the response categories of an item are ordered among themselves. Suppose that the categories of an item i are arranged from smallest to largest and denoted by $K = 0,1,2,\ldots, m_i$, where $(m_i + 1)$ is the number of categories of i-th item. The probability that a respondent j chooses a particular or higher category of item i can be given by an extension of the 2-parameter logistic model by Eq. (1):

$$P_{i,k}^{+(\theta_j)} = \frac{1}{1 + e^{-a_i(\theta_j - b_{i,k_i})}} \quad (1)$$

Where:

i = 1, 2, ..., I (I is the number of items in the test);
j = 1, 2, ..., n (n is the total number of respondents);
k_i = 0, 1, 2, ..., m_i) (m_i is the number of categories minus 1 of the i-th item);
b_{i,k_i}: is the difficulty parameter of the k-th category of item *i*, this parameter is known as the location parameter. The difficulty parameter refers to the latent trait level at which the probability of a respondent selecting a response category or a higher order category is 0.50;
a_i: is the discrimination parameter of item *i*: this parameter represents how much an item discriminates between respondents at different levels of the latent trait, determining the "quality" of the item. The higher the value of this parameter, the better the item and the discrimination between respondents at different latent trait levels;
θ_j: is the parameter of respondent *j*, it represents the respondent's score, that is, the respondent's level of satisfaction with the CELESC energy distributor within the IRT;
$P_{i,k}^{+(\theta_j)}$ is the probability of the j-th respondent with Satisfaction level θ_j being in a given category k_i or higher than the i-th Satisfaction level.

The probability of a respondent j choosing a category k in item *i* is given by Eq. (2) [33, 40, 41]:

$$\begin{aligned} P_{i,k_i}(\theta_j) &= P_{i,k}^{+}(\theta_j) - P_{i,k+1}^{+}(\theta_j) \\ &= \frac{1}{1 + e^{-a_i(\theta_j - b_{i,k})}} - \frac{1}{1 + e^{-a_i(\theta_j - \mathrm{b}_{i,k+1})}} \end{aligned} \quad (2)$$

such that:

$$P_{i,0}^{+}\left(\theta_j\right) = 1 \quad (3)$$

It is observed that, in an item with (m_i + 1) categories, the difficulty parameters m_i need to be estimated, in addition to the item discrimination parameter and according to the definition $b_{i,1} \leq b_{i,2} \leq ... \leq b_{i,m_i}$.

Thus, for each item, the number of parameters to be estimated will be given by its number of response categories minus 1. A contribution of IRT is the amount of information provided for each item at different levels of the latent trait scale. The information function indicates the region of the latent trait where an item better discriminates between respondents, that is, it indicates how much better the item is at each level of the latent trait. These functions can be calculated for each item. The information functions in IRT play a significant role in the description of items, as they guide the choice of items and also verify the efficiency between different items

[42]. To assess the amount of discrimination that an item provides, the item information function (IIF) is used, which in the graded response model is given by Eq. (4):

$$I_i(\theta) = \sum\nolimits_{x=1}^{K_i} \frac{P'_{ik}(\theta)^2}{P_{ik}(\theta)'} \tag{4}$$

where $P'_{ik}(\theta)$ is the first derivative of the response curve of the category evaluated at a given level of the latent trait. The greater the discrimination of an item, the more information it provides to the test. The test's total information curve (TIC) is the sum of all the information functions of each item that composes it. The total information function is used to evaluate item performance, that is, how well a set of items is evaluating the latent trait and is related to the precision needed to estimate the latent trait, so that the standard error of the measurement can be estimated as the inverse of the square root of the total test information value at each latent trait level.

The estimation of the parameters Samejima's Graded Response Model can be done using Maximum Likelihood or Bayesian methods [43]. The estimation process of item and respondent parameters is implemented with R software [37] using the MIRT package [39]. The Graded Response Model evaluates only one latent trait. The verification of unidimensionality is done through Factor Analysis. To assess the unidimensionality of the instrument, Reckase's limit of 20% of the total variance was used [44]. Item calibration generated statistical estimates of item parameters. The satisfaction level was built using anchor levels and anchor items. For this construction, cumulative probability was used to position the items on the scale, according to their categories. Two consecutive levels in the latent trait are considered, X and Y, with X < Y an item *i* is measured as an anchor item at level Y [45] if:

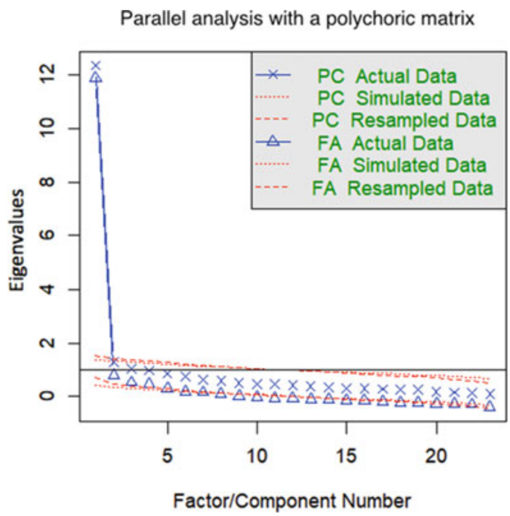
$$\begin{gathered} a_i \geq 1 \\ P(U = 1 | \theta = Y) \geq 0.60 \end{gathered} \tag{5}$$

Thus, the categories were positioned at the level where a respondent with that level has at least 60% probability of choosing that category or higher. The level of satisfaction of the electricity consumer of the analyzed CELESC distributor was estimated from the results obtained in the calibration. Information graphs of the characteristic curves and information curves for each item and the total information curve for the test were analyzed and presented.

4 Results and Discussions

The items answered in the research instrument were submitted to Cronbach's alpha and factor analysis using the criterion of parallel analysis [46] and the variance explained by the eigenvalues of the polychoric correlation matrix to verify the

Fig. 2 Parallel analysis under the polychoric matrix



dimensionality of the data. The result of Cronbach's alpha was 0.94, which demonstrates the reliability of the measure. Figure 2 shows the scree plot of the variance explained as a function of the number of factors (dimensions) of the set of items of the measurement of the "ANEEL index of consumer satisfaction at CELESC – Electricity Distributor".

According to Fig. 2, the parallel analysis indicates that the instrument has one dimension. It is verified that the self-value of the first component is 12.32 and that, in a set of 23 items, it represents 52.17% of the total variance explained by the first factor or first dimension. This result shows the existence of a single latent trait, and evidence that the instrument can be assumed as a one-dimensional IRT model. The result is consistent with the instrument, where the construct Perceived Quality measured from the dimensions: information to the customer, access to the company and reliability in the services, are considered the most important variables in the consumers' perception.

To assess the adequacy of the IRT model adjustment to the existing data, the model adjustment was performed based on measures of the Root-Mean-Square Error of Approximation (RMSEA), Standardized Root Mean Square Residual (SRMSR), Tucker-Lewis Index (TLI) and Comparative Fit Index (CFI) measures. According to Brown [47], RMSEA and SRMSR values below 0.05 are considered desirable for good model adjustment and for the Values of TLI and CFI are considered the values above 0.95 as indicative of good adjustment. The results found using the "M2" function, from the "Mirt" package of the R program, revealed RMSEA $= 0.053$; SRMRS $= 0.068$; TLI $= 0.954$; and CFI $= 0.959$, indicating a good adjustment for the model.

The estimation of the items' parameters and the calculation of the respondents' latent trait were performed using the Samejima's Gradual Response Model. Initially we grouped the categories as very dissatisfied and dissatisfied, Neither dissatisfied

Table 3 Estimate of discrimination (a) and difficulty (b) parameters in the ANEEL consumer satisfaction index

Items	a	SE(a1)	b1	SE(b1)	b2	SE(b2)	b3	SE(b3)
V7	1.557	0.126	−2.230	0.174	−1.093	0.101	1.169	0.107
V8	1.646	0.139	−3.006	0.253	−1.780	0.139	−0.030	0.074
V9	1.452	0.130	−2.800	0.243	−1.808	0.153	−0.090	0.08
V10	1.796	0.154	−1.939	0.156	−0.918	0.096	0.311	0.081
V11	1.902	0.154	−1.623	0.124	−0.943	0.089	0.244	0.074
V12	2.209	0.201	−2.693	0.214	−1.767	0.129	−0.573	0.072
V13	1.393	0.160	−2.033	0.225	−1.249	0.154	0.218	0.107
V14	2.159	0.173	−1.877	0.134	−1.066	0.089	0.137	0.069
V16	2.059	0.154	−1.298	0.100	−0.466	0.071	0.569	0.076
V17	1.336	0.150	−3.394	0.361	−2.409	0.233	−1.247	0.127
V18	1.489	0.124	−2.078	0.170	−1.091	0.106	0.580	0.088
V20	2.072	0.172	−1.742	0.131	−1.051	0.092	0.090	0.071
V21	2.402	0.208	−2.543	0.192	−1.493	0.109	−0.268	0.067
V90	2.069	0.166	−2.229	0.161	−1.241	0.097	0.137	0.070
V24	1.660	0.137	−1.743	0.130	−1.033	0.097	0.205	0.077
V25	1.955	0.143	−1.670	0.119	−0.291	0.069	1.052	0.091
V91	1.067	0.117	0.724	0.113	2.511	0.256	3.964	0.439
V92	1.921	0.147	−2.093	0.148	−0.908	0.083	1.161	0.095
V32	1.978	0.146	−1.797	0.125	−0.476	0.072	1.022	0.089
V37	2.293	0.175	−1.992	0.136	−1.031	0.083	0.232	0.067
V38	3.432	0.267	−1.451	0.089	−0.783	0.065	0.383	0.061
V93	1.027	0.101	−3.294	0.329	−0.874	0.122	0.582	0.112
V94	3.258	0.257	−1.490	0.095	−0.815	0.068	0.110	0.059

Source: Authors, data treated in R software
Note(s): SE: standard error of estimate; a: discrimination parameter; b: difficulty or location parameter (b1 = dissatisfied, b2 = neither dissatisfied nor satisfied, b3 = satisfied)

nor satisfied, satisfied and very satisfied, however we observed that the model showed low frequency in the categories very dissatisfied and dissatisfied, so we opted to group these categories. Table 3 presents the estimates of the coefficients of the one-dimensional IRT model: discrimination – parameter a; difficulty – parameter b; and their respective estimation errors (SE).

It can be seen in Table 3 that the parameter estimates are consistent, with most items showing good discrimination ($a > 1.02$). Items V7, V10, V12, V21, V25, V32, V37, V38, V90, V92, and V94 discriminate very well ($a7 = 1.557$, $a10 = 1.796$, $a12 = 2.209$, $a21 = 2.402$, $a25 = 1.955$, $a32 = 1.978$, $a37 = 2.293$, $a38 = 3.432$, $a90 = 2.069$, $a92 = 1.921$, and $a94 = 3.258$). On the other hand, item V91 and V93 have moderate discrimination $a91 = 1.067$ and $a93 = 1.027$, with item V91 being more difficult ($b91 = 0.724$). Figure 3 shows the characteristic curves of the items.

Positioning the items on the scale consists of locating the 23 items and their categories on the consumer satisfaction scale. According to Eq. 1, consumer satisfaction was estimated for each respondent. In addition, the item difficulty (parameter

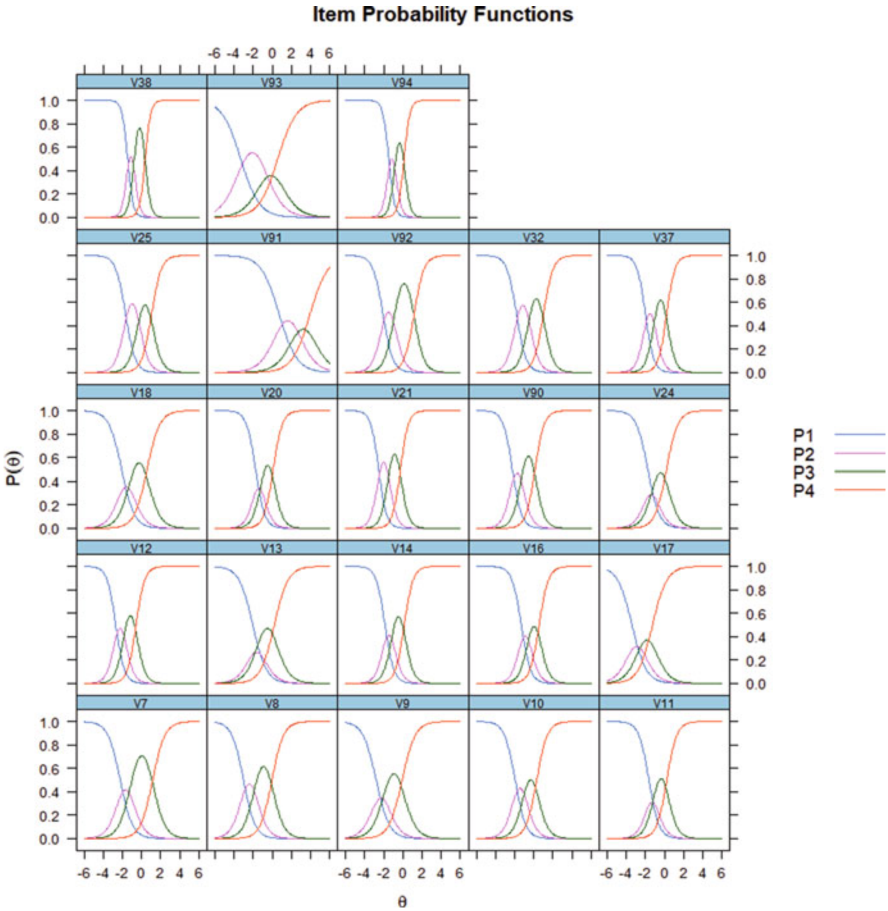


Fig. 3 Curve representing the probability of consumer satisfaction of the items as a function of θ

b) and the score (θ) are on the same measurement scale. Then, all item parameters and the satisfaction level score were transformed into the metric (50, 10), where 50 refer to the mean of the 574 consumers and 10 refer to their standard deviation. The results of this step are shown in Fig. 4, and the interpretations of the levels are shown in Table 4.

According to the positioning of the responses of the items category, the interpretation of the scale level of consumer satisfaction of CELESC – Electricity Distributor is presented. The method presented estimates the difficulty of the item and the satisfaction on the same measurement scale, allowing a direct comparison between the score of each consumer and the items with the highest level of satisfaction for the consumer. When a consumer answers the questionnaire, their satisfaction with the company is measured and the value can be interpreted. The interpretation of the scale in the metric (50/10) is shown in Table 4. The authors defined five levels for the

Scale	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
	-3,5	-3	-2,5	-2	-1,5	-1	-0,5	0	0,5	1	1,5	2	2,5	3	3,5	4
b1 = (very dissatisfied + dissatisfied) to (neither dissatisfied / nor satisfied)		V17	V8 V9 V12	V7 V21 V90	V10 V13 V14 V18 V20 V24 V25 V91 V92 V32 V37 V93	V11 V16 V38 V94										
b2 = (neither dissatisfied / nor satisfied) for satisfied				V17	V8 V9 V12	V13 V21 V90	V7 V10 V11 V14 V18 V20 V24 V92 V37 V38 V93 V94	V16 V25 V32						V91		
b3 = (satisfied to very satisfied)						V17		V12 V21 V90 V24	V8 V9 V10 V11 V13 V14 V20 V37 V38 V94	V16 V18 V93	V7 V25 V92 V32					V91
Level of satisfaction	Very dissatisfied			Dissatisfied			Neither dissatisfied/nor satisfied			Satisfied			Very satisfied			
% Sample consumers	1,05%			15,85%			55,75%			26,31%			1,05%			

Fig. 4 Position of responses for item category b1 (dissatisfied), b2 (Neither dissatisfied/Not satisfied and b3 (satisfied) on the scale (0.1)/(50/10)

interpretation of the scale from: Very dissatisfied, dissatisfied, neither dissatisfied/ not satisfied and satisfied and very satisfied.

To analyze the reliability of the scale, the IRT makes it possible to analyze it through the test's information curve. The purpose of the graph is to identify for which intervals of the latent trait the scale has more information [48]. The graph in Fig. 5 shows the test information curve given by the sum of the instrument's item information. It can be noticed that the set of 23 items produces good information between the interval −4.0 to 2.0 where the continuous line shows the test information curve, and the dotted line presents the measurement standard error, according to the "latent trait" level. The total information curve generated demonstrates the region of the scale in which the instrument is most reliable to measure the level of satisfaction of the residential consumer of CELESC electricity distributor.

Table 4 Interpretation of the levels of the consumer satisfaction scale at CELESC Electricity Distributor

Level of satisfaction	Level interpretation
$10 < \text{item} \leq 25$ points	The respondent at this level of the satisfaction scale probably selected the option “Very dissatisfied” in the items “Easy access to points for receiving and paying the electricity bill” and “Constant energy supply, that is, without a power outage”.
$25 < \text{item} \leq 40$ points	Respondents at this level feel very dissatisfied or dissatisfied in some of the aspects related to Customer information (V24, V90, V21 and V16), Company access (V11, V14, V10) and service reliability (V13, V18 and V20). They feel neither dissatisfied nor satisfied regarding reliability of services as can be seen in items (V8, V9, V13), Company Access (V12 and V17) and Customer Information (V21 and V90).
$40 < \text{item} \leq 55$ points	Respondents at this level feel neither dissatisfied/nor satisfied with items related to access to the company (V11, V14, V10), customer information (V24, V16) and reliability of service (V18, V20), as well as items (V92) related to the perceived value construct, (V7, V25 and V32) to satisfaction, (V37 and V38) to confidence and (V93 and V94) related to Fidelity. They feel satisfied with some items such as: item V37 and V38 that question whether the consumer considers the company reliable, and whether it is concerned with the interests of its customers.
$55 < \text{item} \leq 70$ points	Respondents at this level are satisfied with the group of items V7, V16, V18, V25, V92 and V32. In item V32 for example, “Thinking about the quality of services, would you say that the company is “far from ideal”; “neither far /nor close to ideal” or “close to ideal?” respondents said that the company is close to ideal.
$70 < \text{item} \leq 90$ points	The respondents that are on this satisfaction scale probably on the item “Considering the Quality of the electricity supply, such as, for example, not missing or varying light, speed and punctuality in network repairs, early warnings, etc., how do you evaluate the Price paid?” respondents selected the option as neither expensive/nor cheap and cheap, being very satisfied.

The standard error of the measure demonstrates the amount of errors prevailing in the test, which is actually the inverse of the information I(θ), and whose scale can be seen on the right side. According to [49], the larger the test information curve, the smaller the estimation error.

The frequency of the scores on the satisfaction level of the respondents of the instrument was verified through the frequency distribution Fig. 6.

Most of the responses are on the neither dissatisfied/not satisfied and satisfied levels. Very satisfied and very dissatisfied had the lowest number of responses, however, in none of them the frequency for this category was zero.

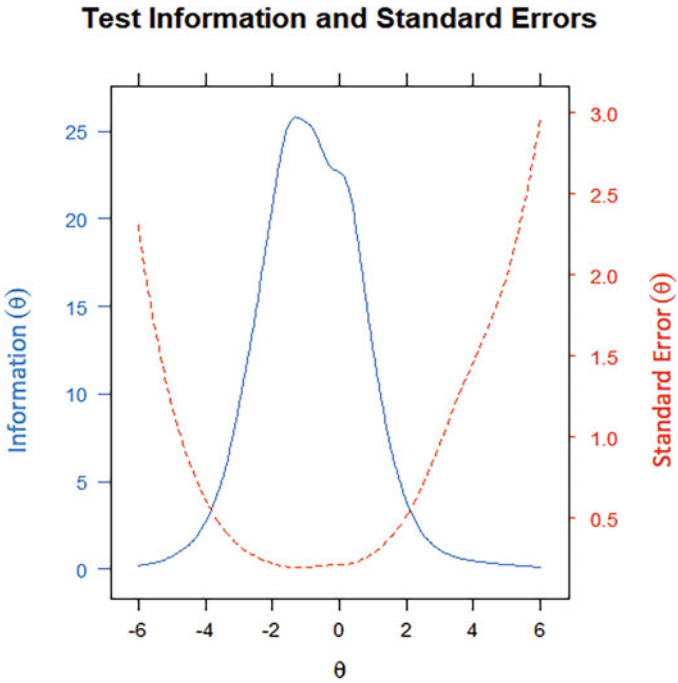


Fig. 5 Total information curve for the test

5 Conclusion

This research aimed to measure the ANEEL Customer Satisfaction Index of CELESC electricity distributor, using the Gradual Response Model of the Item Response Theory. The IRT provides the latent trait scores of each consumer by means of estimating parameters based on the model used, therefore considering the degree of difficulty of the items to compose the consumer's score.

The results showed that 1.05% of consumers are very dissatisfied with the CELESC energy distributor, 15.85% are dissatisfied, and 55.75% are neither dissatisfied/nor satisfied; 26.31% are satisfied; and 1.05% is very satisfied with the energy distributor.

The created scale allows the energy distributor to monitor the measured indicators and evaluate the evolution of consumer satisfaction. The use of this scale will allow the power company to achieve consumer satisfaction if it demonstrates concern for them, providing correct and accurate information when requested, as well as, when demonstrating confidence in the service provided, such as "speed of energy return when there is an interruption".

Other factors that can lead to consumer satisfaction are the perceived value in the economic dimension, indicating that the "energy supply will be constant, that is,

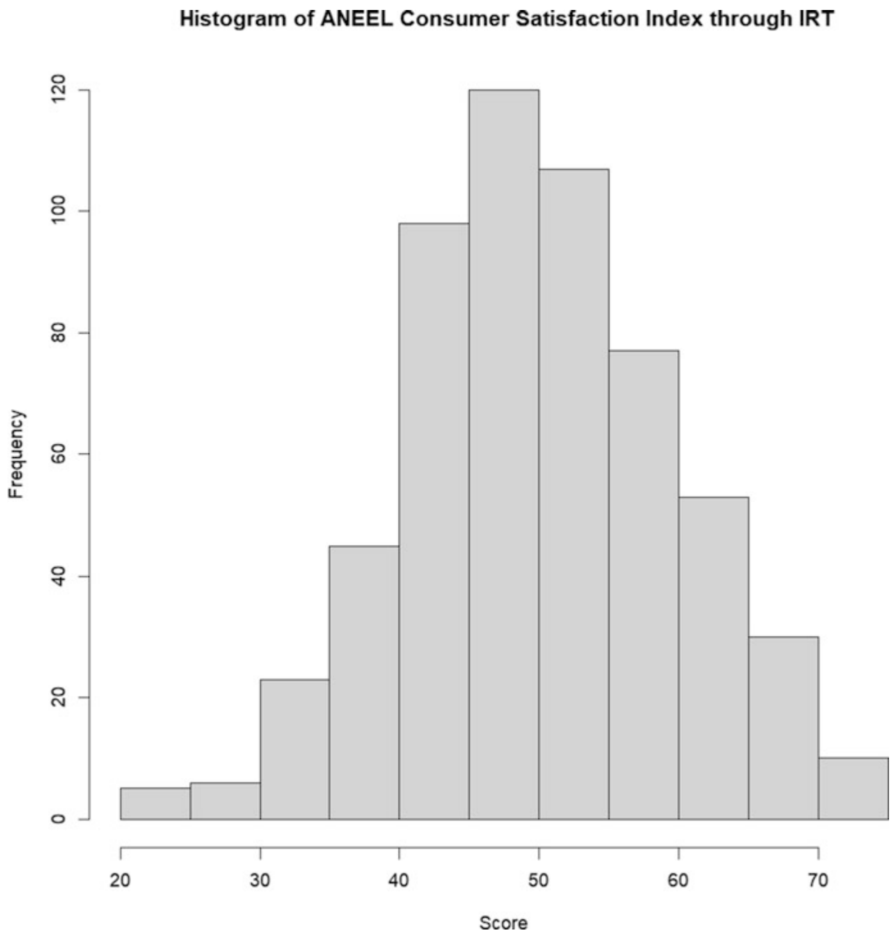


Fig. 6 Histogram with frequency distribution

without power outages", as well as that customer service is done with courtesy and good will of the employee, seeking to solve the problem.

Although consumers are neither dissatisfied/nor satisfied with the amount paid for their bills, they cannot turn to another company, because currently there is a natural monopoly of the electric energy distribution service and the CELESC electric energy distributor, serves the largest number of cities (285) in Santa Catarina. Other distributors for example, the Santa Catarina Electric Energy Distributor Ltda (DCELT) serves 8 cities, the Board of Directors of Cooperativa Aliança (COOPERALIANÇA) serves 4, and the Company Strength and light João Cesa (EFLJC) and Strength and light Company of Urussanga Ltda (EFLUL) serve 1 city each.

Managers to develop strategies to improve the level of consumer satisfaction can use the model created, to achieve continual improvement in service delivery of the Electricity Distributor.

This research differs from the others by offering a tool where managers can interpret the values of the scale and, consequently, define the necessary actions to improve the satisfaction of their consumer.

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References

1. Brasil, *Lei n°. 9.427 de 26 de dezembro de 1996 disponível em* https://legislacao.presidencia.gov.br/atos/?tipo=LEI&numero=9427&ano=1996&ato=f17MTQE5UMJpWT87f. 1996, Diário Oficial da União.
2. Brasil, *Decreto n° 2.335, de 6 de outubro de 1997: Constitui a Agência Nacional de Energia Elétrica-ANEEL, autarquia sob regime especial, aprova sua Estrutura Regimental eo Quadro Demonstrativo dos Cargos em Comissão e Funções de Confiança e dá outras providências*. 1997, Diário Oficial da União.
3. Almeida, R.S., et al. *Qualidade do serviço, satisfação do consumidor e desempenho financeiro das empresas distribuidoras de energia elétrica brasileiras*. in *Anais do Congresso Brasileiro de Custos-ABC*. 2010.
4. Santos Neto, A.S., et al., *Measure of customer satisfaction in the residential electricity distribution service using structural equation modeling*. Energies, 2022. **15**(3): p. 746.
5. Marchetti, R. and P.H. Prado, *Avaliação da satisfação do consumidor utilizando o método de equações estruturais: um modelo aplicado ao setor elétrico brasileiro.* Revista de administração contemporânea, 2004. **8**: p. 9–32.
6. Chenhall, R.H. and K. Langfield-Smith, *Multiple Perspectives of Performance Measures.* European Management Journal, 2007. **25**(4): p. 266–282.
7. de Carvalho, M.S. and G.L. da Silva. *Inside the black box: using Explainable AI to improve Evidence-Based Policies*. in *2021 IEEE 23rd Conference on Business Informatics (CBI)*. 2021. IEEE.
8. Ishizaki, L.Y., J.C. Piai, and M.B. de Morais França. *Os indicadores da distribuição e a percepção da qualidade no fornecimento sob o ponto de vista do consumidor residencial de energia elétrica*. in *Simpósio Brasileiro de Automação Inteligente-SBAI*. 2021.
9. Duarte, P., S.C. e Silva, and M.B. Ferreira, *How convenient is it? Delivering online shopping convenience to enhance customer satisfaction and encourage e-WOM.* Journal of Retailing and Consumer Services, 2018. **44**: p. 161–169.
10. ANEEL, *Índice ANEEL de Satisfação do Consumidor (IASC)*. 2020: Agencia Nacional de Energia Elétrica. Disponível em: https://antigo.aneel.gov.br/iasc.
11. ANEEL, *Pesquisa sobre satisfação dos consumidores residenciais 2022: conheça os municípios participantes. Disponível em:* https://www.gov.br/aneel/pt-br/assuntos/noticias/2022/pesquisa-sobre-satisfacao-dos-consumidores-residenciais-2022-conheca-os-municipios-participantes. 2022.
12. Fornell, C., et al., *The American customer satisfaction index: nature, purpose, and findings.* Journal of marketing, 1996. **60**(4): p. 7–18.
13. ANEEL, *Metodologia IASC*. 2017, Brasília, Brasil.

14. de Andrade, D.F., H.R. Tavares, and R. da Cunha Valle, *Teoria da Resposta ao Item: conceitos e aplicações.* ABE, Sao Paulo, 2000.
15. Peixe, B.C.S., *Mensuração da maturidade do sistema de gestão ambiental de empresas industriais utilizando a teoria da resposta ao item.* 2014.
16. Tezza, R. and A.C. BORNIA, *Teoria da Resposta ao Item: vantagens e oportunidades para a engenharia de produção.* XXIX Encontro Nacional de Engenharia de Produção. Salvador-BA, 2009.
17. Trierweiller, A.C., et al., *Measuring environmental management disclosure in industries in Brazil with item response theory.* Journal of Cleaner Production, 2013. **47**: p. 298–305.
18. Reise, S.P., A.T. Ainsworth, and M.G. Haviland, *Item response theory: Fundamentals, applications, and promise in psychological research.* Current directions in psychological science, 2005. **14**(2): p. 95–101.
19. De Ayala, R.J., *The theory and practice of item response theory*. 2013: Guilford Publications.
20. Peng, L., et al., *A multi-facet item response theory approach to improve customer satisfaction using online product ratings.* Journal of the Academy of Marketing Science, 2019. **47**(5): p. 960–976.
21. Singh, J., *Tackling measurement problems with Item Response Theory: Principles, characteristics, and assessment, with an illustrative example.* Journal of Business Research, 2004. **57**(2): p. 184–208.
22. Bridi, E., et al., *Avaliação da qualidade em serviços na indústria hoteleira por meio da aplicação da teoria de resposta ao item.* Turismo: Visão e Ação, 2020. **21**: p. 173–194.
23. Fernandes, S.M. and A.C. Bornia, *Reporting on supply chain sustainability: Measurement using item response theory.* Corporate Social Responsibility and Environmental Management, 2019. **26**(1): p. 106–116.
24. Fernandes, S.M., R.G. NUNES, and A.C. Bornia. *A influência da composição do conselho de administração na evidenciação ambiental: uma análise nas empresas brasileiras*. in *Anais do Congresso Brasileiro de Custos-ABC*. 2017.
25. Wronski, S.M.F., *Mensuração do nível de disclosure ambiental utilizando a teoria da resposta ao item.* 2018.
26. da Silva Menegon, L., et al., *Design and validation of an aircraft seat comfort scale using item response theory.* Applied Ergonomics, 2017. **62**: p. 216–226.
27. Tirloni, A.S., et al., *Development and validation of instrument for ergonomic evaluation of tablet arm chairs.* EXCLI journal, 2016. **15**: p. 671.
28. Vincenzi, S.L., et al., *Assessment of environmental sustainability perception through item response theory: A case study in Brazil.* Journal of Cleaner Production, 2018. **170**: p. 1369–1386.
29. Cella, D., et al., *PROMIS® adult health profiles: efficient short-form measures of seven health domains.* Value in health, 2019. **22**(5): p. 537–544.
30. Bortolotti, S.L.V., et al., *Avaliação do nível de satisfação de alunos de uma instituição de ensino superior: uma aplicação da Teoria da Resposta ao Item.* Gestão & Produção, 2012. **19**(2): p. 287–302.
31. Giacomelli, S.d.C., et al., *Development of a Food-Based Diet Quality Scale for Brazilian schoolchildren using item response theory.* Nutrients, 2021. **13**(9): p. 3175.
32. Santos, T.S.S., et al., *A new measure of health motivation influencing food choices and its association with food intakes and nutritional biomarkers in European adolescents.* Public Health Nutrition, 2021. **24**(4): p. 685–695.
33. Samejima, F., *Estimation of latent ability using a response pattern of graded scores.* Psychometrika monograph supplement, 1969.
34. Muraki, E., *A generalized partial credit model: Application of an EM algorithm.* ETS Research Report Series, 1992. **1992**(1): p. i–30.
35. Bock, R.D., R. Gibbons, and E. Muraki, *Full information item factor analysis. Applied Psychological Measurement. 1988. 12: p. 261–280.*

36. Jöreskog, K.G. and I. Moustaki, *Factor analysis of ordinal variables with full information maximum likelihood.* unpublished report, 2006.
37. Team, R.C., *A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2022*. 2022.
38. Revelle, W., *Psych: Procedures for Psychological, Psychometric, and Personality Research [R Package Psych Version 2.2. 5].* 2022.
39. Chalmers, P., *Package mirt: Multidimensional Item Response Theory.* http://cran.r-project.org/web/packages/mirt/mirt.pdf. 2022.
40. Samejima, F., *A general model for free-response data.* Psychometrika Monograph Supplement, 1972.
41. Samejima, F., *Departure from normal assumptions: A promise for future psychometrics with substantive mathematical modeling.* Psychometrika, 1997. **62**(4): p. 471–493.
42. Hambleton, R.K., H. Swaminathan, and H.J. Rogers, *Fundamentals of item response theory*. Vol. 2. 1991: Sage.
43. Baker, F.B., *The basics of item response theory*. 2001: ERIC.
44. Reckase, M.D., *Reckase, M. D. (1979). Unifactor latent trait models applied to multifactor tests: Results and implications*. https://doi.org/10.3102/10769986004003207. Journal of Educational Statistics, 1979. **4**(3): p. 207–230.
45. Schmitt, J., et al., *WWH-dropout scale: when, why and how to measure propensity to drop out of undergraduate courses.* Journal of Applied Research in Higher Education, 2020.
46. Horn, J.L., *A rationale and test for the number of factors in factor analysis.* Psychometrika, 1965. **30**(2): p. 179–185.
47. Brown, T.A., *Confirmatory factor analysis for applied research*. 2015: Guilford publications.
48. Pasquali, L., *Psicometria: teoria dos testes na psicologia e na educação*. 2017: Editora Vozes Limitada.
49. Gomes, D.E., *Criação de uma escala para avaliar a percepção dos funcionários de hospitais universitários no Brasil quanto ao ambiente organizacional.* 2014.

Edtechs in the Context of the Industry in Digital Transformation: Main Research Directions

Jocasta Oliveira Maciel, Leozenir Mendes Betim, and Joseane Pontes

Abstract Digital skills and capabilities are among the key requirements of the new digital age. However, to qualify professionals for the digital transformation of Industry 4.0 and 5.0 in the manufacturing sector, it is necessary to adopt new forms of teaching, explore technologies and promote lifelong learning. In this way, new business models must represent disruptive changes that satisfy the market's search for qualified professionals. In this context, Edtechs as startup companies are innovating by transforming teaching through Industry 4.0 technologies, for example, bringing strategies to qualify people for digital transformation, whether by developing online teaching platforms or training people for Industry 4.0 and 5.0. Therefore, research is needed to understand how Edtechs are working on digital transformation and its impact on the future of education and workforce. Thus, the aim of this article is to review the main themes that guide research on Edtechs for digital transformation. For this purpose, a systematic literature review based on the PRISMA methodology, a bibliometric analysis using the VOSviewer software and a qualitative analysis of the portfolio themes using NVIVO 12 were carried out. As main results, 94 articles were found whose themes were highlighted: Learning, Digital, Technologies, Education and System. This shows that the focus of Edtechs is on education, digital learning, and training for new jobs through disruptive technologies.

Keywords Edtech · Digital transformation · Educational technology

1 Introduction

The fourth industrial revolution, along with disruptive technologies such as big data, cloud computing, the Internet of Things, and CPS, is creating a digital revolution in industry and in various aspects of society [1, 2]. Industry 5.0, on the other hand, uses

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technology as a provider of opportunities for people, putting them at the center of the process and focusing on resilience and well-being [3]. One major change is work. According to [4], about 85 million jobs will be updated by 2025, and another 97 million are expected to be created during this period. In this way, jobs are changing rapidly, many activities now require profiles with high qualifications, different skills and competences, and with this comes the need for qualification and re-qualification of the workforce to face this new digital age [5, 6].

People with digital skills are able to use online services such as paying bills, shopping, checking the news, creating content, etc. correctly, which makes life easier and creates more opportunities for personal and professional development [7]. The work of the future will also depend on professionals with digital skills as workers become increasingly autonomous and skilled [8–10].

For the digital transformation to take place, it is necessary to adopt new forms of learning, to invest in digital technologies, digital literacy and organizational culture, both for industry and for education [11, 12]. However, current universities are still not adequately preparing students for this new labor market reality [13], as topics such as artificial intelligence, ethics, sustainability, human-machine interaction, and CPS are not yet part of the curriculum [14].

Therefore, to drive digital transformation, new business models need to meet the demands of the current job market by exploring emerging markets and making disruptive changes [15, 16]. It is in this context that education-focused startups, also known as EdTechs or even Edutechs, are emerging. Although there is still no consensus on the definition of EdTechs, the Association for Educational Communications and Technology [17] defines them as the ethical use of technological processes to improve performance and facilitate learning. For the World Bank [18], EdTechs "support and enrich teaching and learning, and improve the management and delivery of education".

EdTechs are growing in the global market, especially after being accelerated by the Covid pandemic, in which schools and universities around the world had to migrate to online teaching in order to continue their activities [16, 19]. According to a survey conducted in January 2021 by the global education market intelligence platform Holon IQ [20], the updated size of Edtechs in the pre-Covid scenario was $63 billion, with an estimated investment of $ 404 billion by 2025.

In this context, it is important to study Edtechs to understand their impact on digital transformation and, in particular, the trends and research drivers in the face of the education scenario. Having this in mind, the aim of this paper is to identify the main themes that drive research in Edtechs for digital transformation. In order to achieve the objective of this article, a systematic literature review will be carried out using the PRISMA methodology, a bibliometric analysis using the VOSviewer software and a qualitative analysis of the portfolio themes using NVIVO 12.

This paper is organized in the following format: Sect. 2 presents Digital Transformation in Industries and Edtechs, reporting concepts about industry 4.0, 5.0 and Edtechs. Section 3 presents the steps for searching and analyzing the article portfolio by means of a Systematic Literature Review and Bibliometric and Content Analysis. Section 4 presents the results and Discussions, subdivided into sections presenting the bibliometric analysis and content analysis: Digital technologies embedded in lean 4.0 tools and Benefits of integrating digital and lean technologies and their areas of research. Finally, Sect. 4 presents the final considerations.

2 Digital Transformation in Industries and Edtechs

2.1 Digital Transformation in Industries 4.0 and 5.0

The fourth industrial revolution is characterized by the use of disruptive technologies (big data, IoT, CPS, additive manufacturing, robotics, artificial intelligence) and a digital revolution in which processes are intelligent, highly automated, and monitored in real time, enabling the creation of personalized and high-quality products [2, 21].

However, like previous revolutions, Industry 4.0 focuses on increasing process efficiency and making the factory smarter, but leaves aside the human factor in this evolution [22]. The solution to this problem emerges in Industry 5.0 as it is human-centric, seeks greater integration between humans and machines, and values human aspects such as leadership, creativity, decision making, and critical vision [23].

Digital transformation is common to all sectors of the economy, but it stands out in the manufacturing sector for both Industry 4.0 and Industry 5.0. Deloitte [24] showed that between 2018 and 2028, there will be a deficit of 2.4 million unfilled jobs in the manufacturing sector worldwide, which will have an economic impact of $2.5 trillion. In addition, digital transformation is inserted in the daily life of people in the digital age, at work with interaction with intelligent machines and in private life there is interaction between people through social networks and applications [25]. However, the digital transformation is progressing so fast that most people still do not have the necessary skills to deal with it. Therefore, it is necessary to train workers and students to have digital fluency so that they can be qualified to solve digital problems quickly in the rapidly changing technological scenario [26]. Therefore, it is necessary to create training programs for the development of digital skills for the workforce required in the current and future work of Industry 4.0 and 5.0 [27].

2.2 Edtechs

The word Edtech comes from the intersection of education and technology, and according to [17] its definition is: “The study and ethical application of theory, research, and best practices to advance knowledge”. However, the term is still not widely used in the literature, and more research is needed on the topic. According to the [18], Edtechs are innovating in education by providing strategies to prepare students for digital transformation and by creating learning networks with stronger connections between teachers, students, parents, and communities.

However, Edtechs are not just limited to educational technologies and the field of education, they have become a major market in Economy 4.0 around the world. The industry has become a multi-billion dollar industry involving many people, business analysts, managers, venture capitalists and private companies. One example is Edtech BYJU'S, which was one of the biggest sponsors of the 2022 FIFA World Cup, along with ADIDAS, Coca Cola, and Visa [28]. According to [20], by the year 2025, approximately $7.3 trillion will be spent globally on education by governments, businesses, and consumers, but this investment is still considered small compared to other sectors, as the world is going through a new industrial revolution and needs specialized education to qualify and re-qualify workers for the new market reality.

3 Methodology

In order to identify the main topics that drive research in edtech, it was necessary to carry out a systematic literature review based on the PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). Initially, a search was carried out in two databases, Scopus and Web of Science, using the keywords of the topic, with the characteristics of the research as shown in Table 1. In order to obtain a greater number of articles related to the topic, it was decided to use

Table 1 Research protocol

Directions	Protocol
Search terms (Title, Abstract and Keywords)	**Group 1 (Edtech):** "Edtech" OR "Education Technology" OR "Educational Industry" OR "Edutech" OR "Digital Education" OR "educational technology" OR "E-learning" OR "digital learning" **Group 2 (Industry 4.0 and 5.0):** "Industrie 5.0" OR "I5.0" OR "Industry 5.0" OR "Fifth Industrial Revolution" OR "society 5.0" OR "5th Industrial Revolution" OR "Industrie 4.0" OR "Industry 4.0" OR "I4.0" OR "Fourth Industrial Revolution" OR "Fourth Industrial Revolution Internet" OR "4th Industrial Revolution" OR "Smart Industry" OR "Smart Manufacturing" OR "Smart Factory" OR "Digital Transformation" OR "cyber physical system" OR "CPSs"
Search process	OR and AND Boolean Operators
Data base	Scopus (1282) and Web of Science (293)
Publication types	Papers, conference papers, and book chapters
Language	English
Timeline	There was no time cut

Source: Prepared by the authors

synonyms of the words found in the literature and the Boolean operators OR to differentiate them and AND to connect a group of researchers.

The four phases of the PRISMA methodology were then carried out, as follows:

- **Identification:** Initial phase in which the selected databases are searched according to the research protocol and duplicate articles are removed using Mendeley.
- **Screening:** Filtering phase of the articles based on the indication of the methodology, where the articles are first excluded after reading the title, then the abstract and finally the whole article.
- **Inclusion:** Inclusion phase of other articles on the topic to integrate the final research portfolio.

4 Results and Discussions

4.1 Bibliometric Analysis

From the portfolio articles, Excel software was used to organize the data and identify the distribution of publications over the years as shown in Fig. 1.

It is noteworthy that the first portfolio articles on this topic were written in 2017, and the number of publications increased over time. In 2021, many publications were obtained, 33 in total. In 2022, 17 articles were registered until the date of this research. With this data, it is possible to see that the topic is growing, as it is a current and relevant topic in the context of the digital age. Using the VOSviewer software, an analysis was made of the main keywords used in the articles, as shown in Fig. 2. The criterion used was a minimum frequency of 5 times in the articles.

In Fig. 2, we can identify that the main keywords are Industry, Training, Course, Work and Covid. The focus on these words shows the training trend for new jobs.

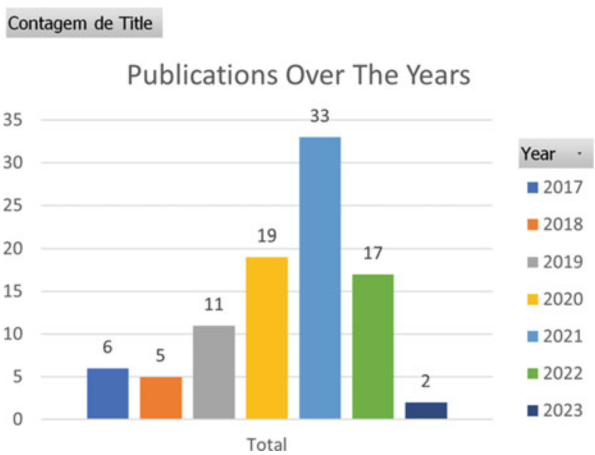

Fig. 1 Publications over the years. (Source: Prepared by the authors)

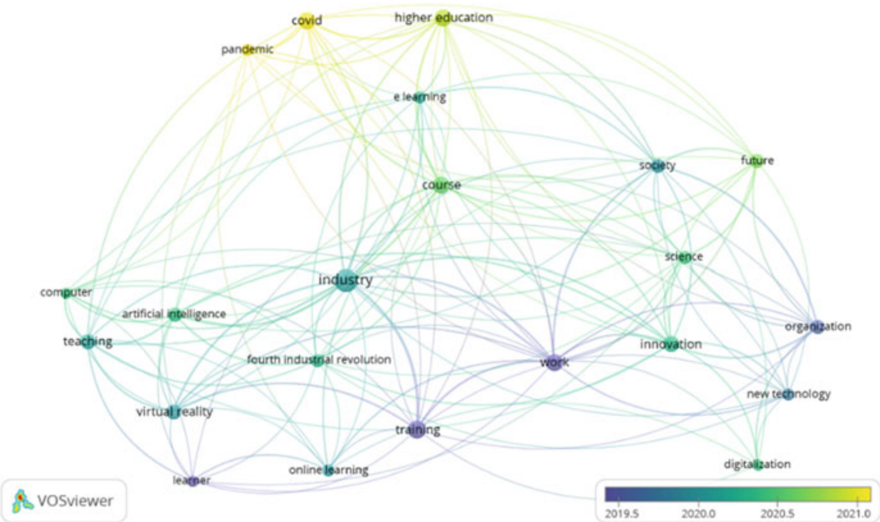

Fig. 2 Main keywords. (Source: Prepared by the authors)

However, all the words highlighted in the figure are relevant to the theme studied, such as Fourth Industrial Revolution, New Technology, Society, among others, since technologies are important factors for Edtechs within the 4.0 industry and the digital age.

The Fig. 2 also shows the correlations between the words and the diameter of the circle represents the intensity between them. The correlations between the words and the diameter of the circle represents the intensity between them. The colors show when they were most cited over the years, for example Covid and Pandemic are in yellow and represent the year 2021, the analysis is consistent considering that the pandemic started in 2020 and researchers started to publish from that year, intensifying publications in 2021. In addition, with the Covid 19 pandemic, there was a growth of Edtechs in the world, mainly due to the migration to online teaching due to the lockdown.

4.2 *Qualitative Analysis*

A qualitative analysis of the portfolio of 94 articles was performed using NVIVO 12 software. This produced a word cloud, shown in Fig. 3, of the 50 most frequent terms in the portfolio articles.

It is noted that the words "learning", "education", "digital", "students", "training", and "technology" are the highlights within the portfolio, which shows that the portfolio is appropriate to the topic studied. All these words are part of the Edtech theme and are related to digital transformation.

Fig. 3 Word cloud. (Source: Prepared by the authors)

4.3 Main Research Drivers for Edtechs in the Context of Industrial Digital Transformation

Next, the NVIVO 12 automatic coding was used to identify the main research drivers of the portfolio according to common terms among the articles. Table 2 shows the main research drivers in Edtechs in the context of digital transformation for industries (*EdIDT*).

EdIDT-Learning Presents teaching and social development strategies, hybrid interaction, online communities to discuss topics for learning and developing digital skills and the challenges of education in the digital age. Edtechs develop technology solutions to overcome the barriers of digital learning for digital transformation with industries.

EdIDT-Digital This theme shows ways to transform schools and universities to the digital environment from platforms, stimulus to digitalization and also the development of skills such as: programming, problem solving, critical analysis of information veracity, ethics and digital behavior, development and learning of applications and also cybersecurity to avoid kidnapping and data theft. Edtechs mainly contribute to the development of technologies for digital transformation and foster the development of skills in industries.

EdIDT-Technologies Industry 4.0 technologies need to be used in education, especially for engineering students, as they will work directly in developing specific solutions to industry 4.0 and 5.0 problems. When engineers and other workers do not have this qualification, industries need to promote this development. Edtechs

Table 2 Main research driving themes

Research drivers (Ed-IDT)	Keywords	Main research topics	Main portfolio authors
EdIDT -Learning	Digital transformation; Digital learning; Online learning.	Teaching strategies to increase student engagement; Learning and Digital Literacy; Digital transformation challenges.	[29–31]
EdIDT-Digital	Digital transformation; Training; Digital education; Digital competence; Digital technologies.	Developing of online communities for learning (online platforms for learning, sharing and exchanging ideas, both for students and teachers); Skills for success in the digital age; School digitalization (modernization of schools and universities using digital technologies for digital transformation)	[30, 32, 33]
EdIDT-Technologies	Cyber-physical systems; Artificial intelligence; Digital twin; Engineering education; Industry 4.0; Industry 5.0.	The Future of Engineering Education; Cloud technology for the future (cloud infrastructure for storing scientific data that is open to the community); Cyber Physical Systems for students (teaching and application for implementation in Industry 4.0)	[14, 33–35, 37]
EdIDT-Education	Digital education; Online education; Education; Open education.	Transition to Digital Education; Educate students to be leaders in new careers; Lifelong learning	[34, 36, 38]
EdIDT-System	New education system; Barriers; Digital education ecosystem	Barriers to Digital Transformation in Higher Education; New teaching systems and methods.	[14, 39, 40]

Source: Prepared by the authors

develop technologies, create specific training for students to qualify and provide support to schools, universities, and industries.

EdIDT-Education This theme focuses on long-term and lifelong digital education. Edtechs provide continuing education for people to upgrade and re-qualify for the job market. In this sense, there is a need to change the structure of engineering courses to meet the workforce: engineering integrated into programming, data and problem solving through transdisciplinary, as well as ethics focused on artificial intelligence and ethical digital behavior. Another aspect is the need for leadership in engineering aimed at contact with intelligent machines and people.

EdIDT-System This theme presents the new learning systems and the ethical, cultural, and political barriers surrounding the systems on updating higher education trainers for the digital transformation era. Another barrier is about the difficulties, in various aspects, of the instructors on the self-development of skills related to digital transformation and the ethical way of dealing with this transformation, especially regarding artificial intelligence. The articles point out that Edtechs help to overcome these barriers in industries.

5 Conclusion

Digital transformation is transforming many aspects of society, including education and work. The work of the future requires new digital skills, and for this, it is necessary to digitize and innovate teaching in order to qualify the workforce required by the market. In this scenario, Edtechs transform teaching through the use of digital technologies. In academia, it is a relevant topic that needs research. Therefore, the aim of this work was to verify the main driving themes of Edtechs in the context of industries undergoing digital transformation.

Based on the methodology used in chapter "An Approach to the Design of Resilient Biomass Supply Chain Using Discrete Event Simulation", the general objective was achieved, as the five most relevant themes for guiding research in Edtechs were: Learning, Digital, Technologies, Education, and System. Among the most relevant keywords within this theme were learning, digital, transformation, education, students, technology, training, virtual and industry. Therefore, the main contribution of this work is to visualize the themes in Edtechs for digital transformation to contribute and facilitate future research on this topic. In addition, this research contributes to the theoretical contribution of Edtechs and the digital age in the literature, since they are growing terms that need even more investigation.

The relevance of this study lies in the fact that they are emerging and necessary topics to be studied in order to understand the changes in teaching and learning to qualify the workforce, resulting from the industrial digital transformation in society. Only from the research and development of emerging themes, it will be possible to understand the different learning and innovation needs of the workforce in the context of industry in digital transformation. Therefore, the analysis of dynamic and innovative business models, such as Edtechs that innovate in this field, becomes a fundamental premise to observe emerging themes and specific and necessary research for industries undergoing digital transformation.

As a limitation, this work was carried out with articles from only two databases (Scopus and Web of Science). Therefore, for future work, it is suggested to research more bases and to cover more case studies with educational startups to identify the barriers, advantages and new forms of teaching developed by them in different countries of the world.

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References

1. Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration*, *6*, 1–10. https://doi.org/10.1016/j.jii.2017.04.005
2. Schwab, K. (2019). *A quarta revolução industrial*. Edipro.
3. Xu, X., Lu, Y., Vogel-heuser, B., & Wang, L. (2021). Industry 4 . 0 and Industry 5 . 0 — Inception, conception and perception. *Journal of Manufacturing Systems*, *61*(September), 530–535. https://doi.org/10.1016/j.jmsy.2021.10.006
4. World Economic Forum. (2020). The future of jobs report 2020 | world economic forum. *The Future of Jobs Report*, (October), 1163. Retrieved from https://www.weforum.org/reports/the-future-of-jobs-report-2020/digest
5. Pontes, J., Geraldes, C. A. S., Fernandes, F. P., Sakurada, L., Rasmussen, A. L., Christiansen, L., . . . Leitao, P. (2021). Relationship between Trends, Job Profiles, Skills and Training Programs in the Factory of the Future. *Proceedings of the IEEE International Conference on Industrial Technology*, *2021-March*, 1240–1245. https://doi.org/10.1109/ICIT46573.2021.9453584
6. Sakurada, L., Geraldes, C. A. S., Fernandes, F. P., Pontes, J., & Leitão, P. (2021). Analysis of New Job Profiles for the Factory of the Future. *Studies in Computational Intelligence*, *952*, 262–273. https://doi.org/10.1007/978-3-030-69373-2_18
7. Mišianiková, A., Hubeňáková, V., Kireš, M., Babinčáková, M., & Šveda, D. (2021). Assessment of Digitalization in Primary and Secondary Schools by SELFIE Survey as a part of School Leaders Training, 252–258.
8. da Silva, L., Perota, B., Treinta, F. T., Mauricio, L., Resende, M. De, Tadashi, R., & Pontes, J. (2022). Evolution of Soft Skills for Engineering Education in the Digital Era, 1–15.
9. Kolade, O., & Owoseni, A. (2022). Employment 5.0: The work of the future and the future of work. *Technology in Society*, *71*(June), 102086. https://doi.org/10.1016/j.techsoc.2022.102086
10. Rossi, A. H. G., Marcondes, G. B., Pontes, J., Leitao, P., Treinta, F. T., De Resende, L. M. M., . . . Yoshino, R. T. (2022). Lean Tools in the Context of Industry 4.0: Literature Review, Implementation and Trends. *Sustainability*, *14*(19). https://doi.org/10.3390/su141912295
11. Abad-Segura, E., González-Zamar, M. D., Infante-Moro, J. C., & García, G. R. (2020). Sustainable management of digital transformation in higher education: Global research trends. *Sustainability (Switzerland)*, *12*(5). https://doi.org/10.3390/su12052107
12. Borin, B., Caroli, M., Casalino, N., Cavallari, M., Di Carluccio, N., Di Nauta, P., & Pizzolo, G. (2022). A New Approach to Enhance the Strategic Impact of Digital Education in Universities and to Foster the Development of a High Performing Common EU Smart Education Ecosystem. In U. V.L., H. R.J., & J. L.C. (Eds.), *Smart Innovation, Systems and Technologies* (Vol. 305 SIST, pp. 211–229). Luiss Business School, Rome, Italy: Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-981-19-3112-3_20
13. Iensen, M. H. F., da Silva, L. B. P., & Pontes, J. (2023). Educational Testbed in the Context of Industry 4.0 and 5.0: Literature Review. In *Optimization, Learning Algorithms and Applications: Second International Conference, OL2A 2022, Póvoa de Varzim, Portugal, October 24-25, 2022, Proceedings* (pp. 667–682). Springer.
14. Gürdür Broo, D., Kaynak, O., & Sait, S. M. (2022). Rethinking engineering education at the age of industry 5.0. *Journal of Industrial Information Integration*, *25*(May 2021), 100311. https://doi.org/10.1016/j.jii.2021.100311

15. Fernandes, C. H., Treinta, F. T., & Pontes, J. (2021). Tecnologias Digitais Identificadas em Fintechs: Uma Revisão Sistemática da Literatura. Retrieved from http://redepdimat.org/engbrasil2021
16. Soto-Acosta, P. (2020). COVID-19 Pandemic: Shifting Digital Transformation to a High-Speed Gear. *Information Systems Management*, *37*(4), 260–266. https://doi.org/10.1080/10580530.2020.1814461
17. AECT (Association For Educational Communications e Technology). (n.d.). Definition for Educational Technology. Retrieved September 22, 2022, from https://aect.org/news_manager.php?page=17578
18. Reimagining Human Connections: Technology and Innovation in Education at the World Bank. (n.d.). *World Bank*. Retrieved October 15, 2022, from https://www.worldbank.org/en/topic/edutech/publication/reimagining-human-connections-technology-and-innovation-in-education-at-world-bank
19. Dhawan, S. (2020). Online Learning: A Panacea in the Time of COVID-19 Crisis. *Journal of Educational Technology Systems*, *49*(1), 5–22. https://doi.org/10.1177/0047239520934018
20. Holon IQ. (2021). Global-Learning-Landscape-Handbook.
21. Kagermann, H., & Wahlster, W. (2022). Ten Years of Industrie 4.0. *Sci*, *4*(3), 26. https://doi.org/10.3390/sci4030026
22. Nahavandi, S. (2019). INDUSTRY 5 . 0 - A Human-Centric Solution. *Sustainability*, *11*, 43–71.
23. Maddikunta, P. K. R., Pham, Q. V., B, P., Deepa, N., Dev, K., Gadekallu, T. R., ... Liyanage, M. (2022). Industry 5.0: A survey on enabling technologies and potential applications. *Journal of Industrial Information Integration*, *26*(August 2021), 100257. https://doi.org/10.1016/j.jii.2021.100257
24. Preparing tomorrow's workforce for the Fourth Industrial Revolution For business: A framework for action. (2018). Delloite Company. Retrieved October 6, 2022, from https://www2.deloitte.com/content/dam/Deloitte/global/Documents/About-Deloitte/gx-preparing-tomorrow-workforce-for-4IR.pdf
25. Brunetti, F., Matt, D. T., Bonfanti, A., De Longhi, A., Pedrini, G., & Orzes, G. (2020). Digital transformation challenges: strategies emerging from a multi-stakeholder approach. *TQM Journal*, *32*(4), 697–724. https://doi.org/10.1108/TQM-12-2019-0309
26. Kateryna, A., Oleksandr, R., Mariia, T., Iryna, S., Evgen, K., & Anastasiia, L. (2020). Digital literacy development trends in the professional environment. *International Journal of Learning, Teaching and Educational Research*, *19*(7), 55–79. https://doi.org/10.26803/ijlter.19.7.4
27. da Silva, L. B. P., Barreto, B. P., Pontes, J., Treinta, F. T., de Resende, L. M. M., & Yoshino, R. T. (2021). Evaluation of Soft Skills Through Educational Testbed 4.0. *Communications in Computer and Information Science*, *1488 CCIS*, 678–690. https://doi.org/10.1007/978-3-030-91885-9_51
28. Williamson, B. (2022). Big EdTech. *Learning, Media and Technology*, *47*(2), 157–162. https://doi.org/10.1080/17439884.2022.2063888
29. Barber, W. (2020). Building Creative Critical Online Learning Communities through Digital Moments. *Electronic Journal of E-Learning, 18*(5), 387–396. https://doi.org/10.34190/JEL.18.5.002 WE - Emerging Sources Citation Index (ESCI)
30. Milenkova, V., Churukova, L., Ovchinnikova, A., & Solovyeva, T. (2022). Digitalization in Education and Learning Activities. In *Proceedings - 2022 2nd International Conference on Technology Enhanced Learning in Higher Education, TELE 2022* (pp. 334–339). Neofit Rilsky Southwestern University, Blagoevgrad, Bulgaria: Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/TELE55498.2022.9801057
31. Hiremath, N. V, Mohapatra, A. K., & Paila, A. S. (2021). A study on digital learning, learning and development interventions and learnability of working executives in corporates. *American Journal of Business*, *36*(1), 35–61. https://doi.org/10.1108/AJB-09-2020-0141
32. Henseruk, H., Buyak, B., & Kravets, V. (2020). Digital Transformation of the Learning, 325–335. https://doi.org/10.34916/el.2020.12.28

33. Misianikova, A., Hubenakova, V., Kires, M., Babincakova, M., Sveda, D., & Safarik, P. J. (2021). Assessment of Digitalization in Primary and Secondary Schools by SELFIE Survey as a part of School Leaders Training. In J. F. (Ed.), *ICETA 2021 - 19th IEEE International Conference on Emerging eLearning Technologies and Applications, Proceedings* (pp. 252–258). Institute of Biology and Ecology, Mánesova 23, KoŠice, 043 52, Slovakia: Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ICETA54173.2021.9726580
34. Iatsyshyn, A. V, Hubeladze, I. H., Kovach, V. O., Kovalenko, V. V, Artemchuk, V. O., Dvornyk, M. S., ... Kiv, A. E. (2020). Applying digital technologies for work management of young scientists' councils. In S. S.O. & S. M.P. (Eds.), (Vol. 2879, pp. 124–154). State Institution the Institute of Environmental Geochemistry, National Academy of Sciences of Ukraine, 34a Palladin Ave., Kyiv, 03680, Ukraine: CEUR-WS. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-85108026323&partnerID=40&md5=454f03e59978be5623e4f4de6f3de7f6
35. Peres, R. S., & Barata, J. (2021). Remote E-Learning for Cyber-Physical Production Systems in Higher Education. In *IEEE International Conference on Industrial Informatics (INDIN)* (Vol. 2021-July). Department of Electrical and Computer Engineering, School of Science and Technology, NOVA University of Lisbon, Caparica, 2829-516, Portugal: Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/INDIN45523.2021.9557429
36. Suárez, L. M. C., Núñez-Valdés, K., & Alpera, S. Q. Y. (2021). A systemic perspective for understanding digital transformation in higher education: Overview and subregional context in latin america as evidence. *Sustainability (Switzerland)*, *13*(23). https://doi.org/10.3390/su132312956
37. Iatsyshyn, A. V, Kovach, V. O., Romanenko, Y. O., & Iatsyshyn, A. V. (2019). Cloud services application ways for preparation of future PhD. In K. A.E. & S. V.N. (Eds.), *CEUR Workshop Proceedings* (Vol. 2433, pp. 197–216). Institute of Information Technologies and Learning Tools of NAES of Ukraine, 9, M. Berlynskoho Str., Kyiv, 04060, Ukraine: CEUR-WS. https://doi.org/10.55056/cte.380
38. Pisoni, G., Renouard, F., Segovia, J., Rossi, A., Molnar, B., & Mutanen, O. P. (2020). Design of small private online courses (SPOCs) for Innovation and entrepreneurship (IE) Doctoral-level education. In C. A., A. G.R., & R. T. (Eds.), *IEEE Global Engineering Education Conference, EDUCON* (Vol. 2020-April, pp. 1662–1668). University of Trento, Eit Digital, Italy: IEEE Computer Society. https://doi.org/10.1109/EDUCON45650.2020.9125153
39. Aditya, B. R., Ferdiana, R., & Kusumawardani, S. S. (2022). Identifying and prioritizing barriers to digital transformation in higher education: a case study in Indonesia. *International Journal of Innovation Science*, *14*(3–4), 445–460. https://doi.org/10.1108/IJIS-11-2020-0262
40. Gorlov, I. F., Fedotova, G. V., Glushchenko, A. V., Slozhenkina, M. I., & Mosolova, N. I. (2020). Digital Technologies in the Development of the Agro-Industrial Complex. In I. Gafurov & R. Valeeva (Eds.), *Lecture Notes in Networks and Systems* (Vol. 87, pp. 220–229). VI Vernadsky Crimean Fed Univ, Humanities & Educ Sci Acad Branch, 2a Sevastopolskaya St, Jalta 298635, Russia PU - PENSOFT Publishers PI - Sofia PA - GEO MILEV STR 13A, Sofia, 1111, Bulgaria. https://doi.org/10.1007/978-3-030-29586-8_26

An Environmental Analytical Model to Assess the Decarbonization Potential of Municipal Solid Waste-Based Hydrogen Production Routes

Francesco Facchini, Giorgio Mossa, and Micaela Vitti

Abstract The hydrogen production route currently identified as most promising from an environmental point of view is water electrolysis. This process does not produce direct emissions and is potentially zero-emission if fuelled by electricity from renewable sources. An electrolyser, however, has a high energy consumption (on average of 5 kWh/Nm^3H_2). This is a barrier to the implementation of electrolysis on an industrial scale. In this regard, the so-called Waste-to-Hydrogen routes represent a valuable alternative. They consist of treating waste to obtain hydrogen as a primary product. This paper aims to evaluate the decarbonisation potential of two MSW-based hydrogen production routes: a WtE plant coupled with an electrolyser (WtE+El) and a gasification plant with a syngas treatment unit to produce H_2 (WtH_2). Consistent with this end, the potentials of two hydrogen production routes were compared with the two most discussed hydrogen production routes. The first is the SMR process, considered the most widely used alternative for hydrogen production. The second is water electrolysis, considered the most promising from an environmental point of view. To this concern, an environmental analytical model was developed to evaluate each alternative based on its associated emissions. The results obtained from the application of the model showed that the best hydrogen production route from an environmental point of view is the WtH_2 route. It shows a total emission amount of 1.18 $kgCO_{2eq}/Nm^3H_2$, which is 8.5% lower than the SMR route, 31% lower than the El route and 63.2% lower than the WtE+El route.

Keywords Circular economy · Energy transition · Hydrogen production · Municipal solid waste management · Environmental analytical model

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1 Introduction

In the current tackle of climate change, the policies on the use of green energies have increased remarkably [1]. Hydrogen is considered a key element in the decarbonisation of the global economy. Its high energy density (about three times higher than gasoline) and the generation of water vapour only from its combustion make it a promising energy carrier. It finds applications in sectors such as transport (responsible for 20–25% of worldwide greenhouse gas emissions), power generation and buildings, and it shows high potential for decarbonising key "hard-to-abate" manufacturing sectors [2, 3]. The new industrialization era, so-called Industry 4.0, requires more energy-intensive technologies (e.g., human-computer-interface, robot, RF location systems, etc.) [4, 5]. This recent trend increases the difficulty to be converted into carbon-free sectors (e.g., cement, steel, and chemicals manufacture) [6]. Hydrogen is already used in these sectors; emissions from hydrogen production to serve "hard-to-abate sectors" are estimated to be 900 $MtCO_2$/y [7]. This significant emission value depends on the hydrogen production process. Currently, almost all hydrogen needed is produced from fossil sources (i.e., natural gas (NG)), mainly through the Steam Methane Reforming (SMR) process [2]. Therefore, an urgent challenge consists of finding solutions to produce low-carbon hydrogen. According to recent studies, in the next years, the identification of hydrogen as a key element for the decarbonisation of many industrial sectors will lead to a significant increase in its demand on a global scale. Consistent with this analysis, it is estimated that hydrogen demand, which has already tripled since 1975, will reach 215 Mt/y (i.e., 2.4 TNm^3/y) in 2030 [8]. The hydrogen production route currently identified as most promising from an environmental point of view is water electrolysis. It is the only hydrogen production route to be identified as potentially "green". This process does not produce direct emissions and, if fuelled by electricity from renewable sources, is potentially zero-emission [9]. An electrolyser, however, has a high energy consumption (on average of 5 kWh/Nm^3H_2). This is a barrier to the implementation of electrolysis on an industrial scale. From an economic point of view, the still high cost of renewable energy and the high cost of facilities make the installation of an electrolyser expansive in terms of operating and investment costs [10]. Moreover, from an environmental point of view, there is currently not enough renewable energy capacity to power the high-volume process. Indeed, it is estimated that an electricity demand of 3600 TWh is needed to produce all hydrogen currently used, more than the total annual electricity generation of the European Union [2]. This implies that an electrolyser must also be powered by electricity produced from fossil fuels (i.e., with the current national energy mix), generating significant indirect emissions. Therefore, a sustainable adoption on a large-scale of electrolysis process requires a rapid and radical energy transition. Consistent with this end, in the current transition phase, it is necessary to identify complementary hydrogen production routes that, on the one hand, ensure the growing demand for hydrogen is met and, on the other hand, enable the production of low-carbon hydrogen [11]. In this regard, the so-called Waste-to-Hydrogen (WtH_2) routes are to be mentioned. They consist of treating waste (e.g., Municipal Solid Waste (MSW), wood, food waste) to obtain hydrogen as a primary product. These solutions have a twofold benefit: on the one hand, they allow to produce hydrogen from alternative renewable sources, and on the other, they allow to manage MSW in accordance with a circular economy (CE) perspective. The MSW is produced globally with an increasing trend [12] and low environmental impact solutions must be promptly adopted in accordance with the so-called waste hierarchy. According to the waste hierarchy, where it is impossible to avoid waste production, reuse it, or recycle it, it should be valorised, recovering material and/or energy [13]. In this context, WtH_2 techniques ensure the valorisation of waste through the production of hydrogen, which can be used as an energy carrier or chemical. WtH_2 conversion methods can be split into thermochemical techniques (i.e., gasification and pyrolysis) and biological techniques (e.g., fermentation, etc.) [14]. To this concern, in [15] a thermodynamic analysis of a WtH_2 route consisting of a gasifier for the treatment of dried unsorted MSW, followed by a catalytic reactor for the steam reforming of the syngas produced, is carried out. The resulting gaseous mixture, composed mainly of CO and H_2, is subsequently sent to a high-temperature shift reactor and a low-temperature shift reactor that, through the so-called water-gas shift (WGS) reaction, make the gaseous mixture composed mainly of CO_2 and H_2. Finally, 99.9% pure hydrogen can be obtained via a pressure swing adsorption (PSA) process. Thermodynamic analysis of the system shows that it is possible to produce, under the operating conditions described, approximately 3 kgH_2/s. In [16] an exergetic analysis of the same system is provided, considering different types of biomasses. More generally, in [17] a review of the biomass gasification process (including MSW) for hydrogen production is provided. Ishaq and Dincer also compare biomass gasification with a system consisting of an electrolyser powered by photovoltaic panels or geothermal energy for hydrogen production. They find that the solution represented by biomass gasification has the highest energy and exergy efficiency [18]. In [19], the potential of integrating an incinerator for electricity and heat production with a gasifier for hydrogen production is also investigated. The authors design a system in which the MSW is sent to both plants: the fraction sent to the incinerator is used to produce thermal energy to power the gasification process and a district heating system. In contrast, the fraction sent to the gasifier produces syngas to be subjected to a WGS reaction. An integrated energy system is also modelled in [20]. To this concern, the authors study a system composed of an induced flow gasifier, a cryogenic air separation unit, a two-stage Rankine cycle, a water-gas transfer reactor, a combined gas-steam cycle, and a proton exchange membrane electrolyser to produce electricity, heat and hydrogen. Similarly, in [21] a multi-generation system based on waste gasification to produce hydrogen, power, heating-cooling and hot water is analysed. Although WtH_2 techniques are valuable in producing hydrogen, it is necessary to compare them with the most common solutions (i.e., non-MSW-based) to understand their potential for producing low-carbon hydrogen.

In this paper, the thermochemical techniques, mainly the gasification process, are explored. This paper aims to evaluate the decarbonisation potential of two MSW-based hydrogen production routes: a WtE plant coupled with an electrolyser

(WtE+El) and a gasification plant with a syngas treatment unit to produce H_2 (WtH_2). Consistent with this end, the potentials of two hydrogen production routes were compared with the two most discussed hydrogen production routes. The first is the SMR process, considered the most widely used alternative for hydrogen production. The second is water electrolysis, considered the most promising from an environmental point of view. To this concern, an environmental analytical model was developed to evaluate each alternative based on its associated emissions (i.e., direct, indirect, and avoided emissions). The application of the model, by considering different average national energy mix, allowed to identify the best alternative per each continent from an environmental perspective. Consistent with this, the national electricity grid emission factor was identified as a key variable for defining the decarbonisation potential of a hydrogen production route.

The rest of the paper is organised as follows: Sect. 2 describes the four hydrogen production routes considered, and the environmental analytical model to compare them is developed. In Sect. 3, the results achieved from the application of the model are discussed. Finally, in Sect. 4, the conclusions of the work are provided with insights for future studies.

2 Materials and Methods

This work aims to assess the decarbonisation potential of MSW-based hydrogen production routes with respect to the currently most employed alternatives. Therefore, two MSW-based hydrogen production routes were considered (i.e., WtE+El, and WtH_2), and they were compared with H_2 production via SMR (i.e., the so-called 'grey hydrogen' route) and H_2 production via an electrolyser fed from the national grid (El). A schematic representation of the four alternatives considered is shown in Fig. 1.

As it can be observed in Fig. 1:

- in the El route, an electrolyser is supplied with electricity from the national grid and water. The hydrogen is produced in a splitting reaction between hydrogen and oxygen molecules. The reacting oxygen is released into the atmosphere.
- In the SMR route, NG undergoes a steam reforming reaction in the presence of a catalyst (usually Ni-based [20]) to produce syngas mainly composed of H_2, CO and CO_2. Since the steam reforming reaction is endothermic, additional NG is burnt to provide the heat necessary for the reaction. Through a WGS reaction, the syngas is enriched with hydrogen, and the hydrogen is separated from the CO_2 in a PSA unit.
- In the WtH_2 route, the MSW undergoes a gasification process to produce syngas, which is then subjected to a reforming reaction in a catalytic reactor. Through a WGS reaction, the gas is then enriched with hydrogen, and, in the PSA unit, hydrogen is separated from carbon dioxide.

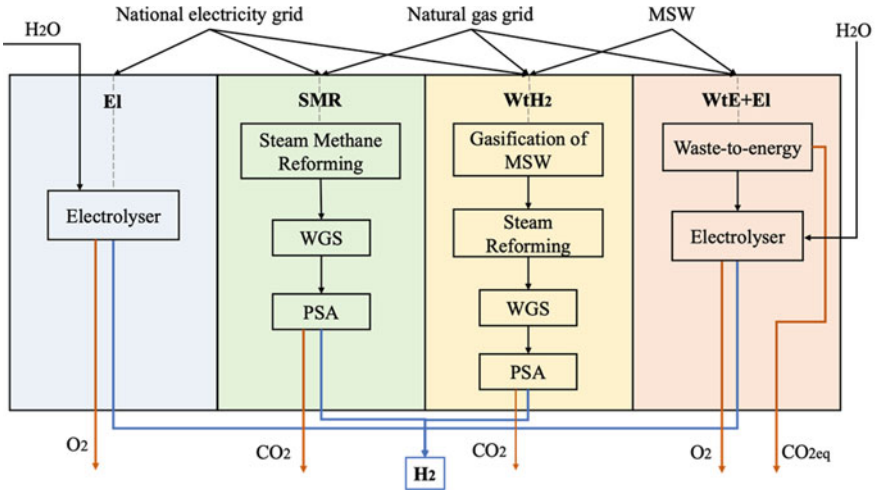

Fig. 1 Schematic representation of the four hydrogen production routes considered

- In the WtE+El route, the MSW undergoes thermochemical treatment to obtain electricity to power an electrolyser. The latter, fed by water, is used to produce pure hydrogen.

An environmental analytical model was developed to assess the decarbonisation potential of the different hydrogen production routes. It allows assessing the total emissions associated with the production of one Nm^3 of H_2 at 99.9% vol% purity. It is, therefore, possible to express the model in accordance with Eq. 1:

$$\varphi\left[\frac{kgCO_{2_{eq}}}{Nm^3H_2}\right] = \varphi_{direct} + \varphi_{indirect} - \varphi_{avoided} \tag{1}$$

Where φ_{direct} are the direct emissions generated by the plants during the hydrogen production process, $\varphi_{indirect}$ and $\varphi_{avoided}$ are expressed according to Eqs. 2 and 5, respectively.

$$\varphi_{indirect}\left[\frac{kgCO_{2_{eq}}}{Nm^3H_2}\right] = \varphi_{EL} + \varphi_{NG} \tag{2}$$

$$\varphi_{EL}\left[\frac{kgCO_{2_{eq}}}{Nm^3H_2}\right] = EL_{cons} \cdot f_{grid} \tag{3}$$

$$\varphi_{NG}\left[\frac{kgCO_{2_{eq}}}{Nm^3H_2}\right] = NG_{cons} \cdot f_{FME} \cdot GWP_{100} \tag{4}$$

Indirect emissions (Eq. 2) were considered as the sum of two contributions, i.e., emissions due to electricity supply φ_{EL} and emissions due to NG supply φ_{NG}. To this concern, EL_{cons} [kWh/Nm^3H_2] represents the electrical consumption of the plant to produce hydrogen and f_{grid} $\left[kgCO_{2_{eq}}/kWh\right]$ is the emission factor of the national electricity grid powering the process (Eq. 3). This parameter assumes a low value in case of a high share of renewable sources used for electricity production; on the contrary in case of low share of renewable sources, it assumes high value.

For the calculation of φ_{NG} (Eq. 4), Fugitive Methane Emissions (FME) were considered. They are defined as methane emissions generated during the production, processing, and transportation of NG and they are calculated as a percentage (f_{FME} [%]) of the total NG consumption of the process (NG_{cons} [$kgNG/Nm^3H_2$]) [22]. To assess these emissions' environmental impact, methane's impact factor on the Global Warming Potential was considered with a time horizon of 100 years (GWP_{100} $\left[kgCO_{2_{eq}}/kgNG\right]$).

$$\varphi_{avoided}\left[\frac{kgCO_{2_{eq}}}{Nm^3H_2}\right] = MSW_{H_2}\cdot f_{disp} \tag{5}$$

The avoided emissions (Eq. 5) correspond to the emissions that would have been generated if the amount of MSW processed to produce hydrogen (MSW_{H_2} $\left[kgMSW/Nm^3H_2\right]$) would be disposed of in landfills, with a specific emission factor of f_{disp} $\left[kgCO_{2_{eq}}/kgMSW\right]$. The contribution related to avoided emissions was evaluated with a negative sign (Eq. 1) since, as mentioned, MSW-based hydrogen production routes have a double benefit. They indeed allow MSW to be valorised, in accordance with a CE perspective, and, at the same time, hydrogen to be produced from renewable sources.

The assumptions of the model are summarized below:

- Dried unsorted MSW is employed to feed the gasifier.
- The Lower Heating Value of MSW is 16 MJ/kg on a wet wt% basis.
- The moisture content of MSW is 15.70% on a wet wt% basis.
- The ash content of MSW is 16.52% on a wet wt% basis.
- The net electrical efficiency of the WtE plant is 25%.
- The gasification process is carried out at a high temperature (>1100 °C) with pure oxygen.
- The electrical consumption of the electrolyser (alkaline technology) is 5 kWh/Nm^3H_2 in the Wte+El route.
- The separation efficiency of the PSA unit is 85%.

The developed analytical model was applied to the four hydrogen production routes considered, assuming the values shown in Table 1.

3 Results and Discussion

The results of the model application are summarised in Table 2.

Table 1 Data on emissions from the four hydrogen production routes are considered for the analytical model application

Variable	El	SMR	WtE+El	WtH_2
φ_{direct}	–	0.91 [11]	6.8 [11]	1.72 [11]
EL_{cons}	5 [11]	0.12 [23]	–	0.74 [11]
f_{grid}	0.342[a] [24]			
NG_{cons}	–	0.3 [23]	0.07 [11]	0.06 [11]
f_{FME}	–	3.5% [22]		
GWP_{100}	–	32 [25]		
MSW_{H_2}	–	–	4.64 [11]	1.09 [11]
f_{disp}	–	–	0.79 [25]	

[a]The reported value refers to the global average grid emission factor

Table 2 Results obtained from the environmental analytical model application

Emissions	El	SMR	WtE+El	WtH_2
φ_{direct}	–	0.91	6.8	1.72
φ_{EL}	1.71	0.04	–	0.25
φ_{NG}	–	0.336	0.08	0.07
$\varphi_{indirect}$	1.71	0.376	0.08	0.32
$\varphi_{avoided}$	–	–	3.67	0.86
φ	1.71	1.29	3.21	1.18

A critical evaluation of the same results is reported in Fig. 2.

As it can be observed in Table 2 and Fig. 2, the hydrogen production route with the lowest total emissions is WtH_2. It shows total emissions of 1.18 $kgCO_{2eq}/Nm^3H_2$ distributed as follows. The most significant share is represented by direct emissions, which constitute 59.3% of the sum of the absolute values of emissions, followed by avoided emissions, which constitute a share of 29.7%. It is noteworthy that in this hydrogen production route, indirect emissions have a not very significant influence, amounting to 11% of the sum of the absolute values of emissions (8.6% coming from electricity consumption and 2.4% coming from NG consumption). It should also be noted that, in the configuration analysed for the WtH_2 alternative (Fig. 1), it is not included to capture and reuse the CO_2 separated in the PSA unit. In the case of CO_2 capture and reuse, the direct emissions from the WtH_2 route would be drastically reduced, making this solution even more advantageous from an environmental point of view. On the contrary, the other MSW-based hydrogen production route considered, i.e., WtE+El, shows the highest total emissions of 3.21 $kgCO_{2eq}/Nm^3H_2$. Also, in this scenario, the most significant contribution is represented by direct emissions, which constitute 64.45% of the sum of the absolute emissions values, followed by avoided emissions, which represent 34.8%. In this case, since there are no emissions related to electricity supply, the share of indirect emissions is even less significant than in the WtH_2 route; indeed, it accounts for 0.75% of the sum of the absolute emissions values. However, in the case of the WtE+El route, it is impossible to make the same consideration as in the case of the WtH_2 route about CO_2 capture and reuse. The PSA unit included in the WtH_2 route allows to obtain carbon dioxide with a high degree of purity, making its capture and reuse economically viable in the considered

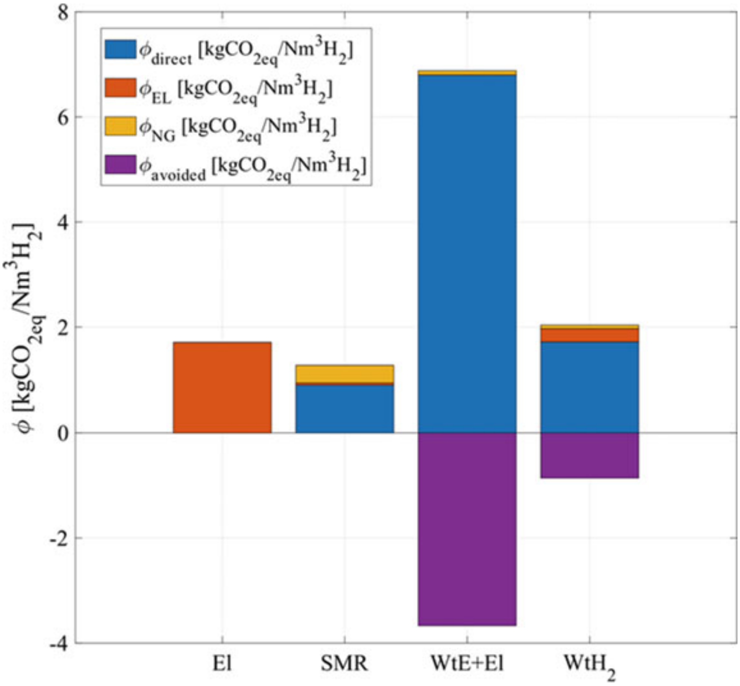

Fig. 2 Results obtained from the environmental analytical model application

plant configuration (Fig. 1). On the contrary, in the case of the WtE+El route, the low concentration and purity of CO_2 in the flue gas do not justify cost-effective reuse of carbon dioxide.

The SMR hydrogen production shows total emissions of 1.29 kgCO$_{2eq}$/Nm^{3}H$_2$, lower than the WtE+El route (i.e., 3.21 kgCO$_{2eq}$/Nm^{3}H$_2$) but higher than the WtH$_2$ route (i.e., 1.18 kgCO$_{2eq}$/Nm^{3}H$_2$). Also, in this case, the most significant share of emissions is represented by direct emissions (i.e., 70.76%). Unlike the previous cases, for the SMR, indirect emissions account for 29.24% of total emissions (i.e., 165% higher than the value recorded for WtH$_2$). Specifically, 3.11% of total emissions depend on emissions from the electricity supply and 26.13% from the NG supply. In this case, a PSA unit for syngas purification is considered. However, this option does not lead to the same benefits already observed in the case of the WtH$_2$ alternative. Indeed, in the case of SMR, a significant amount of emissions due to fossil fuel and electricity consumption would be generated (i.e., 0.376 kgCO$_{2eq}$/Nm^{3}H$_2$). On the contrary, in the case of the WtH$_2$ alternative, the avoided emissions from the disposal of MSW would lead to a negative overall emissions balance (i.e., −0.54 kgCO$_{2eq}$/Nm^{3}H$_2$).

The El hydrogen production route shows total emissions of 1.74 kgCO$_{2eq}$/Nm^{3}H$_2$. Only one type of emission due to the electricity supply is considered for this alternative. In this case, assuming a f_{grid} of 0.342 $\left[kgCO_{2_{eq}}/kWh\right]$, i.e., the global

Fig. 3 Results obtained from the environmental analytical model application in the different continents by considering the different f_{grid} values. All the f_{grid} values were assumed according to [24]

average value of the emission factor, emerged that this alternative is the second most impactful among those considered. This result confirms what generally emerges in the literature, i.e., that electrolysis is the alternative with the highest potential from an environmental point of view, but its very high energy demand makes it sustainable only if fuelled by green energy. Therefore, the results achieved lead to identifying the best hydrogen production route from an environmental point of view on the different continents according to the corresponding average value of f_{grid} (Fig. 3).

As can be observed in Fig. 3, the best alternative on most continents is WtH_2. It is indeed the best solution in North America (average f_{grid} 0.32 $kgCO_{2eq}$/kWh), Europe (average f_{grid} 0.29 $kgCO_{2eq}$/kWh), and Oceania (average f_{grid} 0.43 $kgCO_{2eq}$/kWh). The SMR is the best alternative in Africa (average f_{grid} 0.9 $kgCO_{2eq}$/kWh) and Asia (average f_{grid} 0.5 $kgCO_{2eq}$/kWh). It can also be observed that the El route is the best alternative only in South America (average f_{grid} 0.18 $kgCO_{2eq}$/kWh). The WtH_2 route is more resilient to changes in the way electricity is produced than the El route. The latter is applicable in countries with a 'green' national energy mix. On the contrary, the WtH_2 is the best alternative in countries with an average f_{grid} value. The SMR alternative is the best solution in countries with a high f_{grid} value due to the significant amount of indirect emissions generated. Finally, it can be observed that the WtE+El route is never preferable due to the significant amount of direct emissions.

Therefore, the WtH_2 hydrogen production route represents a concrete solution to support the decarbonisation of strategic economic sectors through hydrogen production in an energy transition phase. The study proved that the El route is the most promising from an environmental perspective, but it strongly depends on the national energy mix.

4 Conclusions

The objective of this work was to evaluate the decarbonisation potential of two MSW-based hydrogen production routes (i.e., a WtE plant coupled with an electrolyser and a gasification plant with a syngas treatment unit to produce H_2) by comparing them with the currently most discussed hydrogen production routes (i.e., SMR and El). In this regard, an environmental analytical model was developed to evaluate each alternative on the basis of its associated emissions (i.e., direct, indirect, and avoided emissions). The results achieved from the application of the model showed that the best hydrogen production route from an environmental point of view is the WtH_2 route. It shows a total emission amount of 1.18 $kgCO_{2eq}/Nm^3H_2$, which is 8.5% lower than the SMR route, 31% lower than the El route and 63.2% lower than the WtE+El route. This alternative ensures a dual benefit due to MSW's valorisation and low-carbon hydrogen production. On the contrary, the El route may be worse even than alternatives that use fossil sources as feedstock (i.e., SMR) due to the high energy demand (i.e., 5 kWh/Nm^3H_2) and, consequently, the national energy mix. The application of the model by considering different average national energy mix allowed to identify the best alternative for each continent from an environmental perspective. Consistent with this, the national electricity grid emission factor was identified as a key variable for defining the decarbonisation potential of a hydrogen production route. This analysis confirmed that the WtH_2 route is a viable alternative for low-carbon hydrogen production in countries with an average f_{grid} value (around 0.3 $kgCO_{2eq}/kWh$). On the contrary, the El route was found to be the best in locations where electricity is already produced in a particularly 'green' way. Therefore if, on the one hand, the WtH_2 route represents a viable strategy in the mid-time for the decarbonisation of the economy, on the other hand, further actions are needed to accelerate the energy transition process.

Although this model represents a useful and general tool for comparing hydrogen production routes, this work has some limitations. Firstly, only waste-to-hydrogen routes based on thermochemical techniques have been considered, neglecting biological ones. Furthermore, emissions from the supply of raw materials (e.g., transport and collection of MSW) and from the decommissioning of plants (e.g., electrolysers) have been neglected. In this regard, future studies could improve this research work by introducing additional emission components and considering the entire life cycle of the plants. Moreover, it would also be interesting to apply this model to contexts describing the situation of a hard-to-abate sector in order to gain a concrete understanding of what kind of support for decarbonisation the different alternatives provide.

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References

1. N. Mignoni, P. Scarabaggio, R. Carli, and M. Dotoli, "Control frameworks for transactive energy storage services in energy communities," *Control Eng Pract*, vol. 130, p. 105364, Jan. 2023, https://doi.org/10.1016/j.conengprac.2022.105364.
2. International Energy Agency, "The future of hydrogen." https://www.iea.org/reports/the-future-of-hydrogen (accessed Jan. 17, 2023).
3. S. Digiesi, M. P. Fanti, G. Mummolo, and B. Silvestri, "Externalities reduction strategies in last mile logistics: A review," in *2017 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI)*, IEEE, Sep. 2017, pp. 248–253. https://doi.org/10.1109/SOLI.2017.8121002.
4. A. Florio, G. Avitabile, and G. Coviello, "Multiple Source Angle of Arrival Estimation Through Phase Interferometry," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 69, no. 3, pp. 674–678, Mar. 2022, https://doi.org/10.1109/TCSII.2022.3141247.
5. S. Digiesi, A. Lucchese, and C. Mummolo, "A 'Speed—Difficulty—Accuracy' Model Following a General Trajectory Motor Task with Spatial Constraints: An Information-Based Model," *Applied Sciences*, vol. 10, no. 21, p. 7516, Oct. 2020, https://doi.org/10.3390/app10217516.
6. F. Superchi, A. Mati, M. Pasqui, C. Carcasci, and A. Bianchini, "Techno-economic study on green hydrogen production and use in hard-to-abate industrial sectors," *J Phys Conf Ser*, vol. 2385, no. 1, p. 012054, Dec. 2022, https://doi.org/10.1088/1742-6596/2385/1/012054.
7. International Energy Agency, "Hydrogen: energy system overview." https://www.iea.org/reports/hydrogen (accessed Jan. 17, 2023).
8. International Energy Agency, "Global hydrogen demand by sector in the Net Zero Scenario, 2020-2030," 2022. https://www.iea.org/data-and-statistics/charts/global-hydrogen-demand-by-sector-in-the-net-zero-scenario-2020-2030 (accessed Jan. 24, 2023).
9. A. Boretti, "There are hydrogen production pathways with better than green hydrogen economic and environmental costs," *Int J Hydrogen Energy*, vol. 46, no. 46, pp. 23988–23995, Jul. 2021, https://doi.org/10.1016/j.ijhydene.2021.04.182.
10. T. International Renewable Energy Agency, Green Hydrogen Cost Reduction Scaling Up Electrolysers to Meet the *1.5°C Climate Goal H 2 O 2*. 2020. [Online]. Available: www.irena.org/publications
11. A. Borgogna, G. Centi, G. Iaquaniello, S. Perathoner, G. Papanikolaou, and A. Salladini, "Assessment of hydrogen production from municipal solid wastes as competitive route to produce low-carbon H2," *Science of The Total Environment*, vol. 827, p. 154393, Jun. 2022, https://doi.org/10.1016/j.scitotenv.2022.154393.
12. A. v. Shah, V. K. Srivastava, S. S. Mohanty, and S. Varjani, "Municipal solid waste as a sustainable resource for energy production: State-of-the-art review," *J Environ Chem Eng*, vol. 9, no. 4, p. 105717, Aug. 2021, https://doi.org/10.1016/j.jece.2021.105717.
13. A. Pires and G. Martinho, "Waste hierarchy index for circular economy in waste management," *Waste Management*, vol. 95, pp. 298–305, Jul. 2019, https://doi.org/10.1016/j.wasman.2019.06.014.
14. J. Lui, W.-H. Chen, D. C. W. Tsang, and S. You, "A critical review on the principles, applications, and challenges of waste-to-hydrogen technologies," *Renewable and Sustainable Energy Reviews*, vol. 134, p. 110365, Dec. 2020, https://doi.org/10.1016/j.rser.2020.110365.
15. M. Ozturk and I. Dincer, "An integrated system for clean hydrogen production from municipal solid wastes," *Int J Hydrogen Energy*, vol. 46, no. 9, pp. 6251–6261, Feb. 2021, https://doi.org/10.1016/j.ijhydene.2020.11.145.
16. Y. Zhang, P. Xu, S. Liang, B. Liu, Y. Shuai, and B. Li, "Exergy analysis of hydrogen production from steam gasification of biomass: A review," *Int J Hydrogen Energy*, vol. 44, no. 28, pp. 14290–14302, May 2019, https://doi.org/10.1016/j.ijhydene.2019.02.064.
17. M. A. Salam, K. Ahmed, N. Akter, T. Hossain, and B. Abdullah, "A review of hydrogen production via biomass gasification and its prospect in Bangladesh," *Int J Hydrogen Energy*, vol. 43, no. 32, pp. 14944–14973, Aug. 2018, https://doi.org/10.1016/j.ijhydene.2018.06.043.

18. H. Ishaq and I. Dincer, "Comparative assessment of renewable energy-based hydrogen production methods," *Renewable and Sustainable Energy Reviews*, vol. 135, p. 110192, Jan. 2021, https://doi.org/10.1016/j.rser.2020.110192.
19. S. Rudra and Y. K. Tesfagaber, "Future district heating plant integrated with municipal solid waste (MSW) gasification for hydrogen production," *Energy*, vol. 180, pp. 881–892, Aug. 2019, https://doi.org/10.1016/j.energy.2019.05.125.
20. H. Ishaq and I. Dincer, "A new energy system based on biomass gasification for hydrogen and power production," *Energy Reports*, vol. 6, pp. 771–781, Nov. 2020, https://doi.org/10.1016/j.egyr.2020.02.019.
21. Y. E. Yuksel, M. Ozturk, and I. Dincer, "Energy and exergy analyses of an integrated system using waste material gasification for hydrogen production and liquefaction," *Energy Convers Manag*, vol. 185, pp. 718–729, Apr. 2019, https://doi.org/10.1016/j.enconman.2019.02.033.
22. G. U. Ingale *et al.*, "Assessment of Greenhouse Gas Emissions from Hydrogen Production Processes: Turquoise Hydrogen vs. Steam Methane Reforming," *Energies (Basel)*, vol. 15, no. 22, Nov. 2022, https://doi.org/10.3390/en15228679.
23. A. Susmozas, D. Iribarren, and J. Dufour, "Life-cycle performance of indirect biomass gasification as a green alternative to steam methane reforming for hydrogen production," *Int J Hydrogen Energy*, vol. 38, no. 24, Aug. 2013, https://doi.org/10.1016/j.ijhydene.2013.06.012.
24. "Carbon Footprint Country Specific Electricity Grid Greenhouse Gas Emission Factors." [Online]. Available: www.carbonfootprint.com
25. IEA, "Methane and Climate Change." https://www.iea.org/reports/methane-tracker-2021/methane-and-climate-change (accessed Jan. 09, 2023).
26. R. L. Verma and G. Borongan, "Emissions of Greenhouse Gases from Municipal Solid Waste Management System in Ho Chi Minh City of Viet Nam," *Urban Science*, vol. 6, no. 4, p. 78, Nov. 2022, https://doi.org/10.3390/urbansci6040078.

Bullwhip Effect in the Supply Chain: An Exploratory Study in a Brazilian Company

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Abstract To satisfy customers' needs, companies are required to forecast the demand for their products to determine production capacity and resources. However, when the forecast and the actual demand are different, the bullwhip effect occurs. Even though it is not a recent phenomenon in the supply chain management, the bullwhip effect has been researched to understand its causes and propose solutions to minimize it. This is an exploratory study that aims to analyze the occurrence of the bullwhip effect before and during the COVID-19 pandemic, to identify its possible causes. A case study was conducted in a Brazilian company. The data collected refer to 2019 and 2020. The results confirm three causes of the bullwhip effect predicted in the literature: processing of demand signals, price fluctuation and use of rationing strategy. In addition, the findings allow establishing that the crisis caused by the COVID-19 pandemic also influenced the occurrence of the bullwhip effect. To contribute to the research on the bullwhip effect in crises, this article develops a case study in a company that manufactures plastic tubes and accessories for use in construction.

Keywords Bullwhip effect · Supply chain · COVID-19 · Crisis

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1 Introduction

Market demand is defined by the number of products that will be consumed by customers. To understand it, companies must analyze the current situation, identifying existing consumers and competitors. It is also important to study market variation, since it is not necessarily about the effectiveness of consumption, but its demand.

To meet consumer requests, companies must manage their supply chain, which consists of a network that connects suppliers, manufacturers, warehouses, distribution centers and commercial outlets, so that goods are produced and distributed in the correct quantities, to delivery points and on time, minimizing total system costs while meeting service level requirements.

Simultaneously, companies need to forecast the demand for their products to determine the productive resources needed. This forecast can be made from the total sales, in each place and time frame. When there is variation between actual and forecasted demand along the supply chain, there is a bullwhip effect [1].

The bullwhip effect can be understood as a phenomenon that involves the amplification and distortion of demand information from the final links of the supply chains towards the primary suppliers [2].

In this dynamic, small variations in downstream demand are enough to cause major disturbances in the information received by upstream suppliers, resulting in excess inventories, low service levels, lost sales, poor use of productive resources, unnecessary transport, among others [2].

Despite not being a recent phenomenon in the context of supply chain management, the bullwhip effect has been the subject of several studies that seek to understand its causes.

The bullwhip effect has been studied from different perspectives. Some studies assess the behavior of supply chain actors through management games, empirical studies, statistical models, modeling, simulation, and control theory. All aim to understand the behavior of the bullwhip effect considering different types of industries [3].

Existing investigations consider different industrial sectors, e.g., healthcare and airlines [4]. There are few works that study the bullwhip effect in crises. A recent investigation analyzed the bullwhip and ripple effect behavior in 165 companies, 98 airlines and 67 buyers and suppliers, after the COVID-19 pandemic. The results indicate that the ripple effect increased after the pandemic, but the bullwhip effect did not [5]. However, the generalization of these results can only be made after further studies in different contexts.

During the pandemic, problems related to importation, lack of workforce, decrease in demand, stoppage of activities and supply difficulties arose due to interruptions in the supply chain [6]. The impacts of the pandemic were evident, mainly in relation to the increase in demand for diversifying suppliers on a global scale; the occurrence of the bullwhip effect from the combination of an increase in demand and a decrease in supply; the return of lean systems and local productions;

and the development of contingency risk recovery strategies to deal with crises [7]. Therefore, it is important to analyze the bullwhip effect in this scenario.

Thus, to contribute to the research on the bullwhip effect in crises, this article develops a case study in a Brazilian company that manufactures plastic tubes and accessories for use in construction. In general, this industrial sector has been little explored, despite being responsible for the manufacture of functional products, which, historically, has been the focus of the development of the theory of supply chain management [3].

The objective of this work is to explore the bullwhip effect before and during the COVID-19 pandemic, seeking to identify its possible causes. To perform the analysis, data were collected from 2019 to 2020. This is an exploratory study, which aims to provide greater familiarity with the problem, to make it more explicit, and to improve ideas and identify new findings.

2 Literature Review

2.1 Bullwhip Effect

The bullwhip effect affirms that policies adopted by companies can rise undesirable behaviors in the supply chain. The causes of the bullwhip effect are related to the consequences of poor production management and misperceptions of demand feedback [2].

There are four possible causes of bullwhip effect: processing of demand signals, price fluctuation, rationing strategies and order policies [8]. Demand forecasting, lead time, price fluctuation, and inflated orders are the factors that most contribute to the changes in demand and the bullwhip effect [1].

In addition, demand forecast distortions has negative effects on the economy and supply chain performance. Therefore, it is important to identify and understand the causes of the bullwhip effect and its impact on companies, which can include supply chain inefficiency, overproduction, orders excess, wasted resources, and inventory build-up at all levels of the logistics network [8].

The bullwhip effect control can be accomplished using supply chain control tools. It is necessary to quantify it, considering all stages of the supply chain, and measuring the variation. The analysis of the relationship among variation, demand forecasts and lead time indicates the actions needed to minimize the bullwhip effect [1].

2.2 Related Works

The bullwhip effect has been explored from different perspectives. Braz et al. [8] developed a literature review to understand the causes and consequences of the bullwhip effect in closed supply chains with reverse flows, identify the differences in the bullwhip effect in forward and closed supply chains, and analyze strategies that can be used to minimize the bullwhip effect. The results indicate that the bullwhip effect occurs in the same way in forward and closed supply chains, presenting similar causes. However, most of the studies did not consider the quality of the products returned, which can increase variability, as it adds one more variable to the process.

Possible sources of the bullwhip effect were investigated through the analysis of several scenarios, considering periodic inventory reviews, forecast errors, fixed supply lead time, variable order cost, fixed purchase costs, among others. The findings show that demand signal processing, rationing strategies, ordering policies and price fluctuation are common sources of the bullwhip effect [2].

Frazzon et al. [9] analyzed the influence of demand information on the emergence of the bullwhip effect. A supply chain composed of five organizations with a bidirectional relationship with the flow of information and materials was represented and simulated using the beer game. A scenario without information sharing and another with sharing were considered. In the first, the variation in demand increased significantly from the consumer to the supplier. In the second, the variation was considerably smaller. Thus, the results establish that the greater the information sharing, the smaller the bullwhip effect. However, the bullwhip effect cannot be eliminated due to the stochastic behavior of demand.

A dynamic simulation model of an electronics company was developed by Vaz and Maldonado [10] to identify and analyze the differences and impacts of the bullwhip effect in companies that use reverse logistics. The outcomes indicate a significant variation in demand, which implies the aggravation of the bullwhip effect.

Araújo, Coti-Zelati and Queiroz [11] built a conceptual model to study the bullwhip effect based on three hypotheses: (1) Transaction cost theory has a positive effect on supply chain management; (2) Transaction cost theory can reduce the bullwhip effect in the supply chain; and (3) Supply chain management can reduce the bullwhip effect. However, the hypotheses were not validated by empirical studies and statistical techniques.

Gouvêa [12] conducted a case study of the bullwhip effect in a coffee production. This work concluded that the bullwhip effect occurs because there is no synchronization between production and customers' orders, resulting in inventory excess. The type of freight contract also influences the bullwhip effect. Thus, other types of contracts that allow the obtention of different amounts can contribute to increasing the producer's margin of action and reducing the bullwhip effect. However, this study considers only one subject in the supply chain.

Based on the works described above, it can be concluded that the bullwhip effect is a relevant subject and of interest to companies. Moreover, theoretical works and the use of simulation models have been prioritized. Therefore, empirical studies are lacking and there is room for the development of other case studies to obtain new results on the causes and effects of the bullwhip effect or confirm existing results.

Furthermore, existing studies do not seem to consider the bullwhip behavior in crises. The COVID-19 pandemic has had consequences for the world economy, which include a drop in stock market values, a drop in gross domestic product, stoppage of activities, in addition to import and export, and labor problems, which directly affect the supply chain [7]. Thus, it is evident the need to study the bullwhip effect in this.

3 Methodology

This research can be classified as qualitative, exploratory, and descriptive.

This article conducts a case study. This methodology is relevant because it highlights the practices applied to the real world. The use of case studies has been successful in several areas of knowledge.

The following steps were pursued to develop the case study: characterization of the problem, definition of the object of study and context, number of cases, elaboration of the research project, data collection, data analysis and report writing [13].

In a crisis such as the one caused by COVID-19 pandemic, market uncertainty can generate the bullwhip effect. Thus, referred to the characterization of the problem, definition of the object of study and delimitation of the number of cases, this article studied the supply chain of a Brazilian company in the sector of manufacturing plastic tubes and accessories for use in construction, to verify the occurrence of the bullwhip effect, as well as its causes.

Regarding the context, in the first 2 months of the pandemic, there was a significant drop in the company's sales and interruptions of the operational centers. Two months later, the situation was reversed and there was a sudden rise in demand and a shortage of raw materials in the supply chain. Thus, the company ended the year with positive results in terms of sales volume, but with negative results in terms of revenue.

In the data collection stage, the managers responsible for planning, supply and commercial areas were consulted about the demand, quantities and sales values, price variation of raw materials and products, availability of supplies, production capacity, unforeseen events caused by the pandemic, among others. Internal documents were also consulted and analyzed to collect data relevant to this study.

The analysis focused on a qualitative approach, whose main objective is to explore different perspectives, according to the experiences of the participants [13].

4 Results

To analyze the occurrence of the bullwhip effect, data were collected from 2019 (pre-crisis) to 2020 (crisis).

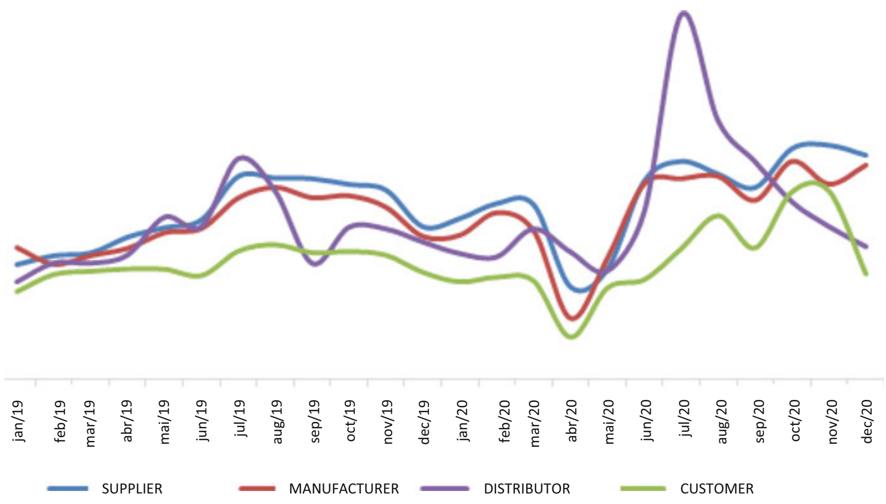

Fig. 1 The bullwhip effect in the supply chain

The bullwhip effect can be seen from the variations in orders placed by the actors of the supply chain. In this case study, the actors include supplier, manufacturer (company studied), distributor and customer. Figure 1 shows the orders volume in the pre-crisis and crisis. The bullwhip effect can be observed in the crisis.

It is possible to observe a drop in the orders volume at the beginning of the crisis in Brazil (April/2020). For the manufacturer, the consequences were a reduction in revenue, payments postponement, a reduction in the number of orders placed with suppliers and renegotiation of commodity titles. These actions are typical of the downward bullwhip effect, that occurs when demand drops, and the company needs to reduce production capacity.

In addition, it is observed that the manufacturer's orders volume is not consistent with the distributor's orders volume, but with the supplier's orders volume. This behavior is unexpected, but it can be explained by the shortage of PVC resin, which is the raw material most used in hydraulic installations in homes.

During the crisis, several factors influenced the shortage of this raw material worldwide, such as: interruption of electricity supply in Europe, snowfalls in the USA, interruption of exports from China, maintenance of factories in Brazil and Argentina, among others. In this context, the manufacturer bought the maximum quantity offered by the supplier.

In general, the orders volume of the distributor is higher than the orders volume of the customer. However, in the crisis, there is an inconsistency in the behavior of the distributor in June/2020 and July/2020, which impacts the other levels of the supply chain significantly, i.e., the manufacturer and the supplier.

The distributor behavior can be interpreted as a strategy to increase inventories and ensure the service level. This action is common in periods when there are not enough conditions to meet the orders volume. This proved to be assertive, as there was an increase in the customers' orders volume from June/2020. This increment may represent the market recovery after the initial months of the crisis, marked by idleness and reduced capacity of the production process, and low volume of orders. Therefore, it is assumed that the distributor was able to attend all customers orders.

However, probably the manufacturer has not been able to attend all the distributor's orders due to raw material unavailability. From July/2020 to November/2020, distributor's demand overlapped the supply of the manufacturer, indicating that all items produced were consumed. This, associated with the increase in demand from June/2020 to July/2020, when the manufacturer is not able to meet the demand for having reduced its production capacity, indicates that the manufacturer probably was not able to meet all distributor orders.

It can be concluded that the main impacts of the bullwhip effect for the manufacturer are the reduction of production capacity, the idleness of equipment and employees, and, mainly, the reduction of the profit margin, which made the crisis period end with record sales, but not revenue.

To minimize the impacts of the bullwhip effect, the manufacturer adopted five strategies: prior sharing of material purchase planning, anticipation of orders, development of new suppliers, importation, and safety stock increment.

The prior sharing of material purchase planning with suppliers and the anticipation of orders refers to the relationship with the supplier and the demand flow, to ensure that the volume and deadlines are known to plan and adapt their production capacity.

The development of new suppliers and the increase in imports are related to the number of suppliers approved, increasing the possibilities of supplying materials and guaranteeing supplies in times of worldwide shortages.

Finally, the safety stock increment allows for higher volume purchases and aims to avoid stock unavailability and to ensure the full operation of production.

4.1 Causes of the Bullwhip Effect

The items produced by the manufacturer were grouped according to their function and the raw materials required. For each item, data were collected about sales volume and price from January 2019 to December 2020.

The PVC knee item, which is a connection for pipes, responsible for modifying the direction of the water pipe, used for renovation and construction of homes, showed the greatest increase in sales volume (23.92%). On the other hand, the item PVC pipe, which is used in connection with the knee, to conduct water, presented greater variation in relation to the sale price (38.14%). Both are produced with PVC resin.

As they present the most significant variations, the PVC knee and the PVC tube were selected as the object of this study. The sales volume of the items in the pre-crisis and crisis were compared to investigate their behavior. Figure 2 shows the difference between the PVC knee sales volume in the crisis and pre-crisis.

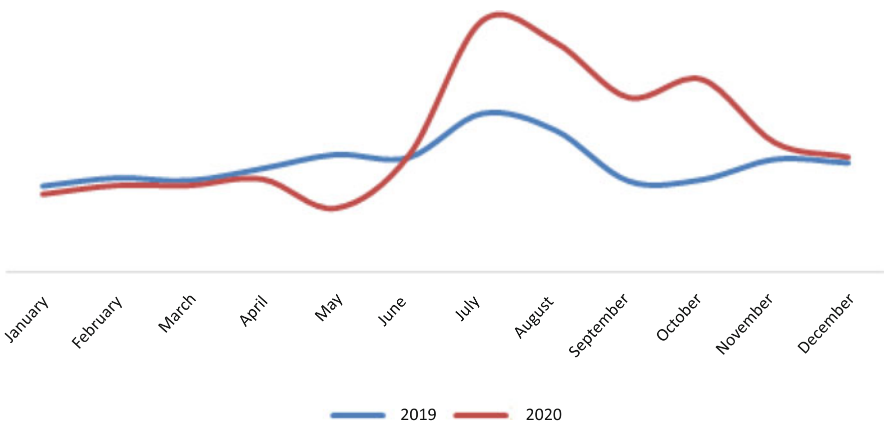

Fig. 2 Sales volume of PVC knee in the pre-crisis and crisis

During the crisis, there were more accentuated raises and drops throughout the year, evidencing greater variability in demand. In May/2020 there was the biggest drop in PVC knee sales volume. This drop was due to the reduction in demand and supply of the item, because of the stoppage of operational centers. On the other hand, in July/2020, the sales volume reached the maximum level, influenced by the expressive and unexpected increase in demand from June/2020. In the following months, sales fluctuated, reflecting the unavailability of PVC resin in the market.

One of the main causes of the increase in demand for the PVC knee is related to home renovations. This is because, in the crisis, people were asked to stay at home, in social isolation, and many decided to do or anticipate some remodeling to improve the comfort of home.

However, since plastic pipes and fittings for use in construction are not essential products, there has been a delay in the rise in demand. In fact, the demand for PVC knee began the crisis period with a sharp drop and later increased significantly.

On the other hand, PVC pipe did not show a significant increase in relation to sales volume. The variation in PVC pipe sales volume between the pre-crisis and crisis can be seen in Fig. 3.

Such as the PVC knee, the PVC pipe sales volume dropped, with April/2020 and May/2020 being the worst months of the crisis. The sales peak happened in July/2020, both in the pre-crisis and crisis. However, in the crisis, the sales volume is significantly higher. This may be related to the behavior of the global market for the construction industry, which dropped at the beginning of the crisis and grew from June/2020.

Therefore, it can be concluded that the pandemic impacted the variation in demand, driven by the inadequate processing of demand signals, confirming the results of previous studies that indicate that this is one of the causes of the bullwhip effect [2].

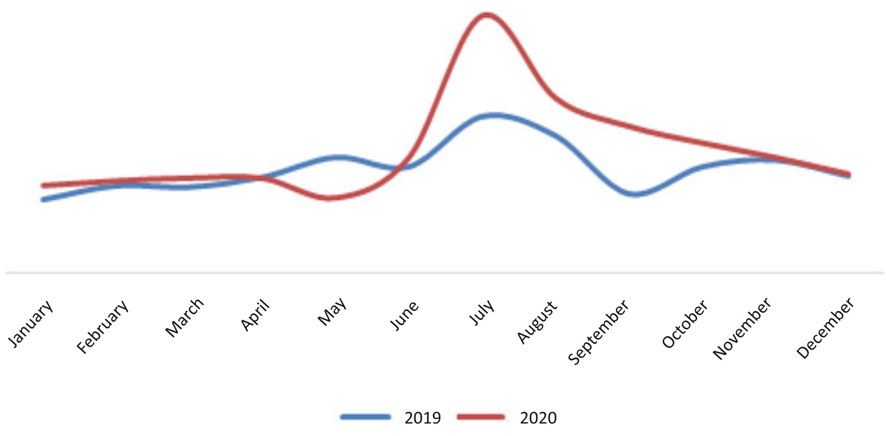

Fig. 3 Sales volume of PVC pipe in the pre-crisis and crisis

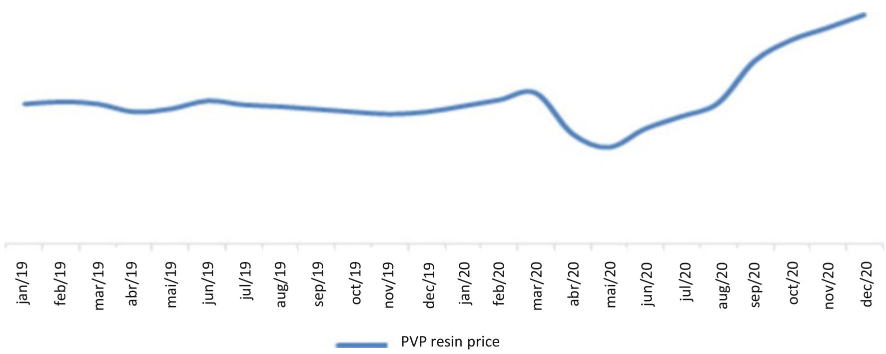

Fig. 4 PVC resin price

Variations in sales prices were also observed, which were not proportional to the quantity sold. This may be explained by the fact that other factors than sales volume influenced the PVC knee and PVC pipe prices during the crisis. Thus, to better understand these factors, the relationship between the price and sales volume of each item was analyzed.

Price variations in the crisis occurred more frequently, being the most expressive in the months of September/2020 to November/2020. This variation represents an adjustment in the price of the item.

To identify the factors that influenced this price adjustment, it is necessary to understand the behavior of the price of PVC resin, which is the raw material for the manufacture of PVC knee and PVC pipe. Figure 4 shows the variation in the price of PVC resin, in the pre-crisis and crisis. Prices are presented in dollars and the exchange rate variation is not represented in the behavior of the chart.

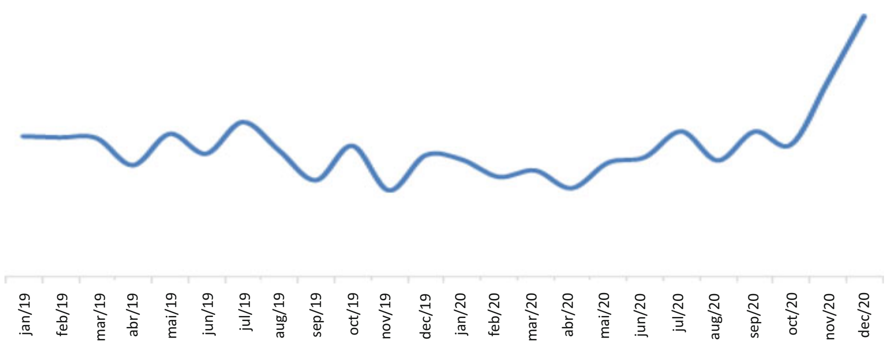

Fig. 5 PVC pipe sales price/volume

PVC resin was in shortage during the crisis. In Brazil, there are few suppliers of this raw material. This made the company to look for other suppliers, including international ones. However, high exchange rates often made the purchase unfeasible. The lack of resin impacted the production process and, consequently, the company was unable to fully meet the demand. Therefore, it can be concluded that the increase in the price of PVC resin influenced the price readjustment of the PVC knee. This conclusion was confirmed through semi-structured interviews with managers from planning, supply, and commercial areas.

The PVC resin price in the global market also influenced the price of PVC pipe, whose variation divided by sales volume can be seen in Fig. 5.

There is a drop in the price/sales volume ratio at the beginning of the crisis (April/2020). However, this drop can also be observed in the pre-crisis (April/2019). In general, the price/sales volume ratio shows similar behavior in both periods, but to a lesser extent in the pre-crisis. From October/2020, there is a significant increase in the sales price of PVC pipes, caused by the increase in the price of PVC resin, which represents approximately 80% of the materials used to manufacture the item.

The company tried to pass on the price adjustments to customers as they were adjusted by suppliers. However, due to the high volatility, it was not possible to transfer the values at the same speed in which the price of raw materials increased. Thus, the company chose to prioritize the loyalty of customers and, consequently, did not change the amounts of orders in progress, reducing its profit margin.

Therefore, it is possible to concluded that the price fluctuation occurred on larger scales and in unexpected patterns for all subjects in the supply chain, enhancing the occurrence of the bullwhip effect in the crisis. This result confirms that price fluctuation is one of the causes of the bullwhip effect [2].

The supply chain actors that can be involved in the bullwhip effect are the market, retailers, distributors, manufacturers, wholesalers, among others. In this work, the behavior of the distributor was analyzed, considering the lack of PVC resin. Figure 6 represents sales of products that use PVC resin to the distributor.

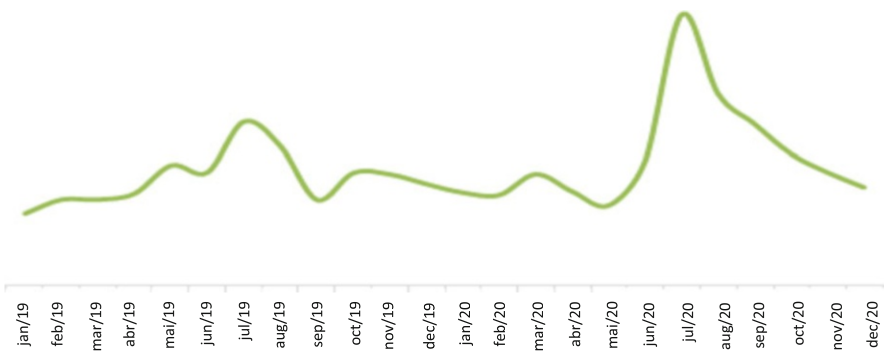

Fig. 6 Sales of product made with PVC resin to the distributor

The sales peak in the crisis (July/2020) may indicate the use of the rationing strategy by the distributor. This means that the distributor considered the possibility of a shortage of PVC knees and PVC pipes, due to the lack of PVC resin worldwide, and increased the order size to guarantee themselves a good share.

In fact, this hypothesis was confirmed by the sales team, which reported that it was necessary to increase the average stock of PVC knees and PVC pipes from 45 days (pre-crisis) to 60 and 90 days, respectively, to avoid inventory problems.

This scaling up around demand caused a domino effect along the supply chain, which is the bullwhip effect. Thus, the company anticipated customer orders and increased the level of safety stock.

However, the shortage of PVC resin forced it to operate in a shortage regime, i.e., it was necessary to rationalize deliveries and production capacity, as there were not enough conditions to meet the demand volume. Therefore, the use of the rationing strategy by the distributor was one of the causes of the bullwhip effect for the company studied.

Customers may place orders in larger quantities than the demand for other reasons. One involves the ordering policy, which is related to ordering costs and volume discounts offered by suppliers. To verify whether this is the case, the ordering policies were analyzed.

The distributor uses the following ordering policies: standard time, demand accumulation, and advance scheduling. The standard time policy is used for products with relatively stable production flow and sales, while the demand accumulation policy is used for products with low sales volume. The advance scheduling policy depends on the demand forecast made.

During the crisis, there were no changes in ordering policies of the distributor, or the company studied. This confirms that the increase in the distributor's order quantity in July/2020 was due to the use of a rationing strategy, which contributed to the bullwhip effect.

Therefore, it can be said that the company studied was impacted by the bullwhip effect in the crisis and that the probable causes for the occurrence of this effect were the inadequate processing of demand signals, price fluctuation and the use of rationing strategy. This result corroborates the existing theoretical studies that indicate them as possible causes of the bullwhip effect [2].

Furthermore, the crisis itself seems to influence the occurrence of the bullwhip effect. This is because during the pandemic, several problems emerged that impacted the supply chain, for example, decrease/increase in demand, decrease in supply, interruption of imports and exports, shortages of raw materials and supply difficulties. The combination of these problems leads to the bullwhip effect [7].

Thus, it is recommended to add crises (e.g., natural disasters, pandemics, wars, and strikes) to the possible causes of bullwhip effect, as they can influence demand and prices of products and raw materials, material availability and purchasing policies in a significant and simultaneous way.

5 Conclusion

This article developed an exploratory case study in a Brazilian company that manufactures plastic tubes and accessories for use in construction. The objective was to analyze the occurrence of the bullwhip effect before and during the COVID-19 pandemic, to identify its possible causes.

The data were collected from 2019 to 2020. The actors in the supply chain studied include supplier, manufacturer, distributor, and costumer.

The results indicate the occurrence of the bullwhip effect in 2020. The demand dropped, then increased significantly and suddenly. This was not foreseen by the company, which was impacted by the downward bullwhip effect. This behavior confirms one of the causes of the bullwhip effect: the processing of demand signals.

The shortage the main raw material motivated the price fluctuation and the use of rationing strategies by the actors of the supply chain. This situation corroborates two other causes of the bullwhip effect: price fluctuation and the use of rationing strategies.

Finally, the results indicate that the COVID-19 pandemic was one of the causes for the bullwhip effect, due to its impacts on the supply chain and global economy.

Despite having focused on the analysis of a specific phenomenon and company, this study can be used as a basis for future analysis in other companies in similar circumstances. Future research may consider analyzing the occurrence of the bullwhip effect during the COVID-19 pandemic in companies from other industrial sectors to confirm the results obtained. In addition, research may consider the end of the pandemic to analyze the existence of new cycles of demand variation and the occurrence of the bullwhip effect.

References

1. Kaminsky, P., Simchi-levi, D., Simchi-levi, E. Introdução à gestão da cadeia de suprimentos. In: Cadeia de suprimentos projeto e gestão: conceitos, estratégias e estudos de caso. 3rd ed. São Paulo: Bookman Companhia Editora (2010).
2. Ivanov, D. Revealing interfaces of supply chain resilience and sustainability: a simulation study. International Journal of Production Research 56, 3507–3523 (2018).
3. Brandao, M.S., Godinho Filho, M. Ocorrência e causas do efeito chicote para a cadeia de suprimento de produtos de luxo. Revista de Administração de Roraima 10, 1–25 (2020).
4. Senna, P., Reis, A.D.C., Santos, I.L., Dias, A.C. Healthcare supply chain risk management in Rio de Janeiro, Brazil: What is the current situation? IOS Press Content Library, 511–527 (2022).
5. Scarpin, M.R.S., Scarpin, J.E., Musial, N.T.K., Nakamura, W.T. The implications of COVID-19: Bullwhip and ripple effects in global supply chains. International Journal of Production Economics, 251, 108523 (2022).
6. Nicola, M., Alsafi, Z., Sohrabi, C., Kerwan, A., Al-jabir, A., Iosifigis, C., Agha, R., Aghaf, M. The socio-economic implications of the coronavirus pandemic (COVID-19): A review. International Journal of Surgery, 78, 185–193 (2020).
7. Handfield, R.B., Graham, G., Burns, L. Corona virus, tariffs, trade wars and supply chain evolutionary design. International Journal of Operations & Production Management (2020).
8. Braz, A.C., Gomes, L.A. de V., de Melo, A.M., Nascimento, P.T. de S. The bullwhip effect in closed-loop supply chains: A systematic literature review. Journal of Cleaner Production, 202, 376–389 (2018).
9. Frazzon, E.M., Mendonça, L.H.S., Pinheiro, E.V., Sgnaolin, L. Um modelo de simulação do jogo da cerveja para o estudo do impacto da informação na mitigação do efeito chicote na cadeia de suprimentos: ferramenta para apoio educacional em gestão da cadeia de suprimento. Gestão da Produção, Operações e Sistemas, 11, 53–65 (2016).
10. Vaz, C.R., Maldonado, M.U. Efeito Chicote em Redes de Logística Reversa: um Modelo de Simulação Dinâmica. Produto & Produção, 18, 13–19 (2017).
11. Araújo, D.L.A., Coti-zelati, P.E., de Queiroz, M.J. The bullwhip effect in Brazilian supply chain of organic products: an analysis from the perspective of transaction cost theory. Independent Journal of Management & Production 10, 1015–1035 (2019).
12. Gouvêa, E.K.M. A dissonância entre a produção e a venda de grãos gerada pelo efeito chicote: avaliação em uma propriedade destinada à produção de café orgânico. Monografia - Escola de Minas, Universidade Federal de Ouro Preto, Ouro Preto (2019).
13. Gil, A.C. Como elaborar projetos de pesquisa. São Paulo: Atlas (2017).

Big Data Analytics to Identify Failures in Production Machines and Propose a Preventive Maintenance Plan

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Abstract Data collection and analysis processes are increasingly important for both small businesses and large global enterprises. Data analytics are essential for process control and for providing insights for strategy development. Business intelligence (BI) analysis points out opportunities arising from large volumes of data and is the basis for assertive choices. The objective of this study was to conduct Big Data Analytics to develop a predictive evaluation of machine failures in production in order to propose an effective preventive maintenance plan. The research method adopted was to perform Big Data Analytics to develop descriptive and multivariate statistical evaluation in Python through the investigation of 10,000 occurrences referring to production process records with three types of products and quality variants. The result revealed information about the main failures and their causes, pointing out that the main problem in production is tool wear, clearly caused by excess air and process temperature. Using multivariate statistical analyses, we demonstrated the relationship between process temperature and air temperature, as well as the adverse relationship between rotational speed and torque, and concluded that there were also significant failures from overexertion and lack of energy.

Keywords Big Data Analytics · Python · Statistics · Fault identification · Preventive maintenance

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1 Introduction

In recent years, the implementation of data collection and analysis processes has been increasing in volume and impact for companies of all sizes, sectors, and regions. Data analysis informs control and offers insights that are decisive for building the strategy of each company, from a small enterprise, located in a local neighborhood to large corporations and century-old companies that have several simultaneous businesses and global presence. This is, however, a dynamic and very competitive environment, where having a business strategy is not just a question of management policy, but a real need for longevity. When there is a need to investigate scenarios, investigate failures or errors, and make decisions, being able to act in an effective and fast manner is critical, for the financial sustainability of companies. As such it is crucial to have data and analytics to support decision-making and the formulation of medium and long-term strategic choices.

Big data (BD) is the name attributed to the approach that aims to bring together large volumes of data, with diversified attributes, in a fast and dynamic manner. According to Jha et al. [3], “Huge volumes of real-time or near-real-time data are continuously produced and made available in various forms and from various sources, such as social media applications, shopping portals, search engines, sensors, smart applications and the Internet of Things (IoT).” The term Business intelligence (BI) analytics relates to opportunities arising from evaluating large volumes of data using specific tools and focused on data mining actions, data organization, and treatment, and data visualization to help support organizations in data-driven decision-making. The concept of Big Data Analytics (BDA) is linked to BA, however, BDA translates into advanced analysis-driven actions such as example, data mining activities, machine learning, social media analysis, and data visualization, among others. BD and BDA are often been referred to as tools of fundamental importance for decisions in the corporate environment.

In the specific context of maintenance management transforming data into usable information to support predictive analysis, there is a high volume of data to manage and process [5]. The challenges associated with dealing with such large volumes of data can compromise the sustainability of a maintenance plan and consequently its result, not because it uses the wrong tools, but because it is supplied with data that is unrelated or different from the purpose. In [8] we can see a presentation of a framework to predict customer satisfaction in the restaurant sector using big data analysis. The authors create a synthetic dataset by combining real data with simulated data, which allows them to generate large amounts of data that accurately reflect the characteristics of the restaurant industry. They use machine learning algorithms to analyse the data and predict customer satisfaction levels based on various factors such as food quality, service quality, and environment and this context provides a good example of using big data analytics in a synthetic dataset to predict attitudes and build actions with the suggestion that the framework can be adapted for other industries.

In this study, a predictive analysis of failures in production machines was carried out, making it possible to develop a preventive maintenance plan. Predictive maintenance involves two main components: knowledge inquiry through analytics i.e. prediction and detection of machine tools and scheduling plan with decision support for the required maintenance task to be completed [6]. Considering a database, this investigation presented material with enlightening graphical analysis that provided information that served as a basis for building insights for assertive decision-making about fault solutions in the production line. The objective of this study was to perform BDA to develop a predictive evaluation of machine failures in production to propose an effective preventive maintenance plan.

2 Literature Review

The increasing importance and impact of Big Data over the last few years are greatly determined by the potential of bringing together large volumes of data – stemming from various sources and involving multiple variables. Such data results from the pursuit of organizations' regular operations, and exposure of their products to the market. Over the years we have witnessed the development of new technologies that amplify the volume, accuracy, and timeliness of the data collected, along with the development of knowledge and tech techniques that allow for the rapid analysis of such data, enabling its translation into clear information that can be useful for the construction of different intelligent scenarios, that support the decision making and the construction of solid strategies. BDA plays a critical role in shaping organizations' decision-making [1]. BDA refers to datasets and analytical techniques in applications that are so large and complex that they require advanced and unique technologies for their storage, management, analysis, and visualization [2]. Agility and resilience are essential attributes for decision-making and can be decisive for the assertiveness of business initiatives in the process of exposing their products to the market, whether with advertising actions or brand positioning actions by region or by the target audience. In a procedurally rational (also known as comprehensive or analytical) method of decision-making and problem-solving, relevant data is identified, collected, analyzed, and interpreted to help decision-makers find the best solution based on specific decision criteria [7]. According to Razali et al. [5], "Preventive maintenance is crucial in maintenance management because it protects the good condition of facilities before they fail." In this sense, it becomes even more important to be consciously able to register, consolidate, organize, and analyze data to extract interesting information and ideas that can be translated into strategic actions in favor of the company. In fact, this is the common difficulty that organizations face when they must develop a preventive maintenance plan. Currently, this situation becomes even more complex considering the vast range of data that a company can generate added to the countless data generated by each second in the market [6]. Synthetic data creation can be used to produce large volumes of data that correctly reflect the capabilities of the business model under analysis, overcoming the drawbacks of conventional data collection techniques. This makes it possible to create more accurate predictive maintenance models, which in turn can result in less equipment downtime, increased safety, and managed maintenance costs that can bring cost savings [8].

3 Data and Methods

The data collection that made this study possible was done by accessing the website https://www.kaggle.com [4], considering the difficulty, in general, of obtaining and the difficulty of publishing real datasets of predictive maintenance, the website provided a synthetic dataset that reflects actual predictive maintenance commonly found in industrial sectors built with the best possible knowledge. The dataset consists of 10,000 data points stored as rows with 14 columns referring to the process records of a production line composed of three types of products classified by the letters L, M, or H downwards (50% of all products), medium (30%) and high (20%) as product quality variants and a variant-specific serial number.

A random loading procedure was used to estimate the air temperature [K], which was then normalized using a standard deviation of 2K around 300K. Process temperature [K], which was determined by adding the air temperature plus 10K to a random load process with a standard deviation of 1K. The rotational speed [rpm], was determined using 2860 W of power and a properly distributed noise layer, torque [Nm], which does not show negative values and considers a regular distribution of torque values around 40 Nm with a =10 Nm, tool wear [min], which shows that the quality variants H, M, and L increase the wear of the tool used in the process by 5/3/2 min. A “machine failure” label, that shows whether the machine actually failed at this particular data point if any of the following failure scenarios are true. This base was built in a file in CSV format and does not consider any blank lines or fields. The analysis procedures used in this study involved descriptive and multivariate statistical analysis of the synthetic dataset obtained from the Kaggle website [4]. Python tools were used to perform the analysis, including descriptive and multivariate statistical libraries. The dataset was first loaded into the Python environment and basic descriptive statistics were generated to provide an overview of the dataset. Exploratory data analysis techniques, such as scatterplots and histograms, were used to identify any patterns or strategic relationships in the data, and multivariate statistical techniques, such as Pearson interlocks and cluster analysis, were used to identify any underlying patterns or clusters in the data.

Once patterns and clusters in the data were identified, the results were presented in chart form to provide information on the location of failures and insights to build a preventive maintenance plan. These results are discussed in the next section.

4 Results

4.1 Descriptive Statistics

The graph displayed in Fig. 1, shows the number of items produced by the type of product (M, L, or H). Data shows that product H presents idleness in comparison with the other products M and L. This situation can be originated by production plans where product H is special and therefore reflects its exclusivity in production. The points of greatest stress in the operation are noticed when production reaches quantities produced between 4000 and 5000 units, which indicates an increase in the production of L and M products.

The produced volume of M and L products showed that there is a continuous and, to a certain extent, predictable demand for these items.

Observing the data in Fig. 2, which brings the vision of the production volume in comparison with the type of failure when a failure occurred. Data supported that clearly, the main failure is heat dissipation. In this chart, we could also notice that failures due to the excessive effort, "Overstrain Failures" also deserve attention in the initiatives to mitigate failures in the preventive maintenance plan. By level of representativeness, the failures in the sequence are tool wear – "Tool Wear Failure" – raising concerns with the quality of use of fermenters, mainly in a continuous production system, and failure due to lack of energy – "Power Failure" – which showed that there are times when production performance is interrupted, however, it was also shown not to contain significant recurrence.

The analysis of Fig. 3 suggests that the air temperature reaches a high level when production is at approximately 5000 items. It showed a curve of the gradual rise of the air temperature [K] after the produced volume of 1000. Interestingly, at the start of production, the air temperature [K] continues to drop until the volume produced reaches 1000 items. In Fig. 4, we note that the process temperature reaches a high

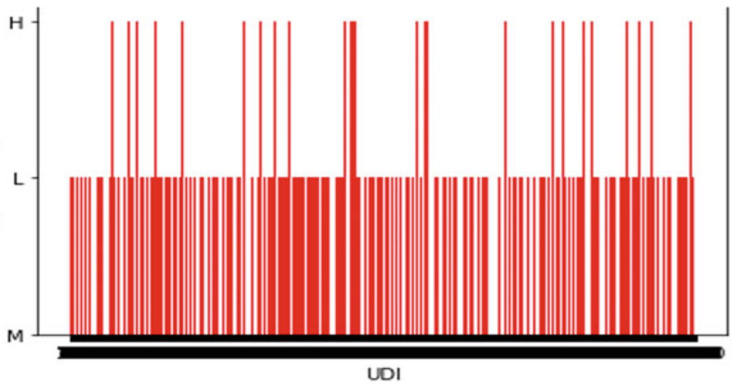


Fig. 1 Quantity of items by type of product

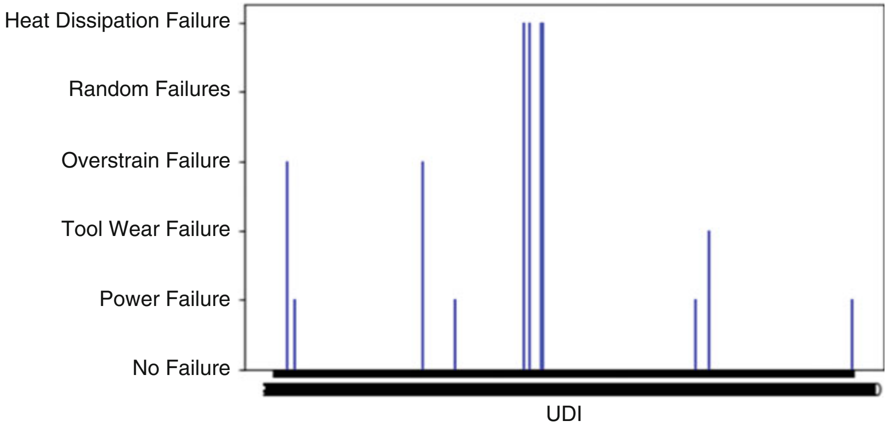


Fig. 2 Number of items by type of failure

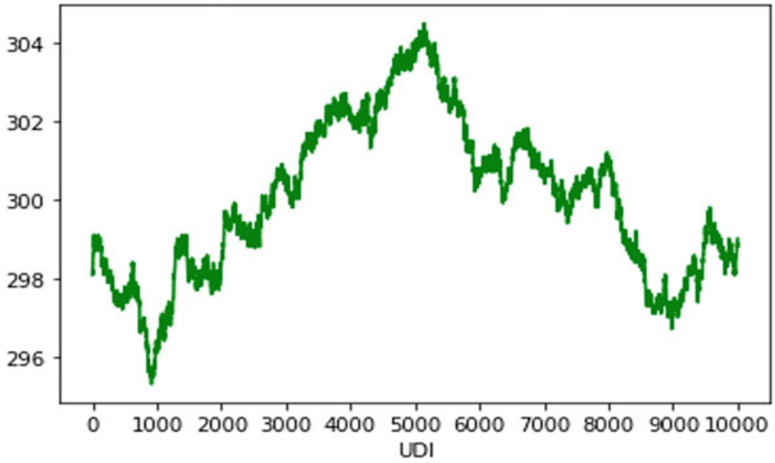


Fig. 3 Number of items and air temperature

index when production is around 5000 items. Similar to the analysis of Fig. 3, a peak was noticed as production evolved from 4000 to 5000 items produced.

In the analysis of Fig. 5, the values for air and process temperature are together. IT is observed a proportionality between the rise and fall in the same points of the production volume, evidencing great heating in specific points in the production.

The analysis of Fig. 6, which classifies the number of items produced by the rotation speed in rpm, pointed to an approximate variation of 500 rpm, observing the rpm range from 2000 to 2500. This also occurs in some moments of the operation, with sharp peaks, for example, where production reaches around 1800 rpm.

Figure 7, which recorded the volume of items produced organized by torque Nm, it was observed that there is torque variation, such as peaks when the torque level

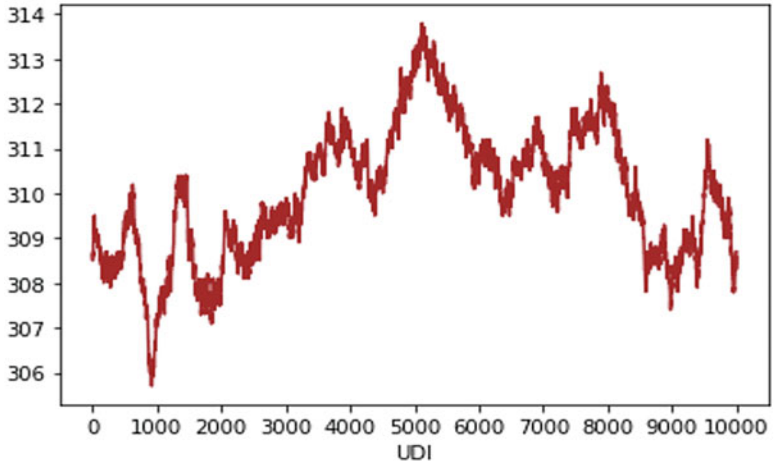


Fig. 4 Production quantity and process temperature

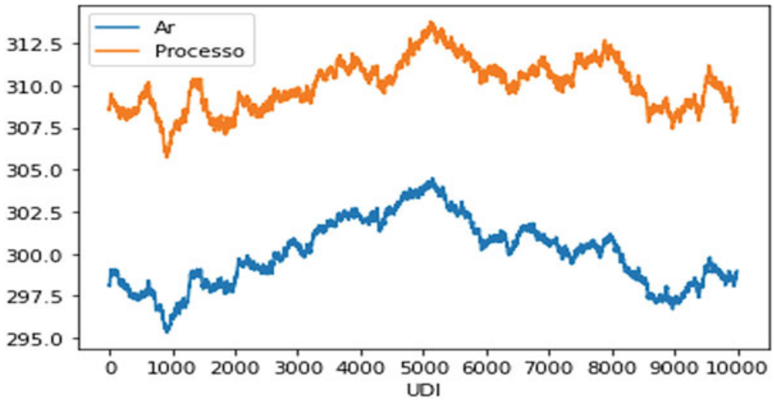


Fig. 5 Air and process temperature

reaches about 78 and 73 Nm, however, it is not discrepant. It was also verified that there is a relatively standard torque range between 20 and 60 Nm during the production process. Figure 8 showed that the trend is that the hotter the air temperature is, the hotter the process temperature will be. At the point of around 290 items produced, there is a decline that recovers again when it reaches around 302 items and thereafter remains incremental.

Figure 9 showed that the dispersion between speed and rotation follows a pattern, because when a greater force is required to overcome inertia, more speed is applied and, with the evolution of production, less speed is applied. This is a negative correlation. It was also noted that most of this effort is found when the production level reaches 1250 and 1500 items and, considering this isolated range, we saw a

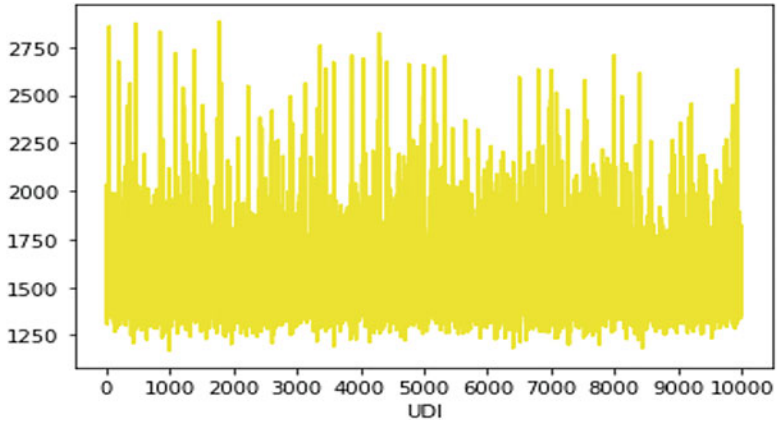


Fig. 6 Production volume and rpm rotation

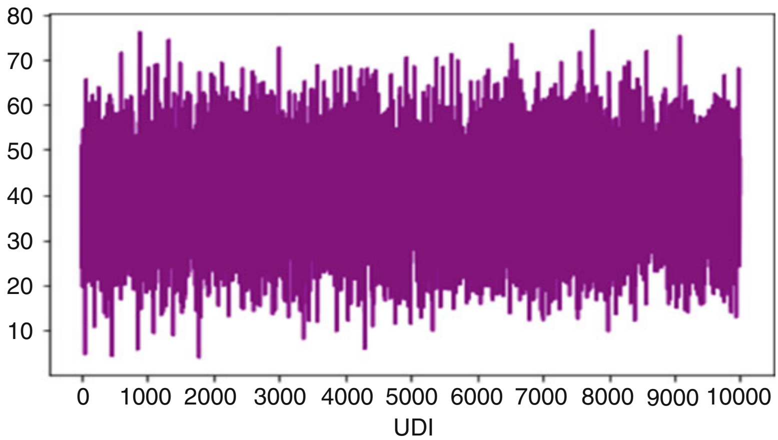


Fig. 7 Production volume and torque

variation from 35 to 78 ratios, which shows great effort with speed and rotation at the beginning of production.

In the following analysis, Bloxplot graphs and correlation graphs are used to explore the data. Bloxplot graphs are interesting for the analysis of points outside the curve, the so-called Outliers because they present five statistics – the minimum, the first quartile (Q1), the median, the third quartile (Q3), and the maximum. Outliers can hide a real result in a data set and can impact, in various ways, the decisions that will be made based on the bases. In view of this, it is essential to carry out a coherent identification of the data and treat them correctly in order to make a sober decision (Figs. 10, 11, 12, and 13).

The following analysis shows the distribution graphs of the process temperature records [K], rotation speed [rpm], torque [Nm], and tool wear [min]. The figures

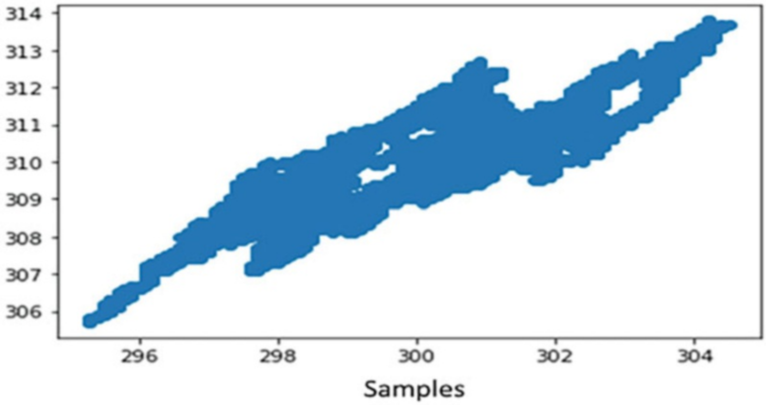


Fig. 8 Air and process temperature

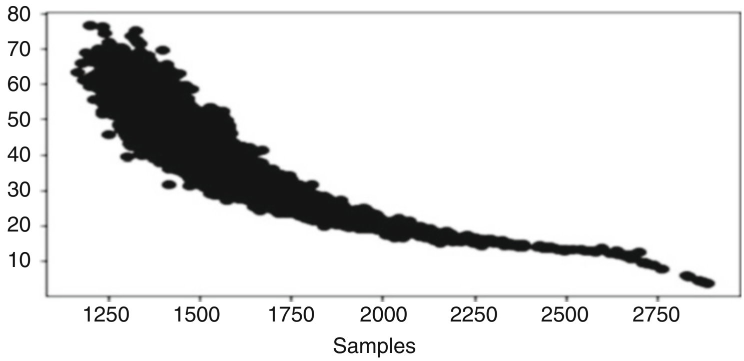
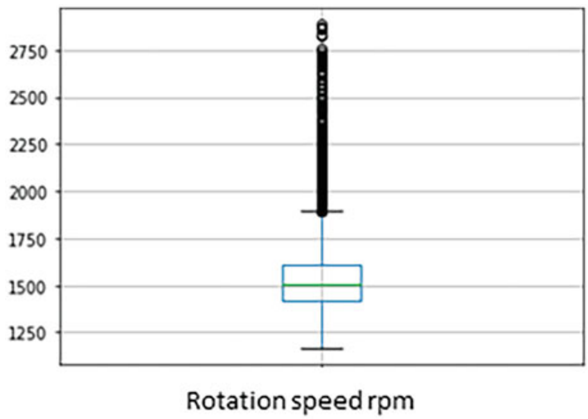


Fig. 9 Speed and rotation

Fig. 10 RPM speed



The observation of Fig. 10 showed apparent outliers when the rpm speed reaches an rpm level greater than 1900

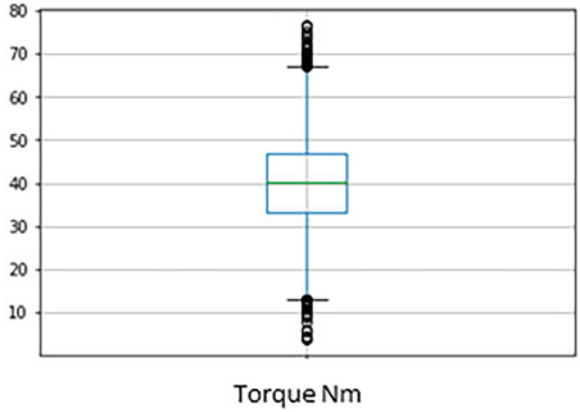


Fig. 11 Touch [Nm]
The analysis of Fig. 11 pointed out apparent outliers in the Nm torque when the torque reaches a number above 78 Nm and also when the torque is below 12 Nm

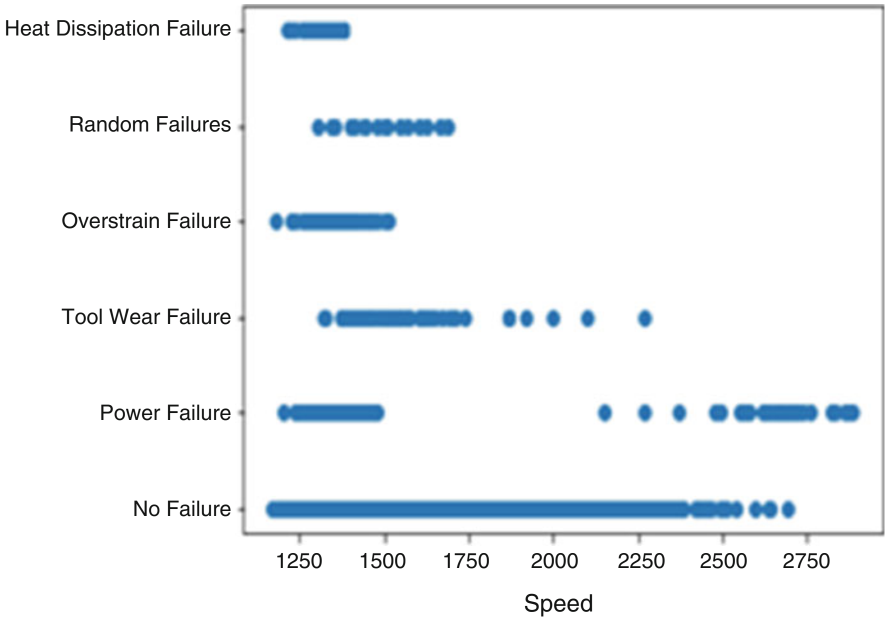


Fig. 12 Speed vs type of failure
In the analysis of Fig. 12, the correlation between speed and type of failure, showed that the main failures occur between 1300 and 1750 rpm

were organized in this way to show the temperature records of the process, speed, and production torque with the intention of elucidating the tool wear per minute (Figs. 14, 15, 16, and 17).

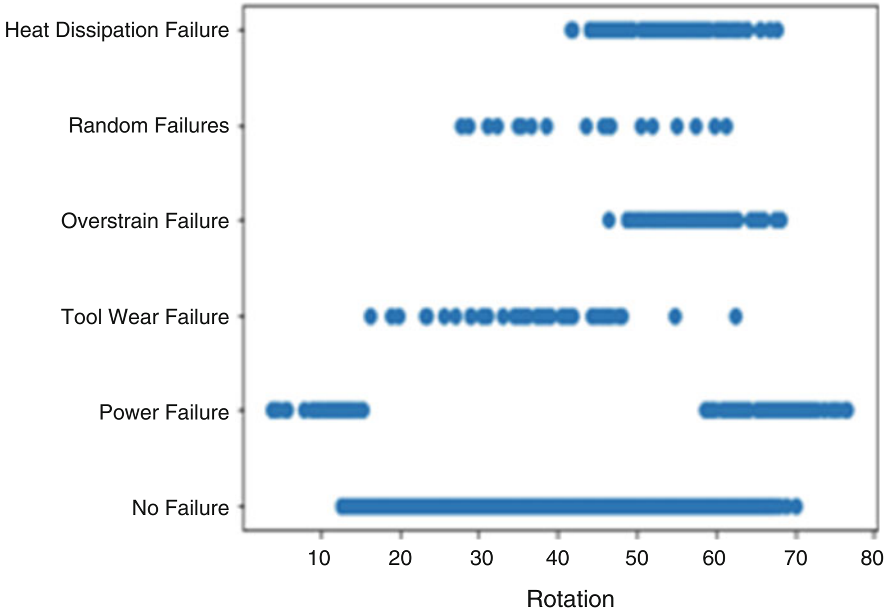


Fig. 13 Rotation vs fault type
The observation of Fig. 13 shows the correlation between rotation and type of failure. The main failures were between 25 and 70 rotations

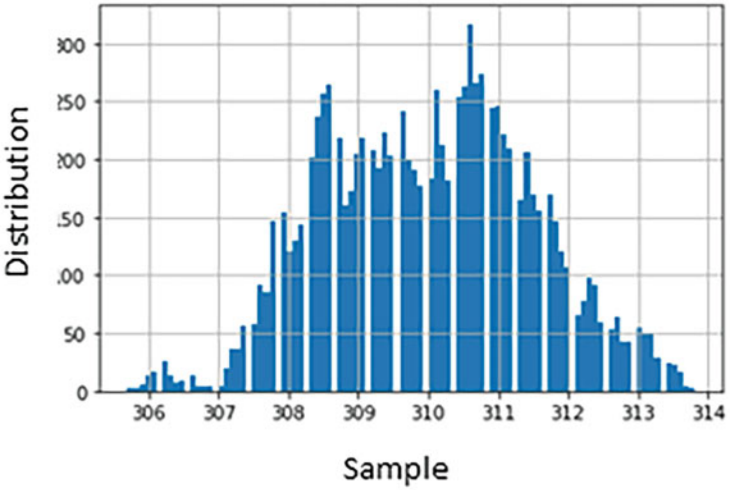


Fig. 14 Process temperature [K]
The analysis of Fig. 14 showed the temperature peaks at the moment of 308.5 and 310.8 approximately

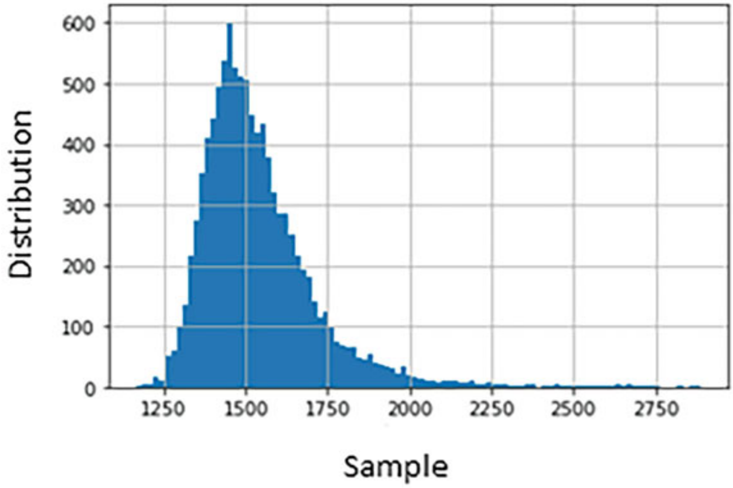


Fig. 15 Rotation speed [rpm]
The check-in Fig. 15 showed the effort at a rotational speed between 1300 and 1700 rpm

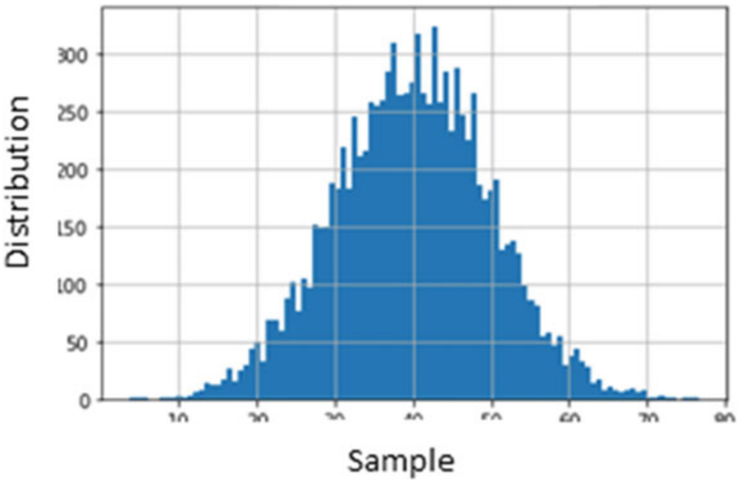


Fig. 16 Torque [Nm]
The verification of Fig. 16, showed a bell-type curve with torque variation between 50 and 310 considering samples between 20 and 60

4.2 *Multivariate Statistics*

The analysis below were carried out using multivariate statistical tools, which present a set of mechanisms that seek to simultaneously investigate a group of changing aspects that represent the items or elements belonging to a sample.

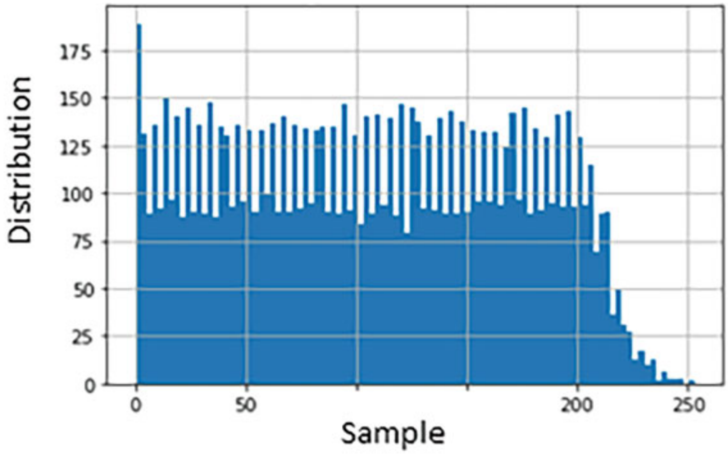


Fig. 17 Tool wear [min]
The analysis of Fig. 17 showed great tool wear between the volume of 0 and 200 samples, still showing a variation of 80 and 130 min

Multivariate statistical techniques are often classified into dependency or interdependence processes. Our intention, with the use of multivariate statistics, was to understand what would be the items related to each other that could impact failures and, mainly, the biggest failure (Figs. 18 and 19).

Figure 20 displays further detail for the comparison and ratio checks. It reveals that there is a strong relationship between air temperature and process temperature, while there is also a low relationship between torque and speed and a moderate relationship between the other items.

By analyzing Fig. 21, using Pearson's correlation, we note the strong relationship between process temperature [K] and air temperature [K], and the adverse relationship between rotational speed [rpm] and torque [Nm] is solidified.

5 Insights and Contributions: Preventive Maintenance Plan

Based on the data presented and with the insights derived from the descriptive and the multivariate statistical analysis, a preventive maintenance plan was prepared for the control and management with real effectiveness capabilities when there is a need for maintenance. The first step is to carry out an inventory of machines and equipment, so that it is possible, in later services, to have a history of adjustments made to each machine with dates, equipment identification, manufacturer's name, and place where it is fixed. This apparently simple step is essential to map and store information about the available equipment, thus providing agility in the operationalization of production tasks and historical visualization of repairs and maintenance carried out.

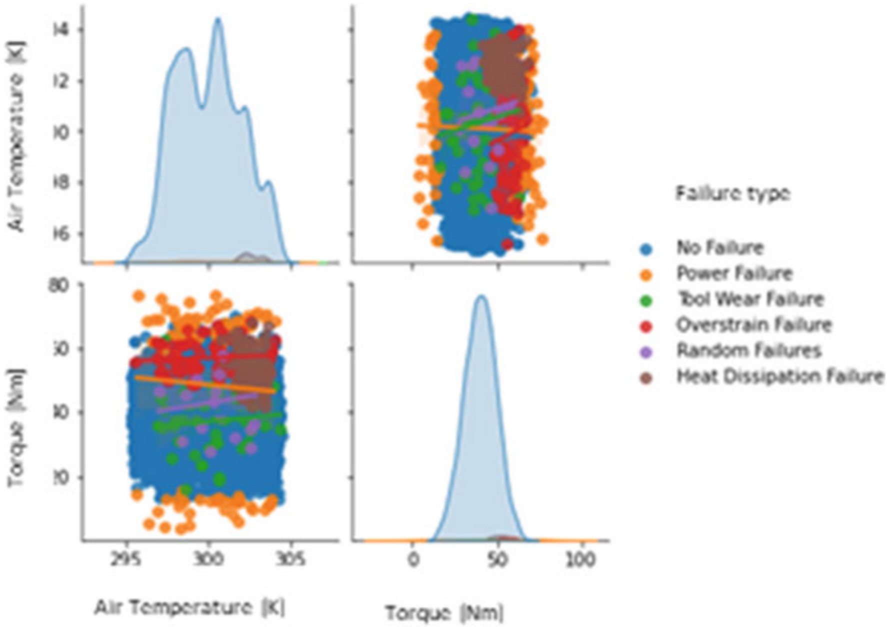


Fig. 18 Touch [Nm] and air temp. [K] vs fault type
The analysis of Fig. 18 suggests that the failure due to the excessive effort – Overstrain failure – was accentuated with the comparison between Air Temperature [K] and Torque [Nm]

The second step is to build a table that contains information about the services and procedures required for each machine. It is normal for the equipment manufacturer to indicate the recommendations and specific needs of each machine per period. The third stage is the creation of a calendar where it is possible to relate each activity to each piece of equipment with those responsible for each sector, such as managers and technicians. The repair time criteria, degree of machine utilization, loss if the machine is not operational and the number of machine stops is recommendations for leaders to have historical information for decision-making. The fourth step is to draw up a clear maintenance budget plan that contains figures considering spare parts costs and service costs for all equipment. It is important to pay due attention to this step to avoid problems with excessive expenses and extra costs at the time of maintenance. The fifth stage considers the training of all workers, whether in the production sector or in the maintenance and safety sector, so that the use of machines on production days is effective and adequate and that maintenance is effective considering the plan carried out and the available resources. The sixth stage consists of monitoring and management through defined indicators, both for production and maintenance, and thus, understanding whether the plan is being carried out as planned or if not to intervene.

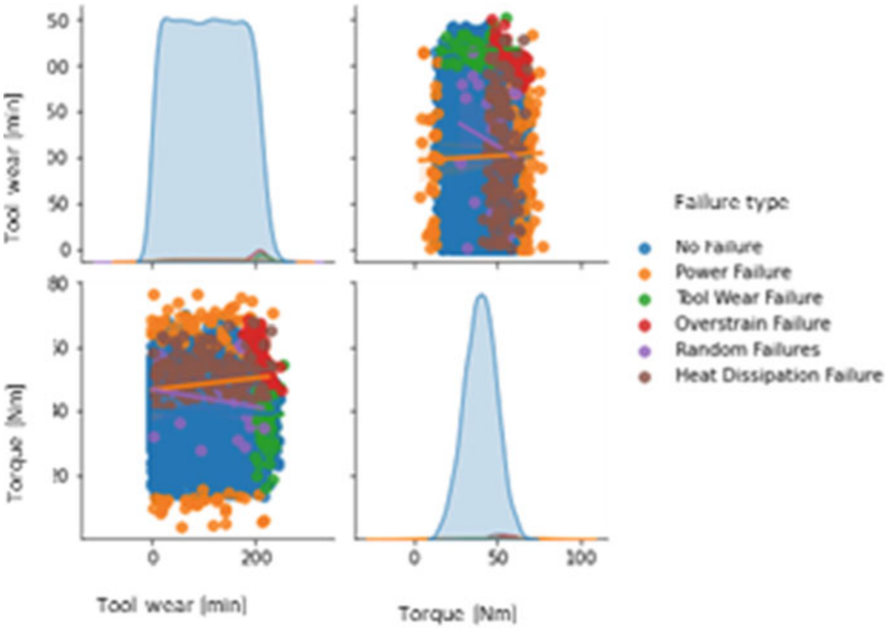


Fig. 19 Tool wear [min] and Touch [Nm] vs failure type
In Fig. 19, we note the impact of failure due to excessive effort and the accentuation of failure due to lack of energy was evident in the comparison between Tool Wear [min] and Torque [Nm]

6 Conclusion

Based on the studies and analyses carried out considering the data presented, we understand that it is essential for the management practice in a production line to have significant indicators and analysis on the production performance and on the management of failures that occur during the process. This study was based on data analysis performed through big data analytics and business intelligence that facilitated the analysis of large amounts of data, which by using the python tool elucidated information that culminated in insights to find the main failures and their causes. Thus, we understand that the main flaw in the production system presented was the wear of tools [min] with great evidence that it occurred due to the high levels of air temperature [K] and process temperature [K].

The air temperature [K] reached at certain points in the production flow, its highest level pointing to more than 304 [K], inherently, the process temperature [K] measured had its highest index at about 312 [K]. This pointed to a similar ascending curve when comparing both temperatures in a single graph, Fig. 5, which proposed the wear is too noticeable at peaks when production starts and reaches 200 items. Through multivariate statistical analyses, we concluded that there were also significant failures due to excessive effort and lack of energy, in addition to showing the relationship between process temperature [K] and air temperature [K] as

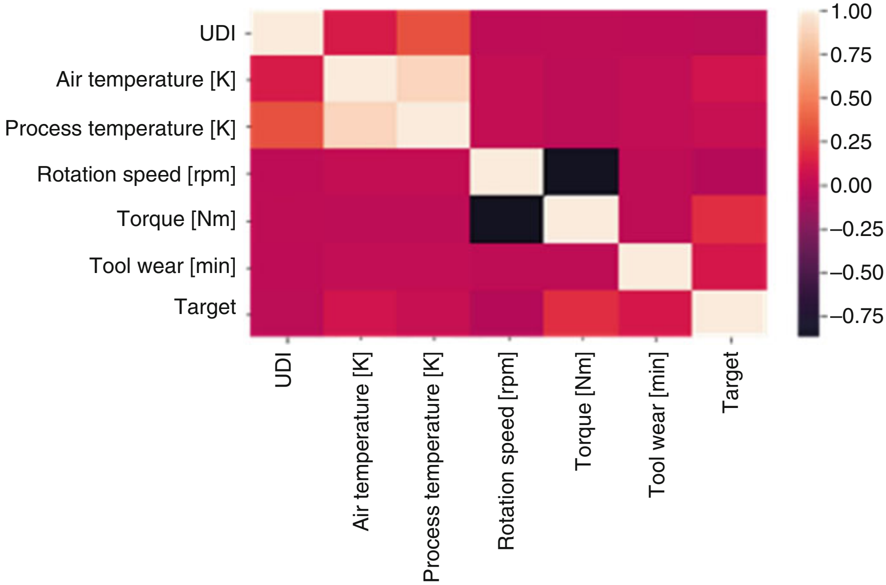


Fig. 20 Pearson correlation

In Fig. 20, we notice that the process temperature and air temperature are related

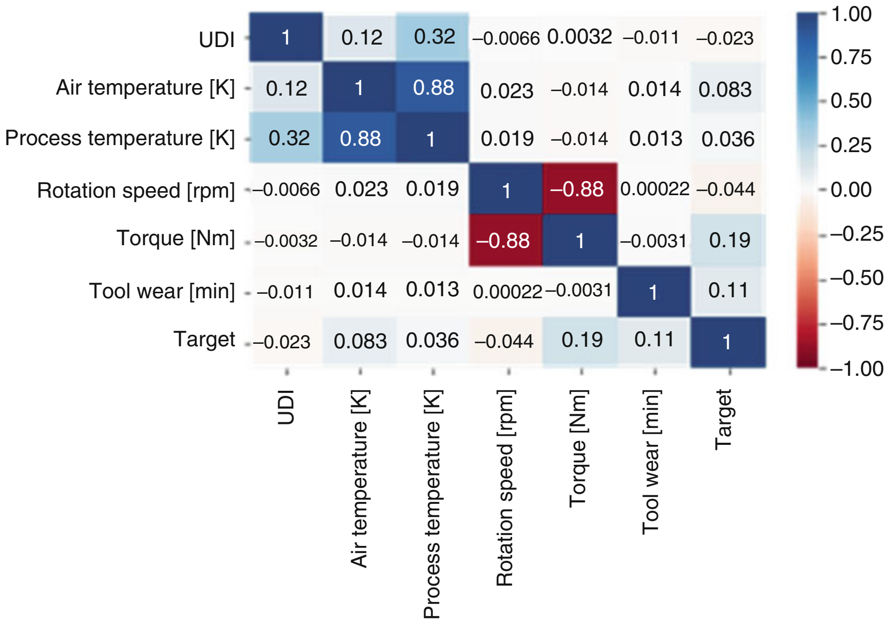


Fig. 21 Pearson correlation

Figure 21 shows the negative relationship between rotational speed and torque well as the negative relationship between rotation speed [rpm] and torque [Nm]. As a theoretical contribution, this research highlighted the importance that new tools, especially those for generating, consolidating and analysing large volumes of variable and simultaneous data, have for the correct construction of data analysis to serve as a basis for solid and effective decisions in the company.

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References

1. Awan, U., Shamim, S., Khan, Z., Zia, NU, Shariq, SM, & Khan, MN (2021). Big data analytics capability and decision-making: The role of data-driven insight on circular economy performance. Technological Forecasting and Social Change, 168. https://doi.org/10.1016/j.techfore.2021.120766
2. Chen, H., Chiang, RHL, & Storey, VC (2012). Business intelligence and analytics: From big data to big impact. MIS Quarterly: Management Information Systems, 36(4). https://doi.org/10.2307/41703503
3. Jha, AK, Agi, MAN, & Ngai, EWT (2020). A note on big data analytics capability development in supply chain. Decision Support Systems, 138. https://doi.org/10.1016/j.dss.2020.113382
4. Kaggle Homepage, http://www.kaggle.com, last accessed 2022/11/30.
5. Razali MN, Othman SH, Jamaludin AF, Maimun NHA, Jalil RA, Adnan YM, & Zulkarnain SH (2021). Big data analytics for preventive maintenance management. Planning Malaysia, 19(3), 423–437. https://doi.org/10.21837/PM.V19I17.1019
6. Sang, GM, Xu, L., & de Vrieze, P. (2021). A Predictive Maintenance Model for Flexible Manufacturing in the Context of Industry 4.0. Frontiers in Big Data, 4. https://doi.org/10.3389/fdata.2021.663466
7. Tabesh, P. (2022). Who's making the decisions? How managers can harness artificial intelligence and remain in charge. Journal of Business Strategy, 43(6), 373–380. https://doi.org/10.1108/JBS-05-2021-0090
8. Tang, R., De Donato, L., Bes̆inović, N., Flammini, F., Goverde, R. M. P., Lin, Z., Liu, R., Tang, T., Vittorini, V., & Wang, Z. (2022). A literature review of Artificial Intelligence applications in railway systems. *Transportation Research Part C: Emerging Technologies*, *140*, 103679. https://doi.org/10.1016/J.TRC.2022.103679

Mapping the Interlinkages Between Humanitarian Operations and Sustainable Development Goals Through Literature Review

Maria Angélica Gomes da Silva, Luiza Ribeiro Alves Cunha, and Adriana Leiras

Abstract Humanitarian Operations (HOs), aimed at minimizing the impact of disasters, have synergies and tradeoffs with the United Nations Sustainable Development Goals (SDGs). The SDGs aim to achieve a better and more sustainable future for all. For example, the affected region's poverty index (SDG 1) may increase due to climate-related disasters (SDG 13), requiring more HOs. If HOs last long, it may lead to the region's dependency on aid, hampering its economic growth (SDG 8). This research aims to map and analyze the interconnections between the SDGs and HOs. To achieve this goal, the research is grounded in a systematic literature review to analyze the state of the art between the topics (SDGs and HOs), proposing a taxonomy and a future research agenda. We contribute to the academic by mapping and analyzing the interconnections between SDGs and HOs.

Keywords Sustainable Development Goals · Humanitarian Operations · Systematic Literature Review

1 Introduction

The Sustainable Development Goals (SDGs), proposed by the United Nations (UN) in 2015, are an urgent call to action from all developed and developing countries in a global partnership for peace and prosperity for people and the planet [1]. The SDGs are intended to achieve a better and more sustainable future for all. Significant progress has been made on some goals, but recent disasters have

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impacted economic and social outcomes worldwide, including worsening poverty and food insecurity [2].

The challenges and effects of the SDGs are interconnected. Thus, actions to reduce poverty, for example, go together with strategies aimed at health, education and actions to reduce inequality and stimulate economic growth [1]. However, the current health and security crises have hampered the progress of some SDGs, as they diverted attention away from long-term goals, such as climate action, and exposed a significant fragmentation in international relations. These successive crises have also primarily affected vulnerable and low-income countries.

Consequently, the impacts on the most vulnerable people push for more Humanitarian Operations (HOs), including short-term disaster response and long-term interventions. HOs aim to minimize disasters' impact, but if they occur carelessly, they can generate dependency on the assisted region, damaging the region's economic growth (SDG 8). Thus, HOs present synergies and tradeoffs with the SDGs.

Therefore, this research aims to map and analyze the interconnections between the SDGs and HOs. To this end, we conduct a Systematic Literature Review (SLR) to analyze the state of the art between the topics (SDGs and HOs). The research question that underpins the research is: What is the current state of the art and gaps associated with the interconnections between SDGs and HOs? We deliver a taxonomy and a research agenda for future research directions.

2 Method

We adopt the eight steps proposed by Thomé et al. [3] to conduct the SLR: (i) Planning and formulation of the research problem; (ii) Literature search; (iii) Data collection; (iv) Quality assessment; (v) Data analysis and synthesis; (vi) Interpretation of results; (vii) Presentation of results; (viii) Updating the review. Our SLR aims to address the research problem of the interconnection between SDGs and HOs mapping the existing literature related to the topic (first step).

As a second step, we selected the databases and keywords, reviewed abstracts, applied exclusion criteria, and reviewed the full texts. We chose the Scopus and Web of Science (WoS) databases because, according to Mongeon and Paul-Hus [4], they have the most comprehensive coverage of literature in the engineering field.

The combination of keywords we propose is broad enough to avoid limitations but narrow enough to avoid unwanted results. The search considers two groups of keywords: the first focused on the SDGs,[1] and the second on the HOs: ("sustainable development goal*" OR "SDG*" OR "agenda 2030" OR "millennium development goal" OR "MDG"[1]) AND ("humanitarian logistics" OR "humanitarian operation*" OR "humanitarian supply chain" OR "disaster* operation*" OR "disaster* response*" OR "disaster* mitigation" OR "disaster* preparedness" OR "disaster*

[1] The SDGs replaced the Millennium Development Goals (MDGs) (2000–2015).

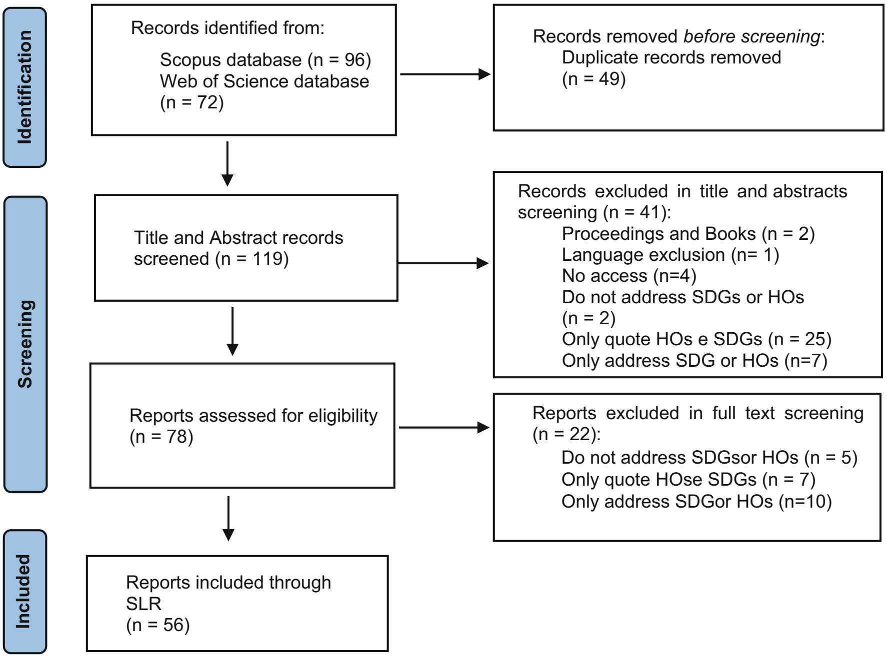

Fig. 1 PRISMA diagram of the literature search steps

recovery”). We searched on titles, abstracts, and keywords in Scopus, and all fields in WoS.

The search was conducted on January 11, 2023, with no date limit, resulting in 96 documents in the Scopus base and 72 in WoS. The following criteria are used to analyze these documents on inclusion or exclusion:

- Inclusion Criteria: addresses the relationship/linkage between SDG and HOs;
- Exclusion Criteria: only cites SDGs or HOs; does not address SDG or HOs; duplicate documents; documents in languages other than English.

Therefore, considering these criteria, we selected 56 for the search. Figure 1 represents the PRISMA diagram [5] referring to the search.

The data collection (third step) is performed by identifying and compiling in supplementary tables the data regarding the year of publication, number of citations, keywords, abstract, methodology, and type of disaster. Describing the method followed in all SLR steps ensured the quality assessment. The analysis and synthesis (fifth step) is performed to obtain the taxonomy, presented in the next section. The next step consists of interpreting the results, which is addressed by discussing the impact of the findings on the interconnection between SDGs and HOs. The presentation of the results is described in this paper, and updating the review is the last step, proposed as future research.

3 Results and Discussions

Table 1 shows the proposed taxonomy. Most articles do not specify which SDG they address, but from what is discussed, it is possible to infer which SDG the research is related to. SDG 3 (health and well-being) is the most cited SDG, followed by SDG 11 (sustainable cities and communities). SDG 1 (poverty eradication), 2 (zero hunger and sustainable agriculture), and 13 (action against global climate change) come third in terms of citations. SDG 4 (quality education), 6 (clean water and sanitation), 7 (clean and affordable energy), 8 (decent work and economic growth), 9 (industry, innovation, and infrastructure), 12 (responsible consumption and production), 15 (earth life), and 17 (partnerships and means of implementation) are cited only once.

Considering the disaster life cycle [6], the preparedness phase is the most addressed (seven articles), followed by response (four articles), and mitigation (three articles). Considering Behl and Dutta's [7] classification, 13 articles address the post-disaster phase, and 1 addresses the pre-disaster. Finally, 10 articles do not focus on a specific disaster phase, 18 address disaster risk, and 2 cover operations management.

Pandemics and epidemics are the most studied disasters (nine articles). This topic has gained attention due to the COVID-19 pandemic, (in fact, five papers cover COVID-19). Most articles do not deal with a specific type of disaster (27 articles); other disaster types studied are volcanoes, earthquakes, floods, hurricanes, and cyclones (as presented in Table 1).

Africa is the most studied continent overall (five articles), and the most studied country is Pakistan (three articles), followed by Chile (two articles), Indonesia (two articles), and Bangladesh (two articles).

Table 2 presents the qualitative and quantitative methodologies used in the articles. Concerning the qualitative, the literature review is the most adopted methodology (ten articles), followed by case study. Quantitative methodologies can be separated by survey, multi-methods, and modeling. However, various papers do not determine a methodology (32 articles).

Most surveys are used to obtain data. Concerning multi methods, a decision analysis (MCDA) combined with satellite remote sensing, analytic hierarchy process (AHP), and interactive multicriteria decision-making (TODIM) are also used. Only one article integrates the SDGs in its System Dynamics modelling [31] to analyze the factors influencing cholera outbreaks in the context of the Yemen War. Some models, such as Ricciardelli et al. [41], use a reduced equation model that elaborates and integrates two models: one estimating the relationship between the level of development and impacts from natural disasters and the other containing the resilience index. Raza et al. [58] develop a technical model of risk-sensitive comprehensive land use planning and development with a training toolbox, and its feasibility is evaluated. Hariyono et al. [13] use structural equation modelling analysis to analyze SDG education's role in disaster preparedness. Stauffer et al. [21] adopt a mixed integer stochastic model to optimize food bank storage and distribution for different

Table 1 Taxonomy

Reference	Disaster phase	Type of disaster	SDG	Relationship of the article with SDG
Rai et al. [8]	Post-disaster	Pandemics (COVID-19)	3	Post-covid perceptions in the SDG framework
Lehmann et al. [9]	General	General	15 (15.3.1)	Visualization of degraded areas
Kumar and Bindu [10]	General	General	General	Suggest methods to improve the resilience of cities to achieve the SDGs
Khan and Mishra [11]	General	General	General	Highlight gaps in disaster risk communication through international agreements, including SDGs
Etim et al. [12]	General	Pandemics (COVID-19)	General	Revalidation and evaluation of the SDGs for healthcare facilities focused on waste management
Hariyono et al. [13]	Preparedness	Tsunami	4	Examines the role of SDG education in disaster preparedness
Tiwari and Shukla [14]	Post-disaster	General	General	Framework for identifying components of a post-disaster management plan to satisfactorily rebuild the well-being of affected people in line with the SDGs
Dzvimbo et al. [15]	General	General	4 and 13	Higher education institutions are essential climate and disaster management partners and their core mission includes public engagement to advance achieving SDGs
Schön et al. [16]	General	Refugee crisis	General	Relationship between human rights and the SDGs
Etinay et al. [17]	Preparedness	General	General	Identify common principles of disaster prevention and relate them to the SDGs
Steptoe et al. [18]	General	General	General	Develop early warning systems for multi-hazard disasters that support the SDGs
Noaman and Alsaffar [19]	Post-disaster	General	General	Support for meeting the SDGs
Eltinay and Egbu [20]	General	General	11	Correlation between Sendai framework for disaster risk reduction and SDGs
Stauffer et al. [21]	General	Food insecurity	2 (2.12)	Addressing the issue of hunger
Hasan et al. [22]	Preparedness	General	General	Disaster reduction to achieve SDGs

(continued)

Table 1 (continued)

Reference	Disaster phase	Type of disaster	SDG	Relationship of the article with SDG
Besiou et al. [23]	General	General	General	Links between SDGs and HOs
Kougkoulos et al. [24]	General	Immigration	8	Labor exploitation of HOs-related immigrants
Zarei et al. [25]	General	General	General	Environmental sustainability in humanitarian supply chains
Schismenos et al. [26]	General	Floods	7 and 13	Incorporation of characteristics into community-led action to promote sustainable development
Inzaule et al. [27]	Post-disaster	Pandemics (COVID-19)	General	Mitigation strategies to reduce the health impact of COVID-19
Karuppiah et al. [28]	Post-disaster	Pandemics (COVID-19)	3 and 17	COVID-19 implications
Greiving et al. [29]	General	General	General	SDG performance measurement
Kurwakumire et al. [30]	Preparedness	General	1 and 3	The link between spatial data, disaster resilience and SDGs
Harpring et al. [31]	Mitigation	Epidemics (cholera)	1, 3, 4, 6, 9 and 11	Use their associated targets in the model as variables that influence the cholera incidence rate
Tselios and Tompkins [32]	General	Natural and technological disasters	General	Prioritization of investments in SDGs
Warner [33]	General	General	General	Integrating disaster risk into the SDGs
Calyx [34]	Post-disaster	Epidemics (Ebola)	General	How the pandemic relates to the SDGs
Khan et al. [35]	Response	General	General	Mass fulfilment centres help meet the SDGs
Van Wassenhove [36]	General	General	General	OM needs innovation to contribute to meeting the SDGs
Wu et al. [37]	Post-disaster	Floods	General	Shelter as a strategy for adapting to climate change and consequently achieving the SDGs
Prayoga et al. [38]	General	Volcano	3 and 11	Disaster risk reduction
Sardi et al. [39]	Preparedness	Floods	General	Increase vulnerable community resilience
Ahmed and Eklund [40]	Preparedness	Natural disasters	Sustainable development	Addresses both rural socio-economic development and disaster preparedness and

(continued)

Table 1 (continued)

Reference	Disaster phase	Type of disaster	SDG	Relationship of the article with SDG
				implications for achieving the SDGs
Ricciardelli et al. [41]	Response	Earthquake	General	Discussion on the development of sustainable cities and communities
Brundiers and Eakin [42]	Post-disaster	General	General	Framework to facilitate documentation and analysis of case studies of sustainability transitions after disasters
Alarslan [43]	Mitigation	General	11	Solutions to achieve SDG 11
Rachmad [44]	Mitigation	Climate disasters	13	SDG 13 support
Hoffmann and Muttarak [45]	Preparedness	General	13	Disaster risk reduction education
Tambo et al. [46]	General	General	General	Advances in universal health coverage and SDGs are essential for healthy development
Aka et al. [47]	General	General	General	Proactive resilience aims to prepare Cameroon to face SDG challenges adequately
Asokan and Vanitha [48]	Post-disaster	Earthquake	3	Relates to health and economy in the post-disaster period
Pelesikoti and Suwamaru [49]	General	General	General	Discussion of policies relevant to commitments such as SDGs
Takeuchi and Tanaka [50]	Pre-disasters and reconstruction	General	General	Building resilient cities with disaster reduction goals
Parvin et al. [51]	General	General	General	The resilience of cities is essential to achieve the SDGs
Drolet et al. [52]	Post-disaster	General	General	Lists the role of women in achieving the SDGs
Iserson [53]	General	Humanitarian catastrophes	General	Development of post-2015 millennium development goals with more accurate measures of progress
Denhart [54]	Post-disaster	Drilling	General	It cites the Millennium's goals to reduce disasters' human and environmental impact
Setiawan et al. [55]	Response	General	General	Sustainable development to improve people's quality of life

(continued)

Table 1 (continued)

Reference	Disaster phase	Type of disaster	SDG	Relationship of the article with SDG
Haque and Burton [56]	General	General	General	Building disaster-resilient communities
Jakubik and Feuerriegel [57]	General	Epidemics (HIV/AIDS)	General	Ending HIV is part of the SDGs
Raza et al. [58]	General	Climate change	General	Support for meeting the SDGs
Ali et al. [59]	General	General	General	Inclusion of indigenous people in disaster risk
Aitsi-Selmi et al. [60]	General	General	General	Innovations to meet the SDGs
Udmale et al. [61]	Post-disaster	Pandemics (COVID-19)	2	Addresses the issue of food insecurity SDG 2
Pramanik et al. [62]	Post-disaster	Cyclone and pandemic	3 and 6	Discussion of the risk of impacts from multiple risks slowing progress on SDGs 3 and 6
Roy et al. [63]	General	General	General	Actions linked to the SDGs to reduce uncertainty in decision-making in energy, climate change and disaster contexts

food types (produce, dairy, and shelf-stable). Similarly, Jakubik and Feuerriegel [57] use a two-stage decision model to find a cost-effective, cross-country allocation of development aid to end the HIV epidemic.

Other approaches focus on data mapping to explore the associations between socioeconomic and political factors and disaster propensity [32] or to determine property boundaries by employing the unified modelling language [30].

3.1 Research Agenda

Our SLR suggests there is a need to study the sustainability challenges of humanitarian supply chains [28], for example, gas emissions [23, 25]. The papers propose the analysis of emissions that impact the environmental supply chain sustainability [23, 25]. Besides, there is a lack of studies covering disaster waste management [12], including partnering with the private sector in construction waste management [19].

Disaster risk reduction is another topic of attention, encompassing disaster mitigation incorporating human concerns [56], such as forced evacuation, shelters management, mental health interventions, and the long-term health impacts of the displaced population [37], and resilience strategies for climate and disaster management policies [15]. Considering disaster recovery, it is suggested to focus also on the

Table 2 Methodologies adopted in the analyzed papers

Methodology	Reference
Literature review	Rai et al. [8]; Lehmann et al. [9]; Kumar and Bindu [10]; Khan and Mishra [11]; Etim et al. [12]; Schön et al. [16]; Etinay et al. [17]; Steptoe et al. [18]; Noaman and Alsaffar [19]; Eltinay and Charles [20]; Zarei et al. [25]
Case study	Ahmed and Eklund [40]
Unidentified qualitative methods	Drolet et al. [52]; Dzyimbo et al. [15]; Besiou et al. [23]
Survey	Hoffmann and Muttarak [45]; Aka et al. [47]; Hasan et al. [22]; Raza et al. [58]
Multicriteria analysis	Kougkoulos et al. [24]; Karuppiah et al. [28]
Econometric analysis	Tselios and Tompkins [32]
Data mapping	Tselios and Tompkins [32]
Mathematical model	Stauffer et al. [21]; Jakubik and Feuerriegel [57]
Structural equation modelling	Hariyono et al. [13]
Unified modeling language	Kurwakumire et al. [30]
System dynamics	Harpring et al. [31]
Reduced equation model	Ricciardelli et al. [41]
Technical planning model	Raza et al. [58]

lasting consequences beyond immediate assistance [14]. Therefore, future research should focus more attention on understanding the underlying root causes and risk factors of disaster risk, including interlinkages between disaster risk reduction, sustainable development, and climate change mitigation and adaptation, and ensuring that disaster risk reduction is integrated into other sectors, policies, and strategies [60].

Data for research development is still an open avenue in HO and SDGs interface [54]. So, we highlight the importance of improving human and technical capabilities with the use of open data tools [20], identifying more objective open access sources for all vulnerability and capability mapping metrics, further increasing the reliability of the outputs [26]. Furthermore, data collectors should come with building systems knowledge, allowing a building systems approach to multi-layered understanding [54]. We also suggest future works include surveys to collect practitioners' opinions [31]. Considering the data visualization, future HOs management research could provide quantitative decision-making tools using new data sources in creative ways to identify human rights violations and thus contribute to a more sustainable world [24].

4 Conclusion

This research aimed at identifying the current state of the art related to linking the SDGs and HOs. We analyzed 56 documents from the Scopus and Web of Science databases based on SLR procedures. We performed a content analysis according to the disaster phase, the SDG, and the relationship of SDG to HOs. The results reveal that the most SDGs addressed are 3 (good health and well-being) and 11 (sustainable cities and communities); thus, these SDGs seem to have a greater relationship with the HOs so far. Besides, SDGs 1, 2, 4, 6, 7, 8, 9, 12, 13, 15, and 17 are also covered. SDGs 5, 10, 14, and 16 are not addressed in any HOs paper of our sample.

The selected articles were mapped according to the methodology used. Most articles use a literature review to relate SDGs and HOs. Considering the modeling used, we concluded that the inclusion of SDGs in modeling still needs to be explored.

We suggest that future research incorporate existing studies in other databases and grey literature sources to encompass the practitioner' point of view. In addition, future research could incorporate other SDGs into modeling to better understand the relationship between SDGs and HOs.

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References

1. UN – United Nations – Do you know all 17 SDGs?, https://sdgs.un.org/goals, last accessed 2022/09/06.
2. Sachs, J., Kroll, C., Lafortune, G., Fuller, G., Woelm, F. Sustainable Development Report 2022. Cambridge University Press.(2022).
3. Thomé, A. M. T., Scavarda, L. F., & Scavarda, A. J. Conducting systematic literature review in operations management. Production Planning & Control, 27(5), 408–420(2016).
4. Mongeon, P., Paul-Hus, A. The journal coverage of Web of Science and Scopus: a comparative analysis. Scientometrics, 106, 213–228(2016).
5. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., . . . Moher, D. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. International journal of surgery, 88, 105906(2021).
6. Leiras, A., de Brito Jr, I., Peres, E. Q., Bertazzo, T. R., Yoshizaki, H. T. Y. Literature review of humanitarian logistics research: trends and challenges. Journal of Humanitarian Logistics and Supply Chain Management, 4(1), 95–130(2014).
7. Behl, A., Dutta, P. Humanitarian supply chain management: a thematic literature review and future directions of research. Annals of Operations Research, 283(1–2), 1001–1044(2019).
8. Rai, P. K., Sonne, C., Song, H., & Kim, K. H. The effects of COVID-19 transmission on environmental sustainability and human health: Paving the way to ensure its sustainable management. Science of The Total Environment, 156039(2022).
9. Lehmann, A., Mazzetti, P., Santoro, M., Nativi, S., Maso, J., Serral, I., . . . Giuliani, G. Essential earth observation variables for high-level multi-scale indicators and policies. Environmental Science & Policy, 131, 105–117(2022).

10. Kumar, K., Bindu, C. A. Resilience master plan as the pathway to actualize sustainable development goals–A case of Kozhikode, Kerala, India. Progress in Disaster Science, 14, 100226(2022).
11. Khan, S., Mishra, J. Critical gaps and implications of risk communication in the global agreements—SFDRR, SDGs, and UNFCCC: 3 select case studies from urban areas of tropics in South Asia. Natural hazards, 111(3), 2559–2577(2022).
12. Etim, M. A., Omole, D. O., Araoye, O. V. Impact of COVID-19 on medical waste management and disposal practices in Nigeria. Cogent Engineering, 9(1), 2038345(2022).
13. Hariyono, E., Admoko, S. Contribution of SDGs in tsunami disaster preparedness education in Indonesia. Science of Tsunami Hazards, 41(4) (2022).
14. Tiwari, P., Shukla, J. Post-Disaster Reconstruction, Well-being and Sustainable Development Goals: A Conceptual Framework. Environment and Urbanization ASIA, 13(2), 323–332(2022).
15. Dzvimbo, M. A., Mashizha, T. M., Zhanda, K., Mawonde, A. Promoting sustainable development goals: Role of higher education institutions in climate and disaster management in Zimbabwe. Jàmbá: Journal of Disaster Risk Studies, 14(1)(2022).
16. Schön, A. M., Al-Saadi, S., Grubmueller, J., Schumann-Bölsche, D. Developing a camp performance indicator system and its application to Zaatari, Jordan. Journal of Humanitarian Logistics and Supply Chain Management, 8(3), 346–373 (2018).
17. Etinay, N., Egbu, C., Murray, V. Building urban resilience for disaster risk management and disaster risk reduction. Procedia engineering, 212, 575–582 (2018).
18. Steptoe, H., Jones, S. E. O., Fox, H. Correlations between extreme atmospheric hazards and global teleconnections: implications for multihazard resilience. Reviews of Geophysics, 56(1), 50–78(2018).
19. Noaman, A. S., & Alsaffar, A. E.A suggestion of a procedural method for the management of post-war waste. Civil Engineering Journal, 5(10), 2143–51 (2019).
20. Eltinay, N., Charles, E. Disaster risk reduction conceptual framework: open data for building resilience in critical infrastructure. In Proceeding of the 33rd Annual ARCOM Conference (2017).
21. Stauffer, J. M., Vanajakumari, M., Kumar, S., & Mangapora, T. Achieving equitable food security: How can food bank mobile pantries fill this humanitarian need. Production and Operations Management, 31(4), 1802–1821(2022).
22. Hasan, M., Moriom, M., Shuprio, S. I. M., Younos, T. B., Chowdhury, M. Exploring disaster preparedness of students at university in Bangladesh. Natural Hazards, 111(1), 817–849(2022).
23. Besiou, M., Pedraza-Martinez, A. J., Van Wassenhove, L. N. Humanitarian operations and the UN sustainable development goals. Production and Operations Management, 30(12), 4343–4355(2021).
24. Kougkoulos, I., Cakir, M. S., Kunz, N., Boyd, D. S., Trautrims, A., Hatzinikolaou, K., Gold, S. A multi-method approach to prioritize locations of labor exploitation for ground-based interventions. Production and Operations Management, 30(12), 4396–4411(2021).
25. Zarei, M. H., Carrasco-Gallego, R., Ronchi, S. On the role of regional hubs in the environmental sustainability of humanitarian supply chains. Sustainable Development, 27(5), 846–859 (2019).
26. Schismenos, S., Stevens, G. J., Emmanouloudis, D., Georgeou, N., Shrestha, S., Chalaris, M. Humanitarian engineering at the sustainability-development nexus: mapping vulnerability and capability factors for communities at risk of water-based disasters. Sustainability science, 16(4), 1185–1199(2021).
27. Inzaule, S. C., Ondoa, P., Loembe, M. M., Tebeje, Y. K., Ouma, A. E. O., Nkengasong, J. N. COVID-19 and indirect health implications in Africa: Impact, mitigation measures, and lessons learned for improved disease control. PLoS Medicine, 18(6), e1003666(2021).
28. Karuppiah, K., Sankaranarayanan, B., Ali, S. M., & Paul, S. K. Key challenges to sustainable humanitarian supply chains: lessons from the covid-19 pandemic. Sustainability, 13(11), 5850 (2021).

29. Greiving, S., Schödl, L., Gaudry, K. H., Quintana Miralles, I. K., Prado Larraín, B., Fleischhauer, M., … Tobar, J. Multi-risk assessment and management—a comparative study of the current state of affairs in Chile and Ecuador. Sustainability, 13(3), 1366 (2021).
30. Kurwakumire, E., Kuzhazha, S., & Muchechetere, P. Informal cadastres as enabling tools for disaster risk management. European Journal of Geography, 12(2) (2021).
31. Harpring, R., Maghsoudi, A., Fikar, C., Piotrowicz, W. D., Heaslip, G. An analysis of compounding factors of epidemics in complex emergencies: a system dynamics approach. Journal of Humanitarian Logistics and Supply Chain Management (2021).
32. Tselios, V., Tompkins, E. L. Can we prevent disasters using socioeconomic and political policy tools? International Journal of Disaster Risk Reduction, 51, 101764 (2020).
33. Warner, R. Governance for resilience: Canada and global disaster risk reduction. Canadian Foreign Policy Journal, 26(3), 330–344 (2020).
34. Calyx, C. Sustaining citizen science beyond an emergency. Sustainability, 12(11), 4522 (2020).
35. Khan, T., Quintana, L., Aguilera, S., Garcia, R., Shoman, H., Caddell, L., … Andrews, R. J. Global health, global surgery and mass casualties. I. Rationale for integrated mass casualty centres. BMJ global health, 4(6), e001943 (2019).
36. Van Wassenhove, L. N. Sustainable innovation: Pushing the boundaries of traditional operations management. Production and Operations Management, 28(12), 2930–2945(2019).
37. Wu, J., Huang, C., Pang, M., Wang, Z., Yang, L., FitzGerald, G., & Zhong, S. Planned sheltering as an adaptation strategy to climate change: Lessons learned from the severe flooding in Anhui Province of China in 2016. Science of the Total Environment, 694, 133586 (2019).
38. Prayoga, A., Wita, L. M., & Vernon, P. (2019, November). Risk Analysis of Sinabung Volcano Eruption in Karo, North Sumatera, Indonesia. In Journal of Physics: Conference Series IOP Publishing, 1363(1), 012017. (2019).
39. Sardi, M. F., Razak, K. A., Zaini Bakri, R. (2019). Assessing disaster risk and resilience: a case study in urban flood vulnerable community in Kampung Asahan, Kuala Selangor. International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences (2019).
40. Ahmed, S., Eklund, E. Rural accessibility, rural development, and natural disasters in Bangladesh. Journal of Developing Societies, 35(3), 391–411 (2019).
41. Ricciardelli, A., Manfredi, F., & Antonicelli, M. (2018). Impacts for implementing SDGs: sustainable collaborative communities after disasters. The city of Macerata at the aftermath of the earthquake. Corporate Governance: The International Journal of Business in Society (2018).
42. Brundiers, K., Eakin, H. C. Leveraging Post-disaster windows of opportunities for change towards sustainability: A framework. Sustainability, 10(5), 1390 (2018).
43. Alarslan, E. Creating sustainable cities through disaster resilience in Turkey. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 42(3/W4) (2018).
44. Rachmad, S. H. Climate Change Communication: Community Knowledge and Preparedness. In Handbook of Climate Change Communication: Springer, Cham, 2, 161–182 (2018).
45. Hoffmann, R., Muttarak, R. Learn from the past, prepare for the future: Impacts of education and experience on disaster preparedness in the Philippines and Thailand. World Development, 96, 32–51 (2017).
46. Tambo, E., Tang, S., Ai, L., & Zhou, X. N. The value of China-Africa health development initiatives in strengthening “One Health” strategy. Global Health Journal, 1(1), 33–46(2017).
47. Aka, F. T., Buh, G. W., Fantong, W. Y., Zouh, I. T., Djomou, S. L. B., Ghogomu, R. T., … Hell, J. V. Disaster prevention, disaster preparedness and local community resilience within the context of disaster risk management in Cameroon. Natural hazards, 86, 57–88(2017).
48. Asokan, G. V., Vanitha, A. Disaster response under One health in the aftermath of Nepal earthquake, 2015. Journal of epidemiology and global health, 7(1), 91–96(2017).
49. Pelesikoti, N., Suwamaru, J. K. ICTs in Pacific Islands’ climate change and disaster risk reduction policy and programs. In Achieving Sustainable E-Government in Pacific Island States. Springer, Cham, 269–303(2017).

50. Takeuchi, K., Tanaka, S. (2016). Recovery from catastrophe and building back better. Journal of Disaster Research, 11(6), 1190–1201(2016).
51. Parvin, G. A., Surjan, A., Shaw, R. Urban risk, city government, and resilience. In Urban disasters and resilience in Asia (pp. 21–34). Butterworth-Heinemann (2016).
52. Drolet, J., Dominelli, L., Alston, M., Ersing, R., Mathbor, G., Wu, H. Women rebuilding lives Post-disaster: Innovative community practices for building resilience and promoting sustainable development. Gender & Development, 23(3), 433–448(2015).
53. Iserson, K. V. Tackling the global challenge: humanitarian catastrophes. Western journal of emergency medicine, 15(2), 231(2014).
54. Denhart, H. Deconstructing disaster: Economic and environmental impacts of deconstruction in post-Katrina New Orleans. Resources, conservation and recycling, 54(3), 194–204(2010).
55. Setiawan, A. A., Sugiarto, S., Zhao, Y., Nayar, C. V., Wijaya, M. E., Melfiana, E., Assidiq, A. F. Development of sustainable power and water supply for remote areas and disaster response and reconstruction in Indonesia. In 2007 Australasian Universities Power Engineering Conference (pp. 1–6). IEEE(2007).
56. Haque, C. E., Burton, I. Adaptation options strategies for hazards and vulnerability mitigation: an international perspective. Mitigation and Adaptation Strategies for Global Change, 10(3), 335–353(2005).
57. Jakubik, J., Feuerriegel, S. Data-driven allocation of development aid towards Sustainable Development Goals: Evidence from HIV/AIDS. Production and Operations Management (2022).
58. Raza, T. Localizing disaster risk reduction and climate change adaptation in planners' and decision makers' agenda: Technical comprehensive model, Quezon City, Philippines. Procedia engineering, 212, 1311–1318(2018).
59. Ali, T., Paton, D., Buergelt, P. T., Smith, J. A., Jehan, N., & Siddique, A. Integrating Indigenous perspectives and community-based disaster risk reduction: A pathway for sustainable Indigenous development in Northern Pakistan. International Journal of Disaster Risk Reduction, 59, 102263 (2021).
60. Aitsi-Selmi, A., Murray, V., Wannous, C., Dickinson, C., Johnston, D., Kawasaki, A., . . . Yeung, T. Reflections on a science and technology agenda for 21st century disaster risk reduction. International Journal of Disaster Risk Science, 7(1), 1–29(2016).
61. Udmale, P., Pal, I., Szabo, S., Pramanik, M., & Large, A. Global food security in the context of COVID-19: A scenario-based exploratory analysis. Progress in Disaster Science, 7, 100120 (2020).
62. Pramanik, M., Szabo, S., Pal, I., Udmale, P., Pongsiri, M., Chilton, S. Population health risks in multi-hazard environments: action needed in the Cyclone Amphan and COVID-19–hit Sundarbans region, India. Climate and Development, 14(2), 99–104 (2022).
63. Roy, J., Islam, S. T., Pal, I., Mahmud, H. White Paper Top Ten Priorities: in Implementation of Low Carbon Sustainable Energy Development and Adaptation Framework to Reduce Disaster Impact in the Context of Bangladesh. International Energy Journal, 21(1A) (2021).

Human Performance of Manual Sorting: A Stochastic Analytical Model

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Abstract The sorting activity is a very common task mainly executed in sectors where there is the need to sort items with specific features from the general material stream moved through a conveyor belt (e.g., waste management, agro-industrial, production lines). Despite the increasing employment of sorting vision systems that automatically select the component to be picked up, the sorting activity is still manually executed by operators. In this context, the behaviour of operators is mainly studied under an ergonomic point of view, without analysing its performance by considering the likelihood of picking up the items. Authors propose a novel stochastic analytical model that allows to evaluate the number of items that can be manually sorted in a given time window. The novelty of the model relies on modelling the likelihood of picking up an item placed on a specific location of the conveyor's belt as a probabilistic function of the time needed to execute the entire sorting movement, based on the sum of the standard time of basic movements. Results obtained are in line with values available in the scientific literature, confirming that the novel stochastic analytical model can be employed as a tool to predict the operator's sorting performance. Future developments will be focused on considering more complex scenarios with multiple type of items to be sorted, different handling strategies, as well as multiple operators placed on the conveyor's belt.

Keywords Manual sorting · Stochastic analytical model · Methods-time measurement (MTM)

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1 Introduction

Sorting activities consist of identifying an item with specific features among others and separate it from the remaining material flow. One of the main issues associated to these activities is to obtain a reliable and efficient sorting process. For this reason, in the last years, multiple machine vision systems and collaborative robots [1, 2] have been developed for a successful sorting process mainly in the agro-industrial sector [3], with the goal of selecting products of better quality [4–6], or to discard defected potatoes [7]. Despite the increasing employment of these systems, sorting lines that employ the human labour are still very common. Manual sorting is dominant in the waste collection, and the number of workers employed is even expected to increase in the recycling industry [8]. Furthermore, sorting factories placed in developing countries lack in modern equipment, bringing to the prevalence of manual tasks in the sorting activity [9]. When sorting activities are carried out manually, workers execute highly repetitive movements, causing exposures to biomechanical risks. Therefore, multiple authors focus the analysis of manual sorting processes on the risk of postural exposures and musculoskeletal disorders [10, 11], as well as on the ergonomic evaluation of the height's sorting table [9]. Other authors studied the manual sorting processes under another point of view, by proposing an evaluation method to analyse the effect of the number and types of items to be selected, as well as the influence of the conveyor's belt velocity on the worker's performance [12–14]. Nevertheless, the existing methods available in the scientific literature lack in evaluating the operator's performance by considering the time needed to carry out movements and execute the sorting (sorting time). A stochastic analytical model is proposed in the present paper, where the likelihood of picking up an item is a probabilistic function of the time needed to reach the specific location, grasp the item, and finally sort it.

The remaining of this paper is organized as follows: the second section is devoted firstly to model the operator's sorting time, and secondly to the description of the proposed stochastic analytical model; the third section is devoted to the analysis of results obtained from the numerical simulation. In the last section conclusions are provided.

2 Material and Methods

2.1 The Operator's Sorting Time

When a subject has to reach a specific target (of given dimension) repeatedly, its motor behaviour will be characterized by both spatial and temporal variability [15]. While it has been observed that the spatial variability is contained within the 96% of the target to be reached, and can be expressed through a gaussian distribution [16], the extent of the time variability can be much greater: hypothetically a subject can perform a reaching movement taking an infinite amount of time. By focusing on the manual sorting, the entire sorting movement is characterized by temporal variability: in this context the temporal variability expresses the sorting time variability. Moreover, there is a minimum amount of time below which a specific sorting movement cannot be performed, i.e., an "incompressible" time. Since the variability associated to a sorting movement (sorting time variability) has a minimum, but is not upper bounded, it can be modelled through a Weibull distribution. To characterize the Weibull distribution that expresses probability distribution of the sorting time, three parameters must be defined: scale parameter (α), shape parameter (β), location parameter (γ) (lower limit). Therefore, γ expresses the incompressible time and can be evaluated as a percentage of the mean sorting time. The mean sorting time (t_{mean}), referring to a Weibull distribution, is given by:

$$t_{mean} = \gamma + \alpha\Gamma\left(1 + \frac{1}{\beta}\right) \tag{1}$$

Where $\Gamma(-)$ is the Gamma function. Therefore, if the mean and the shape (β) are known, from Eq. (1) the scale parameter α can be obtained, and the Weibull distribution defined. By focusing on the shape parameter, if β~4, the mode, mean and median are quite the same (like the gaussian distribution). In the specific case of the sorting lines, operators have a limited time to perform the sorting movement, i.e., the operator must execute movements rapidly. For these reasons, in this context can be assumed that the mode (most frequent temporal value) is lower than the mean sorting time: this case is characterized by values of $1 < \beta < 4$. Therefore, by simply knowing the mean sorting time and by defining β, the Probability Density Function (PDF) of the Weibull distribution expressing the probability distribution of the sorting time (t) is given by:

$$f(t; \alpha, \beta, \gamma) = \frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}} \tag{2}$$

The mean sorting time t_{mean} can be evaluated as the sum of the standard time of basic movements (reach, grasp, move, position, release), given by the MTM (Methods-Time Measurement) [17]. For each basic movement, a standard time value is linked, which depends on defined influence factors (e.g., distance moved, manual control required, size and weight of object to be grasped) [17]. By focusing on the manual sorting, the basic movements of move, position and release referring to the corresponding phases of the overall sorting movement can be neglected. This simplification is justified due to the repetitive nature of the motor task, and the limited time available to the operator to perform the sorting. During the activity, the operator has his gaze almost fixed on the conveyor's belt and the three phases after the grasping (move, position, release), are performed rapidly and automatically. In multiple cases it can be observed that the item is thrown in the corresponding basket: the time after the grasping can be consequently neglected. Therefore, for the evaluation of the mean sorting time t_{mean}, only the standard times referring to the reach and grasp are considered. While the standard time related to the grasp depends on the object dimension ([18], page 102, table 6.5), the standard time associated to the reach depends on the distance moved ([18], page 100, table 6.2). Therefore, by knowing the dimension of the item to be sorted, and its location on the conveyor's belt (within the reachable zone of the operator), the related mean sorting time t_{mean} can be evaluated. Moreover, by defining the shape parameter ($1 < \beta < 4$) and the location parameter γ (as percentage of t_{mean}), from Eq. (1) α is calculated, and the probability distribution of the sorting time is given by Eq. (2).

2.2 The Stochastic Analytical Model

Given an item to be sorted on the conveyor belt, the probability that the operator will not be able to complete the sorting movement, is given by 1 – the probability of executing the sorting movement; it depends on both the location of the item on the conveyor belt, and the allowable time: the first defines the mean sorting time t_{mean}, while the second expresses the time the item is present in the reachable zone of the operator; the allowable time T [s] depends on the conveyor's belt speed v [m/s]: greater v, lower the allowable time T. Let's focus on Fig. 1. Given the longitudinal extension of the reachable zone [m] (X), and v [m/s], the allowable time T [s] is obtained (X/v). Nevertheless, in real cases of manual sorting, it is highly likely that in the reachable zone more than one item has to be sorted. Therefore, it has been divided the reachable zone in a grid composed by $N \times N$ cells, where each cell is sized according to the item dimension, and all the cells have the same size. In Fig. 1, $N = 4$, and each cell is squared ($\Delta X_i = \Delta X = \Delta Y_j = \Delta Y \, \forall \, i, j = 1, \ldots, N$). Therefore, by knowing ΔX [m] and v [m/s], it can be evaluated ΔT [s] (or equivalently T/N). The time window ΔT is the time limit in which the item to be sorted can be grasped while located in a cell (i, j): obviously beyond ΔT the item is located in the next cell along x $(i + 1, j)$.

By considering an item placed in a cell (i,j), there is a specific probability distribution of the operator's sorting time that depends on the location of the cell (i,j) to be reached. As previously described, the mean sorting time $t_{meani,\,j}$ is obtained as the sum of the standard time of reach and grasp, function of the item dimension and the position of the cell (i,j); since the incompressible time $\gamma_{i,\,j}$ has been defined as a percentage of $t_{meani,\,j}$, by assuming β (constant $\forall i, j$), $\alpha_{i,\,j}$ can be evaluated, and the probability distribution $f_{i,\,j}(t; \alpha_{i,\,j}, \beta, \gamma_{i,\,j})$ defined.

Therefore, for a given cell (i,j) the probability that the operator will not be able to complete the sorting movement while the item is within the cell (i,j), is given by:

$$p_{i,j}(t > \Delta T) = 1 - \int_{\gamma_{i,j}}^{\Delta T} f_{i,j}\left(t; \alpha_{i,j}, \beta, \gamma_{i,j}\right) dt \tag{3}$$

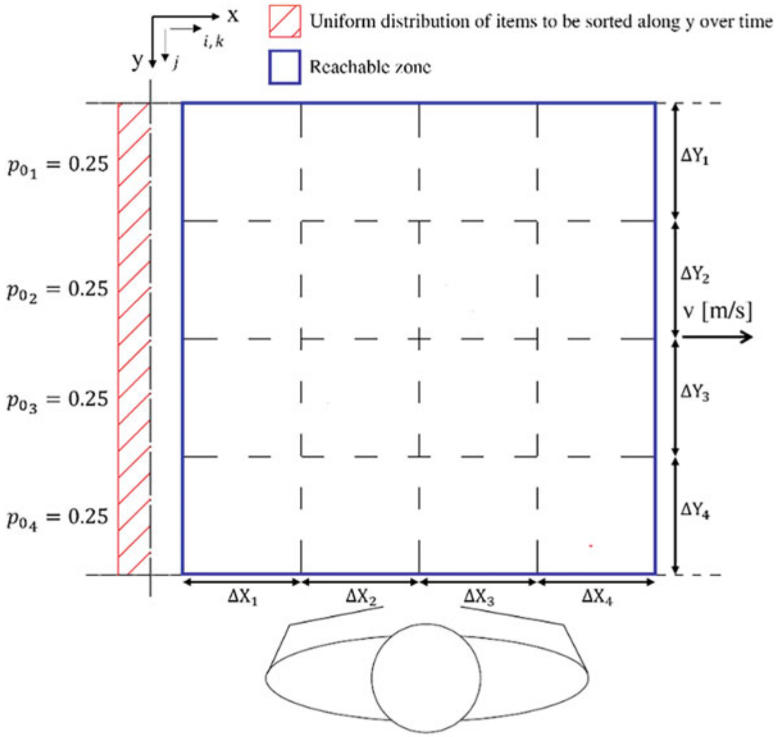

Fig. 1 Operator's reachable zone

$p_{i,\,j}(t > \Delta T) \in [0; 1]$. The integral is evaluated between the minimum value of the operator's sorting time, i.e., the incompressible time $\gamma_{i,\,j}$ and the time window ΔT ($\Delta T > \gamma_{i,\,j} \quad \forall\, i, j$).

In addition, the probability that the item is sorted or not by the operator, depends also on the likelihood that the item is present on the conveyor belt. In this regard, it can be assumed that, before items arrive in the operator's reachable zone, their probability distribution on the conveyor belt is uniform along y ($\forall j = 1, \ldots, N$) (Fig. 1): over time the item can appear indifferently in one of the N cells along y. Therefore, following the assumption of uniform distribution, the probability of finding an item at a specific y is given by $p_{0j} = \frac{1}{N} \quad \forall j = 1, \ldots, N$, with $\sum_{j=1}^{N} p_{0j} = 1$. In Fig. 1, being $N = 4$, $p_{0j} = 0.25 \quad \forall\, j = 1, \ldots, N$.

Consequently, the probability that the operator is not able to complete the sorting movement in the time window ΔT and is not able to sort the item whose likelihood of being in the cell $(1, j)$ is p_{0j}, is given by:

$$p'_{1,j}(t > \Delta T) = p_{0j} \cdot p_{1,j}(t > \Delta T) \tag{4}$$

After a time ΔT (the item moved along x of ΔX), the same item that was present in the first column ΔX_1, is now located in the second column ΔX_2 of the reachable zone. The probability that that the item is located in the cell $(2, j)$ and it will not be sorted by the operator in the time window ΔT, is given by the probability that the item is present and has not been previously sorted ($p'_{1,j}(t > \Delta T)$), multiplied by the probability that the operator is not able to complete the sorting movement within ΔT ($p_{2,\,j}(t > \Delta T)$). Therefore, by considering $k = 1, \ldots, N$:

$$\begin{aligned} p'_{k,j}(t > \Delta T) &= p_{0j} \cdot p_{1,j}(t > \Delta T) \cdot p_{2,j}(t > \Delta T) \ldots p_{k,j}(t > \Delta T) \\ &= p_{0j} \prod_{i=1}^{k} p_{i,j}(t > \Delta T) \end{aligned} \tag{5}$$

Assumptions of the model are the following:

(a) Only one type of item must be sorted
(b) The cell size is defined to contain the item, and the barycentre of the item is placed in the centre of the cell
(c) $\forall \Delta X_i$ (or ΔX_k))d is composed by $N \times N$ cells, the maximum number of items that can be sorted in the reachable zone is N.

Proof. if $p_{i,j}(t > \Delta T) = 1 \;\; \forall i, j \Rightarrow p'_{k,j}(t > \Delta T) = p_{0j} \;\; \forall k, j$ (Eq. 5). Being $\sum_{j=1}^{N} p_{0j} = 1 \Rightarrow \sum_{j=1}^{N} p'_{k,j}(t > \Delta T) = 1 \;\; \forall k$, with $k = 1, \ldots, N$

Therefore, Eq. (5) describes the evolution of the operator's sorting behaviour over time. If $p_{1,\,1}(t > \Delta T) = 0$, it means that the operator is able to sort correctly the item present in the cell $(1, 1)$, within the time window ΔT; due to Eq. (5), $p'_{4,1}(t > \Delta T) = 0$: the information that the operator correctly sorted the item in the cell (1,1), is transferred to the last column ΔX_4 at the corresponding row (i.e., cell (4,1)). Consequently, the probability that the N items present in the reachable zone are not sorted by the operator, is given by:

$$p'_{TOT}(t > \Delta T) = \sum_{j=1}^{N} p'_{N,j}(t > \Delta T) = \sum_{j=1}^{N} p_{0j} \prod_{i=1}^{N} p_{i,j}(t > \Delta T) \tag{6}$$

Finally, the probability that the operator sorts the N items present in the reachable zone in the allowable time T is given by: $p'_{TOT}(t < \Delta T) = 1 - p'_{TOT}(t > \Delta T)$. Therefore, the number of items that are probabilistically sorted by the operator in the allowable time T is given by $p'_{TOT}(t < \Delta T) \cdot N$.

In the following, a numerical simulation is performed to test the stochastic analytical model, and results are compared to the ones found in the scientific literature to verify its effectiveness in evaluating the operator's manual sorting performance.

3 Numerical Simulation

The workplace setup employed to test the stochastic analytical model, is depicted in Fig. 2. It is considered a standard ambidextrous operator whose height is $H = 175$ cm. The shoulder width (SW) and arm length (AL) are estimated as function of H ([19], page 83): SW $= 0.259 \cdot H = 45.3$ cm, AL $= 0.438 \cdot H = 76.65$ cm. The conveyor's belt height is less than the elbow height of the operator within 4 cm, considered as preferred work height [9], while the conveyor's belt width equal to 80 cm. The reachable zone is assumed 80 × 80 cm so that, with a slight inclination of the torso (ergonomically allowable), the operator is able to cover the entire reachable zone. For the manual sorting, it is supposed that the operator must sort PET bottles of maximum 1 lt. Therefore, by considering the dimension of the reachable zone, and the dimension of the item, 16 cells with size 20 × 20 cm ($\Delta X = \Delta Y$) are considered (numbered from 1 to 16, Fig. 2). Each cell has coordinates (i, j), with $i, j = 1, \ldots, 4$.

To obtain the mean sorting time, the sum of the standard time (MTM) of the basic movements of reach and grasp must be evaluated. The first depends on the distance

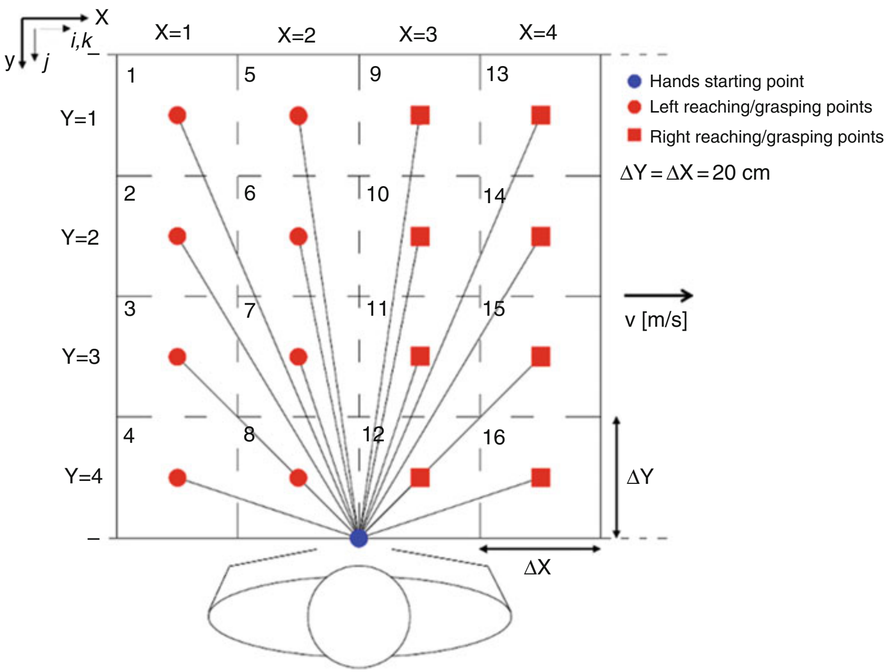

Fig. 2 Workplace setup for the numerical simulation

moved. Since the operator may be required to reach one of the 16 cells to execute the sorting, and thanks to constraint (b), in Fig. 2 the reaching points are defined. The starting point is located on the conveyor's belt, on the operator's centre line (blue circle, Fig. 2), since can be considered as the hands' resting place while the operator is not executing movements. Therefore, from Fig. 2, distances moved are defined, and from ([18], page 100, table 6.2, column C), the corresponding standard times evaluated. For the standard time of grasp, only one value is considered (one type of item) ([18], page 102, table 6.5, case 1B). Therefore, for each cell (i,j) the mean standard time $t_{meani,\ j}$ is evaluated.

As previously discussed, the "incompressible" sorting time $\gamma_{i,\ j}$ (location parameter of Eq. (2)) is a percentage of $t_{meani,\ j}$: $\gamma_{i,\ j}$ is considered as the 35% of $t_{meani,\ j}$. In order to obtain the probability distribution of the sorting time for each cell (i,j), expressed through the Weibull distribution, the scale parameter $\alpha_{i,\ j}$ and shape parameter β must be defined. By assuming $\beta = 2$ $(1 < \beta < 4)$, $\alpha_{i,\ j}$ is obtained from Eq. (1). Consequently, all the parameters of the Weibull distribution, expressing the probability distribution of the sorting time for each cell (i,j) are estimated. In Fig. 3, the probability distribution of the sorting time for each cell of Fig. 2 are defined, by considering the conveyor's belt speed $v = 0.3246$ [m/s]; being $\Delta X = 0.2$ [m] for each cell, the corresponding time window $\Delta T = 0.62$ [s].

To be noticed that being movements symmetric along x with respect to the starting point (Fig. 2), the operator must travel equal distances (i.e. equal standard time of reaching) in case of cells of column 1 and 4, and cells of columns 2 and 3; consequently the corresponding probability distribution of the sorting time is the same.

By assuming that items to be sorted are uniformly distributed on the conveyor's belt along y, being $N = 4$, the initial probability that the item appears at a given y is $p_{0j} = 0.25 \quad \forall\, j = 1, \ldots, 4$.

All the parameters are known to evaluate Eq. (6), and furthermore, it can be evaluated probabilistically the number of items sorted by the operator $(p'_{TOT}(t < \Delta T) \cdot N)$ in the allowable time $T = \Delta T{\cdot}N$. Referring to Fig. 3a and b, being $\Delta T = 0.62$ [s] and $N = 4$, $T = 2.47$ [s].

As discussed previously, by defining ΔX (constant) of the cells, varying the conveyor's belt speed v [m/s], the time window ΔT changes, resulting in a different value of T and $p_{i,\ j}(t > \Delta T)$ (Eq. 3), and therefore a different $p'_{TOT}(t < \Delta T)$. The number of items picked up in the allowable time T, function of the conveyor's belt speed v (0.083–0.5 [m/s]) are depicted in Fig. 4.

To be noticed that the number of items picked up is a decreasing monotonic function with respect to v (or T): the maximum is obtained with the lowest conveyor's belt velocity ($v = 0.083$ [m/s]).

Nevertheless, these results are not confirmed when referring to the same time horizon. In order to evaluate the operator's manual sorting performance, the picker productivity must be considered, i.e., the number of items picked up in 1 min [12, 14]. Results are in Fig. 5.

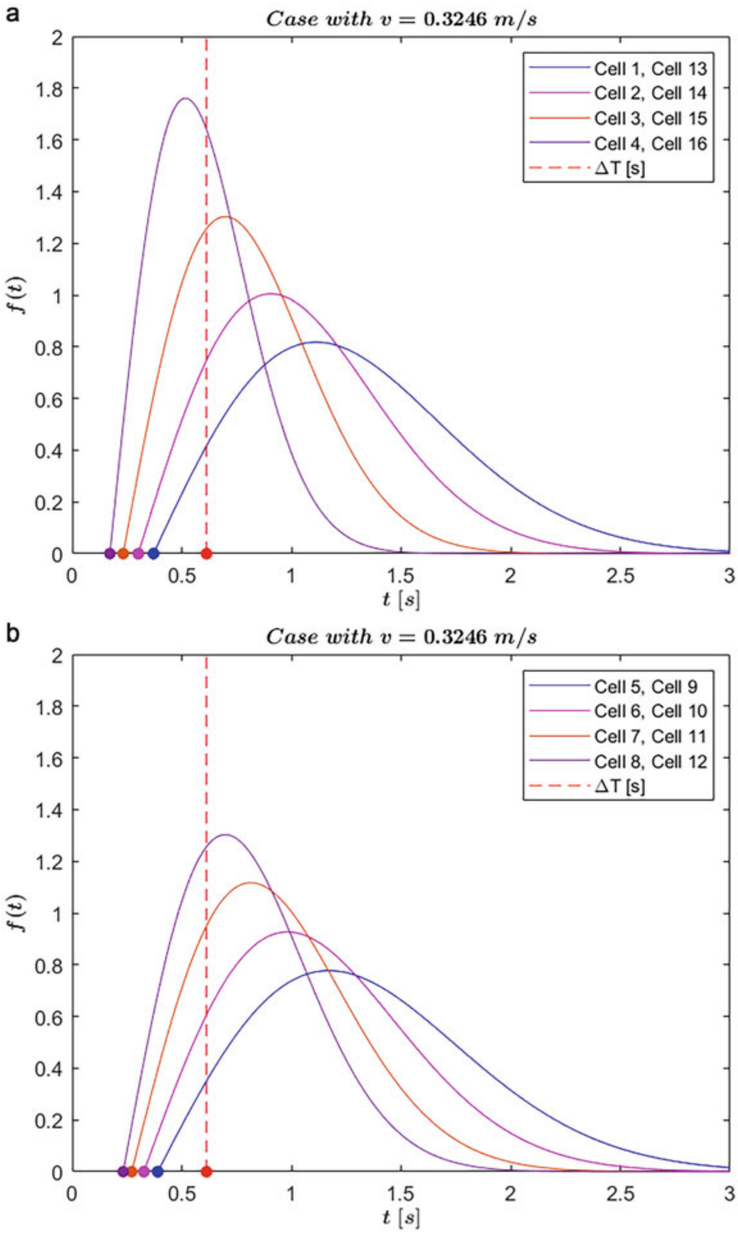

Fig. 3 (**a**) Probability distributions of the sorting time for cells placed in column 1 ($X = 1$) and 4 ($X = 4$) (Fig. 2). (**b**) Probability distributions of the sorting time for cells placed in column 2 ($X = 2$) and 3 ($X = 3$) (Fig. 2)

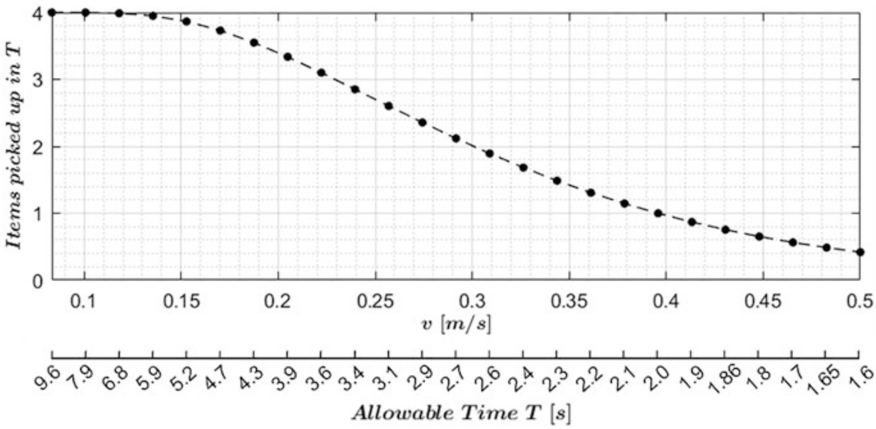

Fig. 4 Number of items picked up in the allowable time T [s], function of v [m/s]

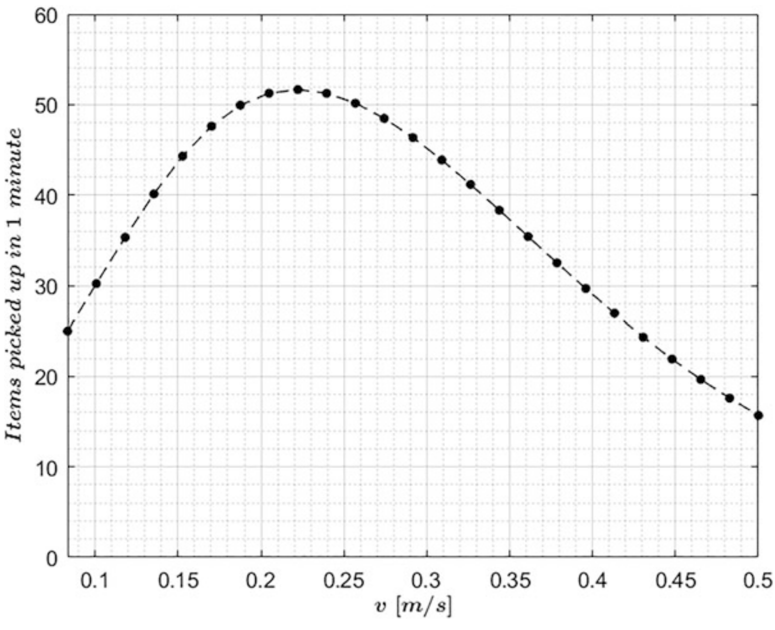

Fig. 5 Number of items picked up in 1 min, function of v [m/s]

Surprisingly, the trend of the number of items picked up in 1 min is not a monotonic decreasing function but has a maximum in the range v = 0.2–0.25 [m/s]. These results are justified by focusing on Fig. 4: at the minimum v (0.083 [m/s]), corresponds the allowable time $T = 9.6$ [s] to complete the sorting movement and pickup $N = 4$ items present in the reachable zone; in this case the performance is maximized since the operator has plenty of time to perform a sorting movement, spending almost 2.4 [s] (T/N) seconds to sort an item. Focusing on the range v = 0.2–0.25 [m/s], the operator has on average 1.17 [s] to sort an item. Consequently, referring to the same time horizon (1 min), it will result that the best manual sorting performance is obtained in the latter case where the operator on average takes half the time to sort an object (1.17 [s] compared to 2.4 [s]).

Moreover, these results are in line with values available in the scientific literature: in particular, by focusing on Fig. 5, with $v = 0.4$ [m/s], almost 30 items are picked up in a minute, as it is obtained in [12, 14].

This last observation confirms that the novel stochastic analytical model can be employed as a tool to evaluate the operator's manual sorting performance.

4 Conclusion

In this paper, the performance of an operator involved in manual sorting activities has been modeled by considering the likelihood of picking up the items. Authors propose a novel stochastic analytical model that allows to evaluate the number of items that can be manually sorted in a specific time. The likelihood of picking up an item placed on a specific location of the conveyor's belt, is a function of the probability distribution (Weibull) of the operator's sorting time, whose mean is evaluated through the sum of standard times related to basic movements.

By considering anthropometric measures of the operator (e.g., height), movements that can be performed (i.e., distances to travel), items to be picked up (e.g., size), type of items, and conveyor's belt speed v, the corresponding manual sorting performance can be evaluated.

By defining the probabilistic distribution of the operator's sorting time fitted on real data obtained from the observation of operators, the proposed model can be employed as a valuable tool in resource allocation problems or workforce scheduling line balancing.

The probabilistic distribution of the operator's sorting time depends on features of the specific operator (i.e., age, experience, manual dexterity, handling strategies (ambidextrous or left-handed), anthropometric measures), as well as on features related to the sorting activities and to the workplace (e.g., number of workstations (i.e. number of operators), types of items, conveyor's belt velocity, production rate). Therefore, the operator's productivity will be affected by both types of features, and the optimal sorting performance will be given by a specific combination of the various factors related to the operator, the activity to be performed, and the workplace.

The next step will be devoted to validating the effectiveness of the stochastic analytical model through a real industrial case study.

Future developments will be focused on considering more complex scenarios with multiple type of items to be sorted, different handling strategies, as well as multiple operators placed on the conveyor's belt.

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References

1. Proia S, Carli R, Cavone G, Dotoli M. Control Techniques for Safe, Ergonomic, and Efficient Human-Robot Collaboration in the Digital Industry: A Survey. IEEE Trans Autom Sci Eng. 2022;19: 1798–1819.
2. Florio A, Avitabile G, Coviello G. Multiple Source Angle of Arrival Estimation Through Phase Interferometry. IEEE Trans Circuits Syst II Express Briefs. 2022;69: 674–678.
3. Facchini F, De Pascale G, Faccilongo N. Pallet picking strategy in food collecting Center. Appl Sci. 2018;8: 1503.
4. Sofu MM, Er O, Kayacan MC, Cetişli B. Design of an automatic apple sorting system using machine vision. Comput Electron Agric. 2016;127: 395–405.
5. Fan S, Li J, Zhang Y, Tian X, Wang Q, He X, et al. On line detection of defective apples using computer vision system combined with deep learning methods. J Food Eng. 2020;286: 110102.
6. Facchini F, Mummolo G, Vitti M. Scenario analysis for selecting sewage sludge-to-energy/matter recovery processes. Energies. 2021;14: 276.
7. Elmasry G, Cubero S, Moltó E, Blasco J. In-line sorting of irregular potatoes by using automated computer-based machine vision system. J Food Eng. 2012;112: 60–68.
8. Engkvist IL, Eklund J, Krook J, Björkman M, Sundin E. Perspectives on recycling centres and future developments. Appl Ergon. 2016;57: 17–27.
9. Emmatty FJ, Panicker V V., Baradwaj KC. Ergonomic evaluation of work table for waste sorting tasks using digital human modelling. Int J Ind Ergon. 2021;84: 103146.
10. Colantoni A, Cecchini M, Monarca D, Bedini R, Riccioni S. The risk of musculoskeletal disorders due to repetitive movements of upper limbs for workers employed in hazelnut sorting. J Agric Eng. 2013;44: 649–654.
11. Kruta de Araújo NC, Cabegi de Barros F, Moriguchi CS, de Oliveira Sato T. Comparison of two methods of sorting recyclable materials on posture among trash sorters in Brazil: a cross-sectional study. Int J Occup Saf Ergon. 2021;27: 957–962.
12. Giel R, Plewa M, Młyńczak M. Analysis of Picked up Fraction Changes on the Process of Manual Waste Sorting. Procedia Engineering. 2017. pp. 349–358.
13. Giel R, Plewa M. Analysis of the impact of changes in the size of the waste stream on the process of manual sorting of waste. Advances in Intelligent Systems and Computing. 2017.
14. Giel R, Młyńczak M, Plewa M. Evaluation method of the waste processing system operation. Risk, Reliability and Safety: Innovating Theory and Practice – Proceedings of the 26th European Safety and Reliability Conference, ESREL. 2017.
15. Schmidt RA, et al. Motor-output variability: A theory for the accuracy of rapid motor acts. Psychol Rev. 1979;86: 415–451.
16. MacKenzie IS. Fitts' Law as a Research and Design Tool in Human-Computer Interaction. Human–Computer Interact. 1992;7: 91–139.
17. MTM-1 Analyst Manual. UK MTMA Ltd.; 2000.
18. Mital A, Desai A, Mital A. Fundamentals of work measurement: What every engineer should know. Taylor & Francis Group; 2016.
19. Winter DA. Biomechanics and Motor Control of Human Movement: Fourth Edition. Wiley; 2009.

Analysis of a Logistics Process Between a Food Service Distributor and a Fast-Food Chain

Silmara A. S. Vicente, Mariana G. S. Souza, Marcelo de A. Carvalhal, and Ana Maria Saut

Abstract The goal of this article was to analyze the off-load rate of a logistics company to an American multinational fast-food chain to find out why they were not reaching the off-load rate target using Total Quality Management strategic tools. Currently, there are three restaurant types: drive-through, shopping centers, and individual stores. This research was initially conducted by mapping which types of restaurants are not reaching the target goals based on data provided by the logistics company. Further analysis was completed by visiting the worst- performing restaurants in the sample data while analyzing why those restaurants were not reaching the target off-load rate. The Total Quality Management measurement tools used were flowcharts, Ishikawa, and PDCA, to verify non-compliance with simple norms pre-determined by the logistics company. The study finds that the lack of sufficient restaurant employees and storage organization were the main reasons that the logistics company did not meet the target off-load rate.

Keywords Supply chain · Total Quality Management · Off-load rate

1 Introduction

With the recovery of the economy after the severe crisis caused by the coronavirus, the away-from-home food sector showed signs of recovery and growth for the year 2022. According to the Foodservice Brazil Institute [1], this sector showed a 48.6% increase in revenue in the first half of 2022 compared to the same period of the previous year, showing that the market is recovering from the pandemic.

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In this scenario, companies that supply food on the streets, such as fast-food restaurants, pick-up trucks and others, should not only be concerned with production and sale, but with effectiveness and efficiency from purchasing supplies to delivering the final product for the consumer. According to Guedes [2], the supply chain is responsible for planning, implementing and controlling the process as a whole, from product request to delivery to the customer.

The supply chain is an area composed of activities ranging from calculation and purchase of raw materials or goods, storage, transport, processing and transformation, to inventory management and distribution [3]. Due to the tasks incorporated by this sector, this research focuses on improving the unloading rate of the delivery process from the logistics operator to the restaurants. This rate is measured by the number of boxes unloaded per hour.

In this context, the present research studied a worldwide fast-food chain with drive-thrus restaurants, in shopping malls and on the street (called in store by the studied companies), with more than 1000 units throughout Brazil, divided between franchisees and own, which have products with different transport characteristics and requirements. This chain uses the service of a logistics operator that distributes these products through special trucks that contain three compartments divided into frozen, chilled and dry, called the cold chain. This article sought to understand the reason for not meeting the download rate target and suggest improvements using quality tools to achieve it. For this, real, practical and measurable examples were used, since the group had access to historical data and followed the process of receiving these products, thus creating gains for both companies.

2 Literature Review

2.1 Process Improvement

According to the Association of Business Process Management Professionals [4], process improvement has three main objectives, the first being cost reduction, which maps and seeks to review unnecessary resources that can be deleted or replaced, the second is the optimization of time, which identifies bottlenecks that cause delays in the process and, consequently, the third point, increased results, which consists of producing more, in less time and with fewer resources, the main objective of organizations.

This study addressed objectives two and three, time optimization and increased results, as opportunities for improvements in the goods delivery process between the logistics operator for the fast-food chain, aiming at time optimization based on the analyzed flow. Gonçalves [5] defines process as any activity or set of activities that has an input, adds value to it and provides an output to a specific internal customer.

2.2 Total Quality Management

Total Quality Management (TQM) was born from the advancement of Quality Control Circles, a Japanese methodology from the early 1960s where it encouraged discussion and suggestions for improvement and the workspace in weekly meetings [6].

According to Paladini et al. [7], the central idea of the TQM is that quality is present in the organizational management function, in an attempt to broaden its focus, not being limited to activities inherent to control. This is a responsibility management philosophy of the leadership of companies that requires the creation or change of the corporate culture and thinking style of all employees focused on the excellence of services, processes and products [6].

With the increase in the use of Total Quality Management (TQM), the rules of the International Organization for Standardization (ISO) emerged, a worldwide organization that standardizes and regulates its use in order to ensure and certify companies that comply with the manual as well, developed by them, called as ISO 9001. In this context, TQM was used to guide this study, even though both companies approached do not currently a ISO 9001 certified, but performed internal and external audits.

2.3 Continuous Improvement

According to Albuquerque [8], the premise of continuous improvement drives the evolution of the quality management system, since companies must continually seek better results combined with improved productivity through the establishment of a culture of improvement. This culture must be able to improve products or, in the case of this study, services to meet the requirements to address future needs and expectations, in addition to correcting and preventing delivery errors, reducing unwanted effects and improving the performance and effectiveness of the delivery system quality management, as well as achieving the defined offload rate [9].

Shiba et al. [10] classify continuous improvement into three levels: Control, aiming to monitor and maintain quality; Reactive, restoring quality when it is below historic or minimum levels; and finally, Proactive, aiming to increase the performance and quality of the object of study.

2.4 Flowchart

The flowchart, or process map, is the representation of the stages of a process in a simple way [11]. It presents, in the form of a diagram, a sequence of steps and branching possibilities existing in a process. In this article, the swimlane flowchart was used to map the process so that it covers everything from the order placed by the restaurant, encompassing the operator's internal phase for validating the request, to the last step, which is the delivery to the restaurant.

The "streak" notation represents how the workflow can cross organizational departments, or even positions in the organization [12]. In the case of this study, it was used to separate the activities under the responsibility of the logistics operator and the fast-food chain.

2.5 Ishikawa Diagram

From the Ishikawa Diagram, or fishbone as it is also known, it is possible to raise the main problematic causes of the studied process, so that they can be classified in areas and then to elaborate the action plan with these causes [13].

For Schneider et al. [14], this tool is defined as a tool used in quality control, in order to contribute to the identification of deviations in the flow, highlighting the existence of possible bottlenecks, which describes the causes in:

(a) Method: causes are related to the method by which the work is performed;
(b) Materials: the cause is related to the materials used in the process, in this case, nonconformity or absence of products;
(c) Labor: deviations are caused by the employee, in the work in question they are related to the driver of the logistics operator and the employee of the restaurant;
(d) Machines: machinery is the cause of deviation. In this research, no causes classified as machines were identified;
(e) Measurement: the lack, or incorrect use of measurement indicators, are the cause of the deviation. In this article, the category "System" was used instead of measurement, as it better fits the scope of the research;
(f) Environment: the environment contributes to the generation of deviations. In the case of this work, the structure was used instead of the environment, as it better contemplates the categorization made concerning the problems.

3 Methodology

This research is a case study since it employs multiple sources of evidence such as: unstructured interviews, document analysis and on-site visits [15].

According to Bryman [16], the characteristics of qualitative research are: emphasis on the subjective interpretation of individuals, definition of the research scope, unstructured approach, and multiple sources of evidence, in this case, different professionals from both companies. According to Sampieri et al. [17], exploratory studies of any nature do not require the formulation of hypotheses due to the lack of prior knowledge about the research problem, therefore this research was considered qualitative and exploratory.

The companies chosen for this study are large and referenced in their fields of business and in quality management, with excellence in strategic planning and inventory, with insignificant levels of problems due to lack of product or errors. However, only 17.83% of restaurants (191 out of 1072) in Brazil reach the unloading rate target, providing an opportunity to improve the process.

In addition to the analysis carried out from the data provided by the logistics operator, the on-site visits to map the unloading process and informal interviews with truck drivers and restaurant employees were of paramount importance to question how the steps actually happened and not just for the theoretical flow presented by management and supervision.

4 Results and Discussion

Initially, the data collected by the logistics operator was received to carry out an analysis of the unloading rate between the years 2019 to 2022 per restaurant, with partial data from January to August 2022. Due to the context of the research and the period of information provided, the data used for the development of this study were mostly from the years 2019 and 2022, as the years 2020 and 2021 were atypical due to the Covid-19 pandemic, changing the functioning of the two companies.

Another stipulated restriction criterion was to define the state of São Paulo as the focus of this study, as it contains 48.23% of the restaurants in the country (517 out of 1072 in 2022), in addition to the proportion of restaurants that reach the unloading target in that state being close to the rate of other restaurants in the Brazilian territory, being 14.89% (77 out of 517) and 17.83% (191 out of 1072) respectively for the year 2022. Following the same analysis criteria, but expanding the scope, we studied the data from 2019 to 2022 and for the three restaurant models illustrated in Fig. 1.

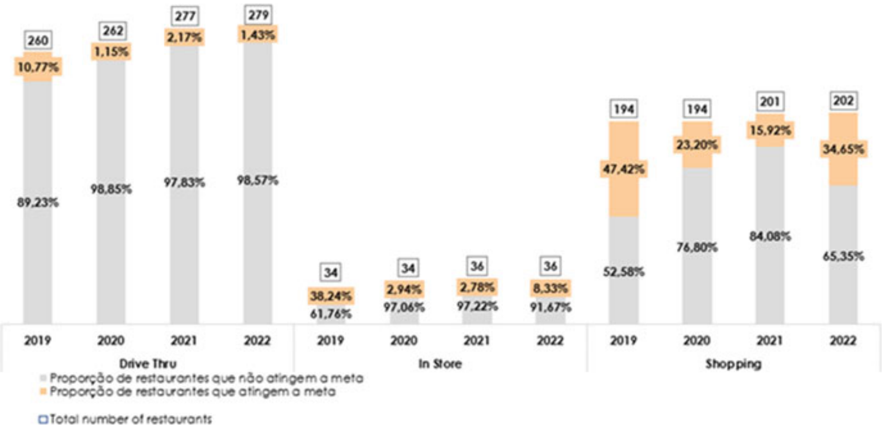

Fig. 1 Proportion of restaurants that achieve versus not achieve target in the state of São Paulo. (Source: Own authorship (2022))

Table 1 Average offload rate of visited restaurants

Store	Type	Target	2019	2020	2021	2022	2022 vs 2019 (%)
A	*Drive-thru*	230	137	88	89	109	−20
B	*Drive-thru*	230	96	92	88	130	35
C	*In store*	180	196	108	134	144	−27
D	*In store*	180	201	97	107	120	−40
E	*Shopping*	140	173	143	44	71	−59
F	*Shopping*	140	348	205	93	88	−75

Source: Own authorship (2022)

When analyzing Fig. 1, it can be seen that more than half of the restaurants did not reach the unloading rate target. Due to the rules of the shopping malls being strict about the period allowed for receipt and time in which each tenant is allowed to use the unloading docks, restaurants of this type have a higher percentage of establishments that reach the target compared to the other two types.

There was a large decline in the percentage of restaurants that reached the target in the years affected by the COVID-19 pandemic (2020 and 2021), but it is possible to see a small recovery for In Stores and shopping malls in 2022, even if it is still far from the target.

After this analysis, two restaurants of each type were chosen in the city of São Paulo, two in street stores, two in Drive-thrus and two in shopping malls, for carrying out on-site visits in order to understand the operation, as well as the main problems and opportunities for improvement in the process. The selection criteria for these visits were due to the fact that they did not reach the target in 2022 and the restriction of the delivery time to be between 06:00 and 23:59, due to security issues imposed by the companies involved in the process.

From Table 1, it is possible to observe that, in the analyzed period, the drive-thrus visited never reached the target; in 2019, in-store restaurants and malls reached the target, but in the subsequent 3 years, they failed to achieve it. In the 2022 vs 2019 comparison, five out of six restaurants have negative rates, that is, a decline in the ability to unload goods. None of the restaurants visited reached the years 2021 and 2022.

As a support tool for this research, Gemba was used, a concept from the Japanese philosophy of quality management which, according to Pinto [18], consists of visiting and monitoring the processes in the place where they are carried out in order to understand the activities as they really happen, not limiting oneself to theory and observing the real.

Based on what was observed and with the help of the logistics operator, a flowchart of the process was developed using lanes to demarcate those responsible for the activities as illustrated in Fig. 2.

As the unloading rate is measured from the beginning of the unloading step, and considering the ideal path of Fig. 2, 62.5% of the activities (five out of eight) are the responsibility of the restaurant, it is possible to emphasize that the establishment is responsible for the bottleneck of the operation and, consequently, for not reaching

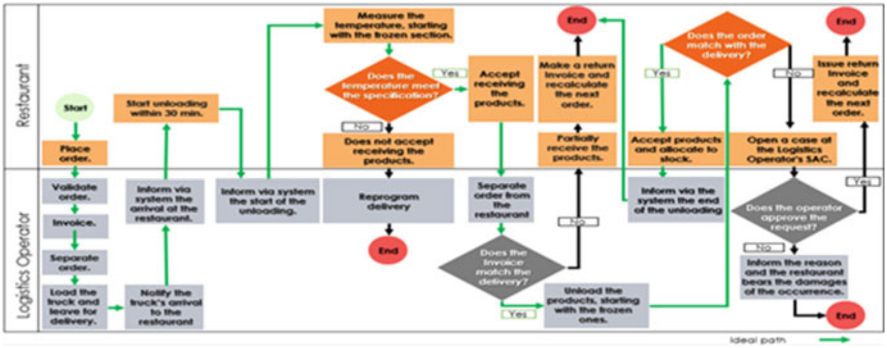

Fig. 2 Process flowchart in lane. (Source: Own authorship (2022))

Fig. 3 *Ishikawa* of delays in receiving goods. (Source: Own authorship (2022))

the goal of the unloading rate. It is also noted that the step of checking the products presented in the flow that occurs manually is carried out in two steps, one by the driver who is responsible for delivering the products and another by the restaurant that receives them.

This repetition cannot be avoided since both parties are representatives of different companies, so it must be ensured that there are no divergences of information in what was delivered and received. For this step to occur more quickly and efficiently, it is possible to implement an inventory management system, based on an ERP (Enterprise Resource Planning) using barcode readers that already exist in the boxes to control the products that have been delivered and their quantities. According to Souza [19], an example of common use for ERPs is the verification of invoices, upon receipt, in order to guarantee the order data with the purchase data, to ensure receipt with the correct quantities.

Once the group had surveyed all the processes that involve the unloading of products in the restaurants, an Ishikawa diagram was developed to identify the causes of the study problem, as illustrated in Fig. 3.

A total of 11 causes were raised. In gray are the six fundamental causes that were treated in this study, namely: lack of standardization in unloading between truck and stock, high response time by the restaurant when the truck arrives, lack of employees in the restaurants when receiving the products, manual checking of products upon

Fig. 4 Detailed flowchart of the product delivery process according to the manual. (Source: Own authorship (2022))

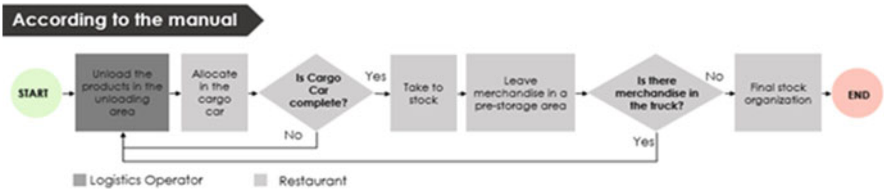

Fig. 5 Detailed flowchart of the product delivery process collected during a visit. (Source: Own authorship (2022))

delivery, lack of sequence of product categories on invoices (frozen, chilled and dry) and lack of prior organization of stock by the restaurant.

The manual of rules between the logistics operator and the restaurants of the fast-food company determines operating rules for the delivery and receipt flow in order to speed up and minimize the effects caused by the lack of employees in the restaurant and non-previous organization of the stock according to illustrated in Fig. 4. However, it was observed that the stock organization stage is not usually performed at the end of receipt, but every time the restaurant employee removes the goods from the truck, already allocating them to the final storage location, as shown in Fig. 5.

This change in the receipt of goods by the restaurants is the main cause of delays in receiving and the non-achievement of the unloading rate target, as well as happening every time the restaurant employee unloads the cart in the warehouse, as seen in Fig. 5, the driver, responsible for unloading the goods from the truck, is idle if there are no more restaurant employees to receive simultaneously.

Currently, the logistics operator cannot measure the driver's idleness and whether the restaurant is obeying the norm due to a lack of data. As a way to solve this problem, the system in which the driver indicates to the logistics operator the beginning of the truck unloading process should have a functionality to inform the moment when the restaurant truck leaves the unloading place and the moment it returns, the interval of this time being the idleness of the driver.

The first stage of the PDCA cycle is planning, as the name implies, it consists of stipulating objectives and then determining programs and procedures to achieve the objectives [20]. With that in mind, the objective was to reach download targets in drive-thrus, in stores and shopping malls, which are 230, 180 and 140 respectively. Based on the problems encountered and with a defined objective, this research

Table 2 Proposer action plan

Description of identified problems	Probable root cause	Improvement action	Responsible
The use of non-standard cars in terms of model and quantity.	Lack of standardization in unloading the truck to the restaurant's inventory.	Standardize the type of cargo car used for robocop model and the quantity of delivery cars to four.	Restaurant
Receipt of wrong products and/or quantities.	Manual conference of all products on delivery.	Implement barcode reader of boxes with conference system.	Restaurant
The driver announces that he is available to unload the products, but the restaurant takes longer than agreed to start the process.	Truck driver waits a long time for the restaurant to respond.	Apply warning in each occurrence, if there are three within a month, in the fourth occurrence the restaurant must be fined.	Restaurant
The number of employees is standardized. There are two employees to receive the goods, but it was observed in on-site monitoring that the restaurants did not comply with this rule.	Lack of employees to receive the products.	Implement a bonus program evaluating the performance of the best stores.	Restaurant
1. Lack of prior organization of inventory by the restaurant 2. Not starting to receive goods within 30 min.	Failure to comply with predefined rules between the logistics operator and the restaurant.	Add functionality to the logistics operator's system to inform the time that the cargo car is away from the unloading location.	Logistics Operator
The unloading takes place in this order: frozen, chilled and dry, but the invoices do not bring the products in the mentioned order and this makes it difficult for the restaurant to check them.	Absence of sequence of product categories in invoices (frozen, chilled and dry).	Implement a rule in the invoice issuance system that follows the sequence of products in the order.	Logistics Operator

Source: Own authorship (2022)

allowed the elaboration of a proposal for an action plan that will be presented to both companies (Table 2).

After preparing the action plan, shown in Table 2, due to the number of restaurants in the fast-food company and the division by type, it was understood that the rules had to be complied with. The annual averages of the unloading rate in the state of São Paulo were raised to define the best restaurant model that both companies can carry out a pilot test, presented in Table 3. To calculate the columns “2022 vs 2019” and “2022 vs Goal” in Table 3, the percentage variation formula was used.

Table 3 Average unloading rate in the state of São Paulo

Type	2019	2020	2021	2022	2022 vs 2019 (%)	Target	2022 vs target (%)
Drive-thru	161	126	133	132	−18	230	−43
In store	166	112	117	135	−19	180	−25
Shopping	146	113	109	128	−12	140	−9

Source: Own authorship (2022)

When analyzing Table 3, it was observed that, in 2022, Shopping-type restaurants presented a variation of only 9% below the unloading rate target, while Drive Thru and In Store presented greater differences: 43% and 25% below, respectively.

Based on the data in Fig. 1, in-store type establishments represent only 6.9% of restaurants in the state of São Paulo, 36 out of 517. Drive-thrus represent 54.0%. Based on the proportion of the number of restaurants and the variation in relation to the target, when focusing on drive-thru type establishments there is a greater potential for operational gain.

5 Final Considerations

With this research, it was possible to identify relevant characteristics of the operation between the logistics operator and the restaurants of a fast-food chain, aspects that influence the unloading time of goods for the three types of restaurants. These models are divided into drive-thrus, in-store and shopping malls with an unloading target of 230, 180 and 140 boxes per hour, however, it is currently below expectations, reaching 132, 153 and 128, respectively.

In this context, this research aimed to map the process of delivery and receipt of goods between the two companies studied, as well as to identify possible causes for not reaching the unloading rate target and to suggest improvements to achieve them, thus providing operational improvements for both parts.

Among the causes raised for not reaching the unloading rate target, it was identified that the most influential one is non-compliance with pre-established rules between the logistics operator and the restaurants. These stipulate that there must be at least two restaurant employees on hand to unload the goods and comply with the correct flow in handling the goods. This flow consists of unloading all the products, leaving the stage of organizing the restaurant's stock for a second time, that is, after the truck has already completed the delivery, which does not occur in the current process. These infractions continue to occur because the restaurant is not penalized for not following the pre-defined agreement, as well as for a lack of data by the logistics operator to measure the time in which the restaurant employee is absent from the unloading point.

In on-site visits, it was observed that a large part of the checking is done manually, such as validating how many and which products the restaurant is receiving and the exact temperature of each compartment of the truck at the time of delivery. This action, currently performed in this way, may cause the process to occur slowly and be susceptible to counting errors and lack of attention.

The proposed solutions for the problems of non-compliance with rules in the download process and manual checking consist of changing and implementing two systems. For the first problem, using the existing system on the driver's smartphone, which indicates the start and end of the delivery operation, the idea would be to complement it with a utility to inform when the unloading cart leaves and returns to the place of unloading the goods. This makes it possible for the logistics operator to also monitor the driver's idleness during the operation.

For the second problem, it will be necessary to implement a new system connected to a code reader device where the products and quantities contained in the invoice (information previously acquired from the logistics operator or via the government system) will be compared with what is being delivered.

As a pilot test, the group suggests starting with drive-thrus, as this is 43% below the target, and represents 54% of the restaurants studied, in addition to being the model that will benefit the most as it is the type with the worst unloading rate.

For the development of future studies, it is necessary to budget the costs for the implementation of the indicated alterations and to study the economic viability of the project in order to finalize the activities of the Plan stage of the PDCA cycle. After implementing the Do step, the next steps, Check and Act, must be carried out to ensure the assertiveness of the process and to analyze whether the expected improvement has been achieved.

References

1. Instituto Foodservice Brasil. Índice de Desempenho Foodservice. São Paulo, 2022.
2. Guedes, Thiago de Andrade. A logística e o serviço de entrega: o impacto de processos logísticos e os fatores que contribuem nas avaliações de estabelecimentos de fast-food. Vitória: Revista de Administração Unimep, v. 19, n. 2, 2021.
3. Rehman, Tahaur *et al.* Supply chain performance measurement and improvement system: A MCDA-DMAIC methodology. Journal of Modelling In Management, Doha, v. 13, n. 3, p. 522–549, 15 out. 2018.
4. ABPMP BRAZIL. Guia para o gerenciamento de processos de negócio corpo comum de conhecimento. Brasil: Abpmp Bpm Cbok Cbpp V3.0, 2013. Available: https://cdn.ymaws.com/www.abpmp.org/resource/resmgr/docs/abpmp_cbok_guide__portuguese.pdf. Acesso em 30/06/2022.
5. Gonçalves, José Ernesto Lima. Processo, que processo? Revista de administração de empresas, v. 40, p. 8–19, 2000.
6. Williams, Richard L. Essentials of Total Quality Management WorkSmart Series. *[S.l.]*: Amacom Books, 1994.
7. Paladini, Edson Pacheco et al. Gestão da Qualidade: teoria e casos. 2. ed. Rio de Janeiro: Elsevier, 2012.
8. Albuquerque, André Felipe de. A perspectiva da gestão da qualidade total (GTQ) como modo de controle organizacional. Caderno de Administração, Maringá, v. 28, n. 2, p. 98–115, 14 jul. 2020.

9. Associação Brasileira De Normas Técnicas (ABNT). NBR ISO 9000: Sistemas de gestão da qualidade –fundamentos e vocabulários. Rio de Janeiro, 2015.
10. SHIBA, Shoji; GRAHAM, Alan; WALDEN, David. TQM: Quatro Revoluções Na Gestão Da Qualidade. Porto Alegre: Bookman, 1997.
11. Tavares, Priscilla Angélica *et al.* Aplicação das sete ferramentas da qualidade em uma recapagem de pneus no centro-oeste de Minas. 2013. 18 f. – Curso de Engenharia de Produção, Unifor, Minas Gerais, 2013.
12. Pavani Júnior, Orlando; Scucuglia, Rafael. Mapeamento e gestão por processos – BPM. Gestão orientada à entrega por meio de objetos. Metodologia GAUSS. São Paulo: M. Books do Brasil, 2011.
13. Fornari Junior, C. C. M. Aplicação da Ferramenta da Qualidade (Diagrama de Ishikawa) e do PDCA no Desenvolvimento de Pesquisa para a reutilização dos Resíduos Sólidos de Coco Verde. São Paulo: INGEPRO, 2010.
14. Schneider, M. D., Vieira, A. C. P., Zilli, J. C., & Schutts, C. M. (2015, November). Diagrama de Causa-Efeito de Ishikawa: Estudo do Fluxo logístico em um Comércio de Materiais de Construção. In XV Mostra de Iniciação Científica, Pós-graduação, Pesquisa e Extensão.
15. Cauchick-Miguel, Paulo Augusto et al. Metodologia De Pesquisa Em Engenharia De Produção E Gestão De Operações. 3. ed. Rio de Janeiro: Elsevier Editora Ltda, 2018
16. Bryman, A. Research methods and organization studies. Londres: Unwin Hyman, 1989.
17. Sampieri, R. H.; Collado, C. F.; Lucio, P. B. Metodologia de pesquisa. 3. ed. São Paulo: McGraw-Hill, 2006.
18. Pinto, Inês Catarina Borges. Implementação de metodologias Lean numa linha de enchimento de bebidas. 2018. Tese de Doutorado. Universidade de Coimbra.
19. Souza, Cesar Alexandre de. Sistemas integrados de gestão empresarial: estudos de casos de implementação de sistemas ERP. 2000. Tese de Doutorado. Universidade de São Paulo.
20. Ahuja, H. N. et al. Project Management: techniques in planning and controlling construction projects. New York: John Wiley & Sons, 1994. 505p.

Sales and Operations Execution – S&OE: A Perspective on the Brazilian Scenario

Ana Lígia Vieira Rodrigues, Guilherme Gomes, Carlos Manoel Taboada Rodriguez, and Marina Bouzon

Abstract In recent years, the business interest in supply chain planning processes has become notorious. The concept of Sales and Operations Planning (S&OP) aims at medium-term tactical planning. However, it was observed that due to the volatility of demand in the short term and the latent scarcity of certain raw materials worldwide, the focus of the S&OP process has shifted from the short to the near term, seeking to cover the gap between tactical plans and supply chain execution. Given this scenario, it was necessary to develop a structured process that would encourage collaboration between a company's functions and its stakeholders to identify deviations between what was planned and what was achieved to support decision-making regarding route requirements on a regular and near-term basis. This process has been recently named Sales and Operations Execution, S&OE, with a planning horizon of up to 3 months and weekly reviews. The present study aims to understand the current state of implementation of the S&OE process in Brazilian companies of different sizes and segments through a survey conducted with 51 respondents from 38 companies. The knowledge, experience, and implementation level of the S&OE process is still low in Brazil, with improvement opportunities in the four dimensions: people, processes, technologies, and data. It was found that companies with greater experience, knowledge, and a higher level of S&OE implementation perform significantly better in terms of the level of service, inventory health, and forecast accuracy.

Keywords Sales and operations execution · S&OE · S&OP · Supply chain management · Supply chain planning

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1 Introduction

With the advent of globalization and technology that connects all parts of the world in real-time, consumers now have information with quality and speed not seen before. This new reality leads to constantly changing consumer behaviors, making the demand of the industrial world very uncertain, requiring intense integrated planning activities throughout the supply chain [31]. According to Christopher [8], for companies to thrive at this juncture, it is essential to anticipate the market's desires with the best possible quality and a satisfactory horizon capable of providing companies with quality information and the necessary time to make adjustments in their supply chains to gain competitive advantages [38]. This situation has been exacerbated considerably by the demand volatility arising from the COVID-19 pandemic, which according to McMaster et al. [24], has forced organizations to develop capabilities in terms of transparency, trusting relationships, and real-time information exchange between clients and suppliers, requiring a structured process for short-term supply chain execution.

Good demand planning is the basis for Sales and Operations Planning (S&OP) and Sales and Operations Execution (S&OE) processes. The S&OP process originated in the United States, whereby through a cycle, usually monthly, planning is performed of all business functions in an integrating manner, providing a series of benefits at the tactical level, i.e., medium-term [2]. Noroozi S and Wikner [39] state that interest in S&OP has been growing over the past decade, both in academia and business, causing the number of industries implementing the process to increase. According to Grimson and Pyke [12], S&OP is responsible for synchronizing the demand and supply chain to obtain maximum returns. To that end, two components are essential: sales planning, based on the demand forecast, and the production plan, which defines the capacity needs, inventory levels, and backlogs [37]. Carvalho [6] asserts that in volatile environments with high levels of uncertainty, the traditional planning hierarchy—S&OP—aligned with MPS (master production schedule) does not perform as expected. Thus, in recent years, adaptations in the planning process have emerged in the "Weekly S&OP" format focused on the short-term horizon and weekly basis [6]. Achieving planning agility is a trend that has become essential in recent times, leading to the emergence of a new process that aligns tactical planning with operations. Several industries have already implemented it in their routines, and consulting companies have published related articles. This new process is called S&OE – Sales and Operations Execution [1, 40].

S&OE is a relatively new process that follows the bases of the research institution "Gartner", which aims to provide tools and processes for practical operationalization of the plans arising from the S&OP process, being responsible for the short and very short-term horizon, i.e., the scope of execution [33]. According to Carvalho [6], although the S&OE process has been implemented in some companies for many years, it is a topic still little explored by the academic literature. It is clear that even in the S&OP process, which has been widespread in recent decades in companies of various segments, there are still knowledge gaps and research opportunities regarding the characterization of the process, including Global S&OP and large-scale supply chains [42, 41, 43]. The present scientific research article is justified because few academic publications refer to the application of S&OE in supply chain management in Brazil. A search conducted on November 18th, 2021, with the Google Scholar tool with the term "Sales and Operations Execution" found only 19 results. On Scopus and Web of Science, no articles related to the theme were found. The present research gap has been occupied by consulting firms that are constantly promoting research in the area; Apics [2] contributes to the theme that supply chain management is arguably the most evolving area of business technology.

Within this context, the main question of this research is: "Does S&OE contribute to improve the supply chain performance, looking from the perspective of service level, inventory health and forecasting accuracy?" This scientific research article has the objective to evaluate the impact of S&OE process maturity and the supply chain performance.

The specifics objectives of this study are:

- Assess the level of knowledge and application of the S&OE process in the Brazilian scenario;
- Evaluate if S&OE has positively and directly impacted on the service level;
- Evaluate if S&OE has positively and directly impacted on the health or quality of inventories;
- Evaluate if S&OE has positively and directly impacted on the forecast accuracy.

2 Literature Review

2.1 S&OP

According to Wallace [44], S&OP can be defined as a business process that helps companies maintain a balance between supply and demand. This is achieved by focusing on aggregate volumes to control mixed problems more responsively. The author adds that the process is multidisciplinary, involving several levels within the company to interconnect strategic plans to operational processes, positioning it as a tactical supply-chain management tool capable of enabling executives to view the business holistically and offer a window into the future. As per APICS [2], the major benefits delivered by the S&OP process are: (i) better client service; (ii) reduced inventory levels; (iii) improved client service level; (iv) increased order fulfillment; (v) shorter lead times; (vi) increased agility when reacting to changes; (vii) increased productivity and stability; (viii) anticipating future problems. Currently, frameworks are available on the operationalization model of the S&OP process. One of the most widespread comes from the author Wallace [39], who stipulates the following sequential steps: (i) "Data Maintenance"; (ii) "Demand Planning"; (iii) "Supply Planning", (iv) "Pre-S&OP Meeting"; (v) "S&OP Executive Meeting". The use of the Sales & Operations Planning (S&OP) process by companies in the Brazilian scenario has shown significant growth in recent years [5].

2.2 S&OE

Carvalho [6] defines the S&OE process as "a process that connects tactical planning to operational planning by layering the plans generated by S&OP into disaggregated information". According to the "2019 Supply Chain Industry Benchmark Report" conducted by Elemental and Supply Chain and Demand Executive, no matter how mature the S&OP process may be, success is closely measured by how well teams adapt in real-time to mitigate client impact when things do not go as planned. This research also found that while almost all companies surveyed have a defined S&OP process, less than half follow at least basic S&OE practices.

In the webinar "S&OE: the secret ingredient for delivering planned business results," Pukkila [33], who at the time was Research Director at Gartner, stated that S&OE is a planning process with a horizon of 0–12 weeks, weekly cadence, focus on SKUs, orders, and shipments, and its main purpose is to evaluate and enable S&OP plans. S&OE unfolds S&OP plans for short-term planning. For the author, S&OP and S&OE are extremely interlinked, but both have a specific function, and one does not replace the other. Pukkila [33] also states that there is no short-term S&OP because it loses its essence if conducted in a short period. S&OP has the task of defining "how" the supply chain needs to be executed. S&OE is responsible for analyzing scenarios and solving problems, focusing on delivering S&OP results in greater detail and frequency, being enough to respond to exceptions. The main motivation for developing and using the S&OE process is to meet demand in volatile planning environments. An important aspect of this process is the collaboration between the sales and supply chain planning departments. Nullipady and Raju [29] state some of the benefits that can be achieved by implementing the process, the main ones being: reducing inventory by approximately 25% and improving the level of client service.

3 Proposed Model

This study aims to understand the relevance of the Sales and Operations Executions concept and its contributions to companies in executing the supply chain. As detailed in the following topic, the companies researched in this study were segregated into S&OE process implementation maturity levels according to their experience, knowledge, and implementation time to support three research hypotheses presented in the Fig. 1.

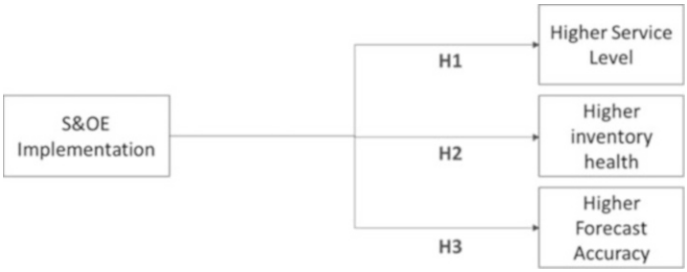

Fig. 1 Research hypotheses

3.1 Hypothesis 1

"S&OE positively and directly impacts the client service level". One of the great differentiators of a synchronized, client-driven supply chain is to exceed market expectations regarding short order delivery times, timeliness, and completeness. For Nullipady and Raju [29], the scope of the S&OE process is the promise of executing S&OP plans, synchronizing client demand from the order backlog with production and purchasing plans to increase the service level delivered to clients.

3.2 Hypothesis 2

Please "S&OE positively and directly impacts the health or quality of inventories". The composition of the inventories of each product concerning its level of demand is paramount for a coherent balance between investment or costs with storage and competitive advantage by improving client service level. For Ni et al. [28], a major challenge for most companies regarding supply chain execution processes is adequately supply sales orders with accurate inventories at the location and in the quantity and quality desired by clients.

3.3 Hypothesis 3

Please "S&OE positively and directly impacts forecast accuracy". Reviewing the demand plans generated by the S&OP process before executing them is of fundamental importance to achieve greater accuracy and correct deviations between the planning and the most recent realization. According to Behm [4], S&OE is a continuous process centered on realignments, where the main function is to understand changes in scenarios and receive information to update plans as accurately as possible, which benefits the supply chain in several aspects, such as cost and waste reduction and increased margins and revenue.

4 Methods

Regarding its purpose, the present study is characterized as exploratory. According to Gil [45], exploratory studies aim to develop ideas and lead to relatively systematic procedures for obtaining empirical observations and identifying the relationships between the studied phenomena. For this study, a questionnaire survey methodology was used to determine the perception of S&OE practices in the Brazilian context. The questionnaire was designed to answer all the research questions presented above. The questions were based on relevant literature on the S&OE topic and validated by a group composed of two senior consultants specializing in SCM and who work at Value Chain Consultoria. The questions address aspects such as S&OE practices, reasons to adopt, barriers, and performance difficulties. The five-point Likert scale was considered adequate for assessing these types of questions.

A survey was structured with 26 multiple-choice questions and 2 open questions, with the multiple-choice questions being transferred to a Likert scale, from 0 to 5. Fifty-one professionals from 38 companies answered the questions. All organizations in the sample are companies with an operational presence in Brazil, mostly corporations with many subsidiaries of multinational companies with a wide range of suppliers, product portfolio, demand volatility, several sales channels, and a vast client base, making them typical candidates to benefit from S&OE implementation. Out of 80 questionnaires sent out, 51 questionnaires were received, resulting in an overall response rate of 63.75%. This situation is common in email surveys and can lead to non-response bias [36]. To test for non-response bias, we compared the distribution of the sectors of potential respondents (those to whom the survey was sent electronically) with the distribution of sectors that answered the questionnaires. Using the $\chi 2$ test, we found no statistically significant difference between the sectors, which may indicate a low non-response bias. Of the 51 usable responses, the health products industry accounts for 19.4% of the responses; the food industry and the metalworking industry account for 12.9% each.

Regarding the revenue volume of the companies in the previous year, 58% of the companies had turnovers above 1 billion reais, 29% had sales between 50 and 300 million reais, and 13% had sales below 50 million reais. According to sectors, the distribution of the companies shows that 67% of the respondents position themselves as producers and 23% as retailers or wholesalers. Data analysis was conducted using statistical software (SPSS) and consisted essentially of sorting the variables based on mean values and frequency distributions. The aim was to test whether the mean values of the dependent variables (assumed to be normally distributed) differ between the categories. The following procedure was adopted:

- Test of reliability and internal consistency of responses, Cronbach's coefficient (α), for questions on a Likert scale. The result of the sample shows Cronbach's $\alpha = 0.733$. Cronbach's $\alpha > 0.7$ was considered acceptable for this research as it is an exploratory study [13].

5 Results and Discussions

Four categories were created to present the survey results from the collected data and analysis of sample reliability.

5.1 *Category: S&OE Maturity Perception*

The survey confirms the degree of innovation that the S&OE process represents in supply chain management processes. The results can be seen in Table 1. Only 18% of the responding companies consider their level of knowledge and experience regarding the S&OE process as high or very high. Nevertheless, 61% of the responding companies have had the S&OE process implemented for less than 1 year or have not implemented it at all.

5.2 *Category: S&OE Process Capability*

Regarding adherence to the process—as provided in the literature references—by the researched companies, a significant gap is noted in aspects such as the management of planning, execution horizons, fine scheduling systematics for production and materials, as well as the management of order fulfillment and establishing deadlines. Nullipady and Raju [29] address that the S&OE process should be done by focusing on executing plans over a shorter horizon of 0–13 weeks rather than 3–18 months, which occurs in the S&OP process. In addition, S&OE is a process that breaks down the tactical S&OP plans into less aggregated information that is easier to understand and execute. Lim et al. [20] corroborate that each month the sales department should perform weekly demand updates for the next 3 months, with a low level of product aggregation, similar to MPS (master production planning), but with a weekly cadence.

According to Barrett [3], demand-driven is conceptualized as the synchronized execution of production and logistics processes to satisfy client demand. Rexhausen [34] corroborates that demand-driven uses coordinated technologies and processes

Table 1 Degree of knowledge of the S&OE process

How do you rate the internal team's level of knowledge and experience regarding best practices in S&OE?	
Very low	25%
Low	27%
Average	29%
High	16%
Very high	2%

Table 2 Short-term handling of demand from the S&OP cycle

What is the near/short-term treatment of the demand provided by the S&OP cycles?	
We execute the supply chain purely based on what is achieved	8%
We believe purely in S&OP demand and execute the supply chain by faithfully following these plans	4%
We randomly review points that we believe to be discrepant from S&OP	28%
We use S&OP demand as the basis but correct the execution when there are significant discrepancies up or down	47%
We review S&OP demand weekly based on what is achieved and statistics while considering commercial sensitivities before execution	13%

Table 3 Satisfactory S&OE process deliverables

Of the options below, which deliverables are your company's S&OE process performing satisfactorily?	
Conversion of exception resolution scenarios into DRE simulations for decision making	18%
Fine alignment in the short/very short term with the portfolio management and marketing process to simultaneously drive demand and maximize the use of installed capacity	32%
Proper execution of product launches and discontinuations, ensuring the health of stocks and level of client service	50%
In addition to demand and production/supply plans, it also covers weekly reviews of purchasing, storage, transport, cash flow plans, and reduction of emergency freight cost	24%
Reduction of unforeseen setups	21%
Reduction of emergency freight cost	24%

that collect, analyze, and share real-time demand and inventory information across supply chain partners. Lapide [18] comments that technology becomes a necessary asset to support the large scale of benefits that business processes can offer Supply chain collaboration can increase client satisfaction by reducing lead times, improving service levels, and reducing costs [23]. This finding is demonstrated in Table 2, which shows that only 13% of the companies find the greatest differences between planned and achieved weekly, correcting routes through short-term demand review with the application of statistics and in collaboration with sales and marketing departments.

From the data in Table 3, it was found that only 24% of the companies manage to extrapolate the S&OE process from the demand and production plans and to cover weekly reviews of the plans for purchasing, warehousing, transportation, etc. An increasingly relevant aspect in the current context of increasing portfolio volatility and decreasing product life cycles, the integration of supply chain planning processes with portfolio management processes is required as a strategy to drive demand and maximize the use of installed capacity. The research indicates that only one out of three companies achieve this fine alignment of short and very short term. Pukkila [33] advocates that financial reconciliation is one of the main pillars of success for the S&OE process, which makes the scenarios generated for the resolution of exceptions in the supply chain execution considered from the perspective of potential financial results. However, the survey shows that only 18% of the companies can simulate Income Statements through the S&OE process.

5.3 Category: Demand Driven

The latest practices in supply chain management emphasize the importance of providing products and services that meet market demand and client needs, known as a demand-driven supply chain [21, 22]. A demand-driven supply chain enables organizations to respond nimbly to changing market conditions and optimize inventory management and efficient use of assets. One of the results of this research, presented in Table 4, is that only 22% of companies measure client service level by the client's actual desire, that is, the date the client needs the product or service delivered. The other 78% of the companies measure their service quality by the promised delivery date, ignoring and, in many cases, not even registering the client's information of the date required.

Nevertheless, approximately six out of ten companies do not have rituals for managing indicators focused on the short or very short term, presenting only structured monthly forums for results analysis, as shown in Table 5. Forums like these have relevance in the company's culture and medium and long-term direction. Still, they do not lead the company to focus on short and very short-term responsiveness actions due to the time lag that can reach 30 days caused by the occurrence of the exceptions.

Table 4 Client service level measurement

How is the client service level indicator measured, and what is the reference date?	
We do not have this measurement	11%
Measured from the invoicing of the order and based on the promised date	26%
Measured from delivery to the client and based on the promised date	42%
Measured from invoicing the order based on the client's requested date	11%
Measured from client delivery and based on the client's requested date	11%

Table 5 Management rituals focused on service level

What are the existing management rituals in your company focused on the client service level?	
We do not have standardized rituals focused on expediting client service problem resolution/stock-outs	20%
We do not have standardized ones with a frequency less than monthly, which include service level indicators	4%
We have monthly indicator management forums, which include service level indicators	36%
Client service is where we deal with service issues/stock shortages	33%
We have daily interdepartmental forums for monitoring indicators focused on service level and monitoring the order flow in real-time to give visibility of deviations and support decision making with agility	7%

5.4 Category: Data Driven

Effectively managed demand-driven supply chains increasingly require new technological and managerial approaches for data transparency and collaboration [25]. Technical approaches to demand-driven supply chain involve data analytics to support an appropriate supply chain management system to minimize stock-outs and/or overstocks and raise the firm's bottom line in terms of costs and service levels [27]. According to Król and Zdonek [16], understanding an organization's ability to use data analytics to increase innovation and competitive advantage requires an assessment of where it stands on the data science journey. Currently, data analytics can be divided into five categories, which are defined by tools, techniques, and the approach to data analysis: (1) descriptive analytics, (2) diagnostic analytics, (3) predictive analytics, (4) prescriptive analytics, and (5) cognitive analytics. The present research points out, from Table 6, that 38% of the companies consider their analytical maturity level as initial, and only 2% consider their analytical level as "prescriptive".

Paarma [32] discusses the importance of technology in the management field and its evolution over the years, which has positively impacted organizations in orchestrating the business process. Today, renowned organizations invest in advanced technology to provide solutions that seamlessly coordinate their S&OE processes. The author adds that innovations, such as machine learning (ML) and artificial intelligence (AI), facilitate a closed-loop process, collecting and analyzing important data with greater agility, helping the company identify disruptions earlier and make more assertive decisions. According to Chase [7], demand sensing translates downstream data with minimal latency to understand what is being sold, who is buying the product (attributes), and how the product impacts demand. The present research points out in Table 7 that only 12% of the companies surveyed have demand sensing implemented with at least one client.

5.5 Hypothesis Validation

Based on the evaluation of the survey results, it was found that companies that demonstrate longer implementation time and greater knowledge and experience

Table 6 Application of analytical techniques in the near/short term

How do you consider your company's current analytical technology application level for the near/short term?	
Basic; the data is often disconnected and used in a superficial way	38%
Descriptive; we can only understand what happened in the past	21%
Diagnostic; we can understand what happened in the past and why	23%
Predictive; we can predict what will happen with sufficient accuracy	16%
Prescriptive; we can predict what will happen, and what to do when it happens	2%

Table 7 Level of implementation of demand sensing tools

What is the level of implementation of demand sensing tools?	
We have not applied them	75%
We have applied them to at least one client	0%
We have applied them to some clients	12%
We have applied them to most of our clients	0%
We have applied them to the entire client portfolio	0%

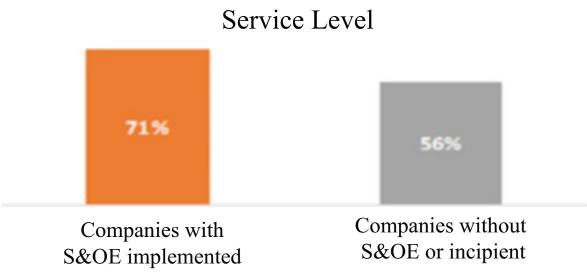

Fig. 2 Service level: companies with S&OE ×without S&OE or incipient

ANOVA[a]

Model		Sum of the squares	df	Mean Square	Z	Sig
1	Regression	5,855	1	5,855	3,508	,067[b]
	Residue	81,792	49	1,669		
	Total	87,647	50			

a. Dependent Variable: VAR00021
b. Predictors: (Constant), VAR00001, VAR 00005

Fig. 3 ANOVA test: service level × implementation time and S&OE knowledge

regarding S&OE present an average client service level of 71%. In contrast, companies that do not have S&OE implemented or use it incipiently have an average service level of 56%. This information is detailed in Fig. 2. For de Almeida and Schluter [9], global service level indicators determine the delivery rate of orders to clients within the agreed timeframe, with the complete order quantity, correct quantities, without product breakdowns, and therefore represent the company's competitive differential in the market. The same test was conducted between the independent variables of knowledge and experience regarding the S&OE process (VAR0001) and implementation time (VAR0005), and the dependent variable service level (VAR00021) linear regression was applied to assess the significance level. Figure 3 shows the results of the ANOVA test. It was found that the p-value is 6.7%. According to Murtaugh [26], a significance level of less than 10% suggests the rejection of the null hypothesis and proves that the independent variables influence the outcome of the dependent variable. In other words, the higher the level of

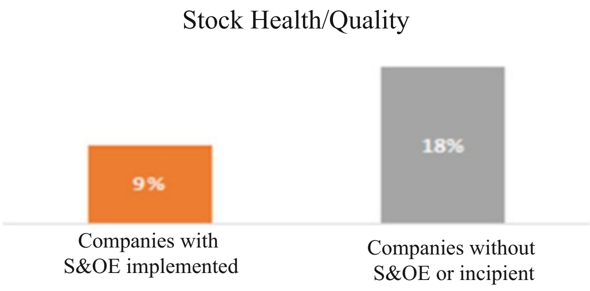

Fig. 4 Health/stock quality: companies with S&OE vs. without S&OE or incipient

ANOVA[a]

Model		Sum of the squares	df	Mean Square	Z	Sig
1	Regression	5,855	1	5,855	3,508	,067[b]
	Residue	81,792	49	1,669		
	Total	87,647	50			

a. Dependent Variable: VAR00023

b. Predictors: (Constant), VAR00001, VAR 00005

Fig. 5 ANOVA test: stock health/quality × implementation time and S&OE knowledge

knowledge and experience regarding S&OE and the longer the implementation time, the higher the level of service, thus validating Hypothesis 1.

The research also concludes that companies that display a longer implementation time and greater knowledge and experience regarding S&OE present an average of 9% of their inventory of finished products classified as obsolete or beyond the policy established by the company. This percentage increases to 18% in companies that do not have S&OE implemented or use it incipiently, as shown in Fig. 4.

Fleischhacker et al. [11] state that to succeed in the client's shopping experience journey, it is essential that the inventory is composed of the right products, in the right quantities, in the right locations, and in the right quality. This combination can be called inventory health. The test was reapplied among the independent variables: knowledge and experience in the S&OE process (VAR0001) and implementation time (VAR0005), and the dependent variable stock health/quality (VAR00023). Linear regression was applied to assess the significance level. Figure 5 shows the results of the ANOVA test. It was found that the p-value is 6.7%, which according to Murtaugh [26], a significance level of less than 10% suggests the rejection of the null hypothesis and proves that the independent variables influence the outcome of the dependent variable. It is possible to validate Hypothesis 2, considering that the higher the level of knowledge and experience regarding S&OE and the longer the implementation time, the higher the level of service.

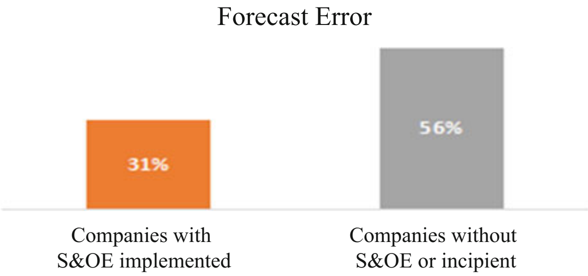

Fig. 6 Forecast error: companies with S&OE vs. without S&OE or incipient

ANOVA[a]

Model		Sum of the squares	df	Mean Square	Z	Sig
1	Regression	26,097	1	13,049	5,773	,006[b]
	Residue	108,491	48	2,260		
	Total	134,588	50			

a. Dependent Variable: VAR00017
b. Predictors: (Constant), VAR00001, VAR 00005

Fig. 7 ANOVA test: forecast error × implementation time and S&OE knowledge

It was also observed that companies that have a longer implementation history and greater knowledge and experience regarding S&OE present an average forecast error of 31%. In comparison, companies that have not implemented S&OE or use it incipiently have an average forecast error of 56%, as shown in Fig. 6. According to Kurzak [17], the objective of forecasting is to provide the most objective and substantial prerequisites possible for making business decisions and analyzing events that might occur, thus leveraging corporate performance in several aspects such as better financial margins, better perception of quality by the market, lower inventory and production costs, among others.

To better explain the correlation between the independent variables: knowledge and experience in the S&OE process (VAR0001) and implementation time (VAR0005), and the dependent variable mean forecast error (VAR00017), linear regression was applied to assess the significance level. Figure 7 shows the results of the ANOVA test. It was verified that the p-value is 0.6%; as such, the null hypothesis was rejected, with a significance level of 5%. This proves that the independent variables influence the result of the dependent variable. We were also able to validate Hypothesis 3, that the higher the level of knowledge and experience in S&OE and the longer the implementation time, the lower the forecast error.

5.6 Managerial Implications

Companies seeking excellence in the supply chain can benefit from implementing S&OE processes. Based on the research, it was found that there are significant practical benefits such as improved accuracy of demand, improved inventory health, and improved client service level. The present study aimed to stimulate companies to review their supply chain planning and execution processes, motivating organizations to establish robust and integrated processes of medium and long-term planning and short and very short-term execution to obtain the competitive advantages of supply chain synchronism and balancing.

6 Conclusions

This study provides a perspective on implementing the S&OE process in the Brazilian scenario through a structured questionnaire. The results show that Brazilian companies are currently going through the initial stages of S&OE implementation, with opportunities for maturation in all four dimensions: people, processes, technology, and data. The results prove the effectiveness of the S&OE process by comparing the performance of the companies based on their experience in the process, knowledge thereof, and history of implementation. Based on the results of the research, the hypotheses presented in chapter "An Approach to the Design of Resilient Biomass Supply Chain Using Discrete Event Simulation" were validated, and it was possible to conclude that the greater the implementation time, knowledge, and experience regarding the subject of S&OE, the greater the possibility of obtaining better results in terms of service level, inventory health, and forecast accuracy.

According to Carvalho [6], one of the greatest limitations of studies related to the S&OE theme is the limitation of literature, especially academic, to base studies on and compare results. The author also adds that more case studies should be conducted in Brazil and worldwide to validate the S&OE process implementation models and their results. For future research, it is recommended that this study be repeated, considering a larger sample size. In addition, it would be useful to conduct interviews with the entities and their partners to ascertain the motivating factors and the vision each party has for implementing S&OE.

References

1. Adexa. Integrated S&OP and S&OE. [s.1]. Adexa, 2016.
2. Apics. Certified in Production and Inventory Management: Learning System. Apics, Chicago, 2018.
3. Barrett, J., 2007. Demand-Driven is an Operational Strategy. *Industrial Management*, *49*(6).

4. Behm, R., 2021. Solution methods for network model formulation and scenario analysis of supply chain optimization problem.
5. Bodenstab, J., 2016. Sales & Operations Execution (S&OE) vs. S&OP.
6. Bremer, C. F., Franciosi, l. A. and Pintão, l. R. T. (2009), “Value Chain Scorecard” *Mundo Logística*, p. 20–29.
7. Carvalho, A.L.D., (2018) *The intermediate link in planning: a multicase study of the Sales and Operations Execution process* (Doctoral dissertation, Universidade de São Paulo). https://doi.org/10.11606/D.18.2018.tde-16072018-100932.
8. Chase Jr, C.W., (2013), “Using demand sensing and shaping to improve demand forecasting”, *The Journal of Business Forecasting*, *32*(4), p.24.
9. Christopher, M., 2016. *Logistics & supply chain management*. Pearson UK.
10. de Almeida, C.M.P.R. and Schlüter, M.R., 2009. *Estratégia Logística*. IESDE BRASIL SA.
11. Fleischhacker, A., Ninh, A. and Zhao, Y., (2015), “Positioning inventory in clinical trial supply chains”, *Production and Operations Management*, *24*(6), pp.991–1011.
12. Gil, A.C., 2002. Como elaborar projetos de pesquisa (Vol. 4, p. 175). São Paulo: Atlas.
13. Grimson, J.A. and Pyke, D.F., (2007), “Sales and operations planning: an exploratory study and framework”, *The International Journal of Logistics Management*.
14. Hair, J.F., Black, W.C., Babin, B.J., Anderson, R.E. and Tatham, R.L., (2014), Pearson new international edition. *Multivariate data analysis, Seventh Edition. Pearson Education Limited Harlow, Essex*.
15. Kreuter, T., Scavarda, L.F., Thomé, A.M.T., Hellingrath, B. and Seeling, M.X., 2021. Empirical and theoretical perspectives in sales and operations planning. Review of Managerial Science, pp.1-36.
16. Król, K. and Zdonek, D., (2020), Analytics Maturity Models: An Overview, *Information*, *11*(3), p.142. https://doi.org/10.3390/info11030142
17. Kurzak, L., 2012. Importance of forecasting in enterprise management. *Advanced Logistic Systems*, *6*(1), pp.173–182.
18. Lapide, L., (2005), “An S&OP maturity model”, *The journal of business forecasting*, *24*(3), p.15.
19. Lim, L.L., Alpan, G. and Penz, B., (2014), “Reconciling sales and operations management with distant suppliers in the automotive industry: A simulation approach”, *International Journal of Production Economics*, *151*, pp.20–36.
20. Lun, Y.V., Lai, K.H., Wong, C.W. and Cheng, T.C.E., (2013), “Demand chain management in the container shipping service industry”, *International journal of production economics*, *141*(2), pp.485–492.
21. Ma, K., Thomassey, S. and Zeng, X., (2020), “Development of a central order processing system for optimizing demand-driven textile supply chains: a real case based simulation study”. *Annals of Operations Research*, *291*(1), pp.627–656.
22. Mbhele, T.P., (2016), “Decoupling paradigm of push-pull theory of oscillation in the FMCG industry”, *South African Journal of Business Management*, *47*(2), pp.53–66.
23. McMaster, M., Nettleton, C., Tom, C., Xu, B., Cao, C. and Qiao, P., (2020), “Risk management: Rethinking fashion supply chain management for multinational corporations in light of the COVID-19 outbreak”. *Journal of Risk and Financial Management*, *13*(8), p.173.
24. Monahan, S.T. and Hu, M., (2015) Sharing supply chain data in the digital era. *MIT Sloan Management Review*, *57*(1), p.95.
25. Murtaugh, P.A., (2014), “In defense of P values”, *Ecology*, *95*(3), pp.611–617.
26. Nguyen, T., Li, Z.H.O.U., Spiegler, V., Ieromonachou, P. and Lin, Y., (2018), “Big data analytics in supply chain management: A state-of-the-art literature review”, *Computers & Operations Research*, *98*, pp.254–264.
27. Ni, Y., Wang, Y., Yao, J. and Li, J., (2013), “Integrated optimisation of scheduling and ordering based on semi-finished goods delayed differentiation”, *International Journal of Production Research*, *51*(16), pp.4805–4819.

28. Noroozi, S. and Wikner, J., 2017. Sales and operations planning in the process industry: a literature review. International Journal of Production Economics, 188, pp.139–155.
29. Nullipady, A.M. and Raju, E., 2020. Sales and Operation Execution A study at SKF Group.
30. Oliva, R. and Watson, N., (2011), "Cross-functional alignment in supply chain planning: A case study of sales and operations planning", *Journal of Operations Management*, *29*(5), pp.434–448.
31. Paarma, L., (2019), "Advanced planning and scheduling (APS) system supported sales and operations execution (S&OE) process".
32. Pukkila, M. (2016), "S&OE: The secret ingredient for delivering planned business results", *Stamfor: Gartner Webinars*.
33. Rexhausen, D., Pibernik, R. and Kaiser, G., (2012), "Customer-facing supply chain practices—The impact of demand and distribution management on supply chain success", *Journal of Operations Management*, *30*(4), pp.269–281.
34. Sax, L.J., Gilmartin, S.K. and Bryant, A.N., (2003), "Assessing response rates and nonresponse bias in web and paper surveys", *Research in higher education*, *44*(4), pp.409–432. https://doi.org/10.1023/A:1024232915870.
35. Seeling, M.X., Scavarda, L.F. and Thomé, A.M.T., 2019. A sales and operations planning application in the Brazilian subsidiary of amultinational chemical company. Brazilian Journal of Operations & Production Management, 16(3), pp.424–435.
36. Stentoft, J., Rajkumar, C., Freytag, P.V. and Mikkelsen, O.S., 2020, October. Sales and operations planning: Empirical insights into perceivedrelevance and lack of implementation. In Supply Chain Forum: An International Journal (Vol. 21, No. 4, pp. 246–259). Taylor & Francis.
37. Wagner, S.M., Ullrich, K.K. and Transchel, S., (2014), "The game plan for aligning the organization", *Business Horizons*, *57*(2), pp.189–201.
38. Wallace, T.F. and Stahl, R.A. (2003), Previsão de Vendas: uma nova abordagem. Trad: Daniel Gasnier, São Paulo, IMAM.
39. Wallace, T.F. and Stahl, R.A., 2003. Master Scheduling in the 21st Century: For Simplicity, Speed, and Success-Up and Down the Supply Chain. TF Wallace & CO.

Implications of COVID-19 on the Use of Public Transport in São Paulo, Brazil

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Abstract The COVID-19 pandemic has impacted not only the health system but also several other sectors of society. Urban mobility patterns have changed due to social distancing and isolation, which have impacted public transport around the world. This paper aims to analyze the effect of the COVID-19 pandemic on the number of passengers transported by public transit buses in the city of São Paulo, Brazil. For this purpose, data were collected from official sources of the municipal government and, subsequently, a quadratic regression model was selected and adjusted, considering the number of passengers transported (y) as the dependent variable and confirmed deaths (x_1) and accumulated fully vaccinated population (x_2) as independent variables. The model confirms that COVID-19 has influenced public transport in São Paulo. As expected, the number of confirmed deaths has a negative effect while the advancement of vaccination has a positive effect on the demand for public transport. The results highlight the importance of vaccination and policies of social distancing and isolation to prevent deaths caused by COVID-19, which brought greater health security to the population. Therefore, these policies encourage a brief resumption of public transport services, reducing the risk of losses for stakeholders. We hope this study will contribute to a greater understanding of the effects of the COVID-19 pandemic on public transit buses in São Paulo, helping policymakers during possible future disasters like the COVID-19 pandemic.

Keywords Public transport · Urban mobility · COVID-19

1 Introduction

The last few years have been marked by the COVID-19 pandemic, a highly transmissible respiratory disease caused by the SARS-CoV-2 virus, the new coronavirus. The disease was first identified in the city of Wuhan, China, in December

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2019, spreading rapidly across the world [1]. In Brazil, the first patient to test positive was diagnosed on February 26th, 2020 and, since then, the country has been considered one of the epicenters of the pandemic [2–4].

Initially, one of the main virus containment policies was social isolation and distancing, causing authorities to restrict people's access to public and private places [5]. However, despite their importance and effectiveness in reducing the spread of COVID-19, such measures have had a significant impact on people's behavior in cities. This created an unprecedented scenario, and the transport sector was one of the most affected [6].

Previous studies have evaluated the impact of COVID-19 on urban mobility around the world. This effort can be explained by the fact that, during a pandemic, time is an important variable for a better understanding and mitigation of events [7]. Since the risk of this type of disaster is increasing, these studies can contribute to a better and faster response to these possibilities [8]. Therefore, it is important to understand the behavior of the variables related to the resilience of urban mobility.

Specifically in Brazil, the urban public transport sector, which previously operated with economic stability and a low degree of uncertainty, faced a sharp drop in the number of passengers due to COVID-19. No benchmarking could provide its return to normality. São Paulo, for example, is the largest and most populous Brazilian city and presented a loss of 51.79% in the number of passengers transported by bus and subway between March and December 2020 when compared to the same period in 2019 [9]. This highlights the serious imbalance that the public transport sector faced during this period.

Most organizations in Brazil and several other countries, whether public or private, are not prepared to respond quickly and effectively to disturbances caused by external factors. Many of them take years to recover or do not survive after a disaster [10]. Thus, when these disturbances occur, the structural failures of organizations are exposed, which highlights the need to restructure their risk management approaches [8]. Passenger transport companies, mainly public ones, need to change both their operational and financial structure, aiming to overcome the reduction in the number of users of their services and provide a better use of their resources, while still providing good service.

Even with the advancement of vaccination, essential for containing the coronavirus, the impacts on the urban public transport sector remain in a challenging situation in Brazil, even with the accumulation of experience and perspectives. This can be explained by the persistence of habits that have grown during the pandemic until today, such as remote work and teaching, e-commerce, and the use of active transport, such as cycling or even walking. Therefore, these new habits also impact urban mobility, including the use of public transport, which has not reached the same number of passengers as before the pandemic yet.

Given the above, studies related to the impact of the COVID-19 pandemic on people's behavior and urban mobility play a key role in truly effective decision-making. Therefore, this paper aims to evaluate the effect of the COVID-19 pandemic on the number of passengers transported by public transport in the city of São Paulo, Brazil. The application in São Paulo was due to its significant national importance.

Public transit buses were used as a delimitation, considering that they are the most used mode of public transport in the city. In addition, they cover a larger number of regions, unlike trains and subways, which only operate in a few specific areas. In the meantime, this study contributes to decision-makers in this sector, assisting them with investments and/or restructuring of public transport, as well as in the elaboration of strategies for future perspectives.

2 Background

The COVID-19 pandemic caused several changes in the world, even affecting urban mobility. Since the beginning of preventive measures to contain the spread of the virus, there have been changes in travel patterns, transport demands, and preferences related to mobility [11]. Since then, several studies have analyzed the impacts of the COVID-19 pandemic on urban mobility around the world.

Fatmi [6] conducted a survey on the immediate change in the behavior of individuals as a result of the COVID-19 pandemic in their daily activities in Canada. The author concluded that outdoor activities decreased by approximately 50% during the pandemic. Cui et al. [12] used real-time data to measure the performance of traffic conditions before and during the COVID-19 pandemic to verify how urban mobility patterns changed in the Geater Seattle region, in the United States. They found that the demand for transportation declined during the COVID-19 pandemic, as well as a significant reduction in the overall average speed rate on major freeways.

The study by [13] analyzed the impact of the confinement measures imposed due to the COVID-19 pandemic on urban mobility in the city of Santander, Spain. The results showed that travel flows were reduced by 76% in this region during the COVID-19 pandemic when compared to previous periods. This reduction reached 93% for public transport. Grassi et al. [14] carried out a similar study in a medium-sized city in Argentina. They found a decrease not only in vehicular flow (~23%) but also in pollutant and greenhouse gas concentrations (~70%) when assessing data from before and during the pandemic. In addition, the study also identified changes in the population's mobility habits, with a decrease of about 66% and an increase of approximately 53% in the use of buses and bicycles, respectively, which is unusual in the city.

Kellermann et al. [15] investigated the mobility behavioral changes induced by COVID-19 by analyzing the travel patterns of Berlin residents over 20 months and comparing them to the pre-pandemic situation. Based on an analysis of nearly 800,000 recorded trips, the study revealed that public transport has continually declined, with trip frequencies and distances traveled decreasing by approximately 50% and 43% respectively. In contrast, cycling was the mode that increased the most, with an increase of approximately 53% in trip frequency and 117% in travel distance.

The study carried out in Spain by [16] analyzed the impact of COVID-19 on urban mobility through the number of passengers per bus line, the use of stops, and the main origin-destination flows in the city. The authors identified a reduction in the supply of buses and the number of passengers. On the other hand, there was an improvement in the reliability of this service, due to reduced travel times. It is also interesting to highlight the findings of the study by [17] in India. The results revealed Indians' willingness to pay more for a transport service that is safer, faster, cleaner, more comfortable, and less exposed to contamination risks when compared to existing public transport.

In turn, the study by [11] sought to identify the impacts of the pandemic on the profile of travel behavior and mobility preferences in Brazil, using a case study of cities located in Rio Grande do Sul. The authors identified that the use of private vehicles grew as the main mode of transport during the pandemic. On the other hand, the use of public transport drastically reduced by approximately 73%. There was also greater adoption of active mobility measures, especially regarding cycling.

In general, changes in mobility affected demands for public transport mainly due to the reduction in the number of passengers during the period in which social isolation and distancing measures were imposed [11, 12, 15, 18, 19]. However, with the availability of vaccines (even if unevenly distributed worldwide), the pandemic appears to be more manageable, and economies appear to be recovering nowadays [15].

However, the transport sector has not recovered the same number of users as before the pandemic. Even after the return of activities, this sector still faces uncertainties about the long-term effects of the pandemic on the choice of mode of transport and on individual travel behavior [15]. In this context, [12] predicted that urban mobility will hardly return to pre-pandemic standards, mainly due to the expansion of remote work and teaching, e-commerce, and active and sustainable mobility, which has gained more encouragement around the world.

3 Methodology

The methodology follows an adaptation of a framework for modeling time series proposed by [20], as shown in Fig. 1. The first step of the methodology consists of the problem and objective definition [21, 22]. For this study, we aim to evaluate the effect of the COVID-19 pandemic on the number of passengers transported by the public transport service of the city of São Paulo, as detailed in Sect. 1.

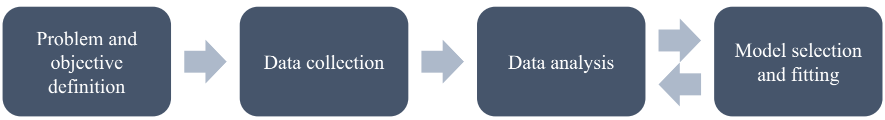

Fig. 1 Steps for the modeling process of time series

Fig. 2 Number, in thousands, of passengers transported and (**a**) confirmed cases of COVID-19, (**b**) confirmed deaths from COVID-19, and (**c**) accumulated fully vaccinated population. (Source: Prefeitura Municipal de São Paulo [9, 23])

Data were collected based on official sources from the municipal government of São Paulo. In this way, the monthly number of passengers transported by public transit buses between April 2020 and September 2022 was obtained [9]. In addition, the monthly number of cases and deaths caused by the coronavirus was collected, as well as the accumulated monthly number of fully vaccinated population (first and second dose) [23]. Figure 2 presents the data that compose the time series of this study.

The third step of the methodology consists of data analysis. Given the context of the pandemic and although the first case of COVID-19 was confirmed in February 2020 in São Paulo, data were collected from April 2020 onwards due to the more severe adoption of social isolation and distancing measures, such as the suspension of face-to-face teaching, work, and commerce activities, among others [5]. The intensity of these measures was influenced by the number of cases, deaths, and subsequent vaccination against COVID-19, influencing the use of public transport by the population. Therefore, these were the independent variables considered in this study.

Finally, a mathematical model was selected and adjusted for the time series. For this purpose, a regression analysis was performed, one of the most widely used statistical tools to establish useful relationships between variables. This relationship is expressed as an equation or model that connects the response variable (dependent) to the predictor variables (independent or explanatory) [20]. The regression analysis results can be found in the next section, as well as the analysis of the data obtained from these results, according to the proposed methodology.

4 Results

The results were analyzed using the Minitab® and RStudio®. First, we measured the degree of relationship between the dependent variable (number of passengers transported) and the independent variables (cases, deaths, and full vaccination) using a correlation matrix, as shown in Table 1.

On the one hand, both death and vaccination variables show a strong statistically significant correlation with the number of passengers transported ($r > |0.700|$; p-value < 0.050). On the other hand, the confirmed cases variable does not have a statistically significant correlation with the dependent variable (p-value > 0.050). This maybe implies that the number of confirmed COVID-19 cases does not provide any information about the number of passengers transported by buses in São Paulo. In addition, Table 1 shows a possible absence of multicollinearity ($r < |0.700|$ or p-value > 0.050), that is, there is no strong statistically significant correlation between the independent variables, which is good for the model interpretation.

From this, we developed regression models according to the aim of this paper. Through the significance values of the coefficients (β) of the terms, it was possible to discard, in fact, the confirmed cases variable from the model, as expected due to the correlation analysis performed. Thus, Table 2 presents the regression model that best fits our study. The model is quadratic and composed of the variables of passengers transported (y) as a dependent variable and confirmed deaths (x_1) and full vaccination (x_2) as independent variables.

In addition to the significance of the coefficients, as already mentioned, the regression model was also selected based on the R^2 and adjusted R^2 values. Selecting a model that maximizes these values is equivalent to selecting a model that

Table 1 Correlation matrix and their respective p-values

	Passengers transported	Confirmed cases	Confirmed deaths
Confirmed cases	−0.342		
	0.064		
Confirmed deaths	−0.707	0.615	
	0.000	0.000	
Full vaccination	0.832	−0.286	−0.646
	0.000	0.126	0.000

Table 2 Summary of the regression model selected

Terms	β	β standardized	T-value	P-value
Constant	146,115.000	9,200.000	15.880	0.000
x_1	−24,877.000	6,010.000	−4.140	0.000
x_2	2.065	0.788	2.620	0.014
x_1^2	2895.000	848.000	3.410	0.002
			R^2	0.822
			Adjusted R^2	0.801

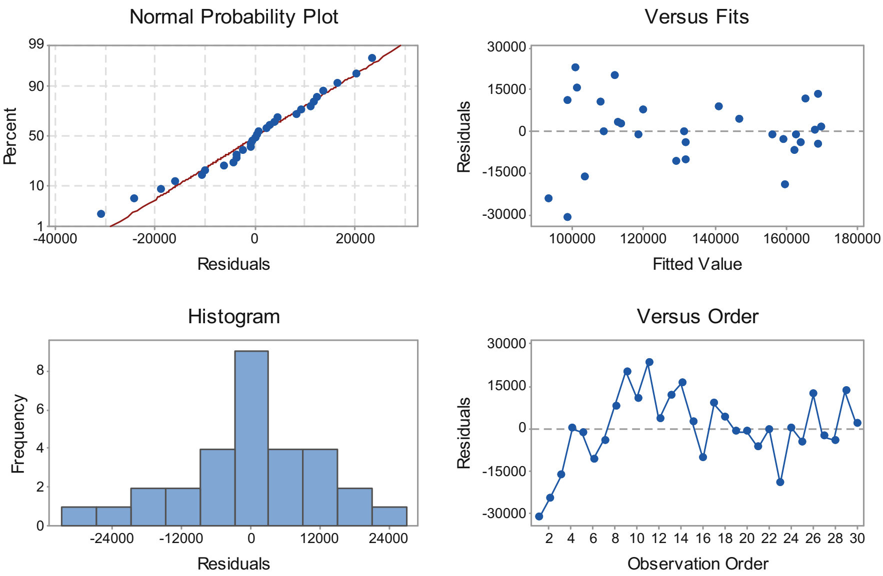

Fig. 3 Residuals plots for passengers transported

minimizes the residual sum of squares, i.e., a model that has a good fit with the time series [20]. Therefore, the model presented in Table 2 explains 80.1% of the variation in the number of passengers transported by public transit buses in São Paulo.

In addition to model selection, a residual analysis is performed to compare actual and fitted values. Figure 3 presents the residual graphs for the number of passengers transported. The first assumption of a reliable model was homoscedasticity, i.e., ensuring that the error variance is constant over time. For this, the residual plots were analyzed, identifying randomly arranged points, a result that meets this assumption.

Finally, another assumption evaluated was the normality of residuals, which also reaffirms the homogeneity of the error variance. The Ryan-Joiner test, similar to the Shapiro-Wilk test, was performed for the residual data. This test was chosen due to its indicated application for small samples. Thus, the normality test presented a

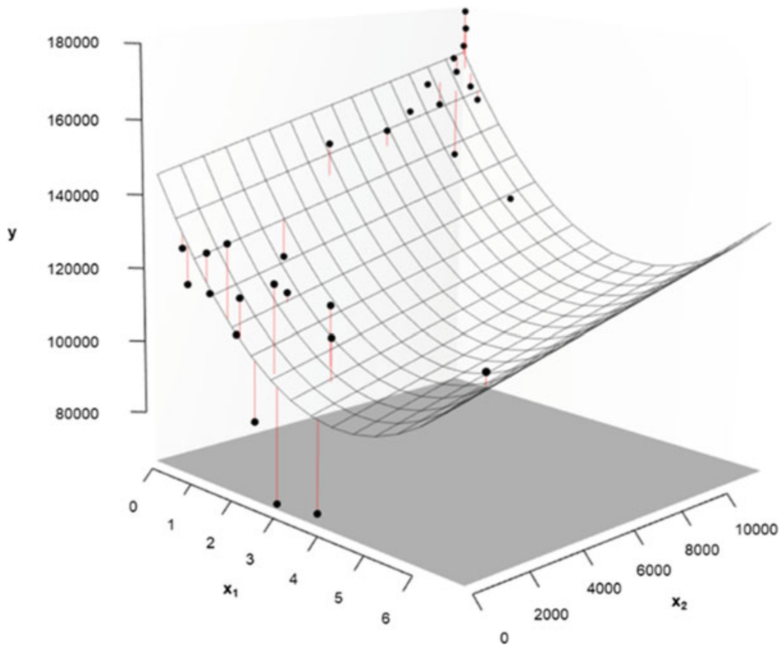

Fig. 4 Actual data scatter plot with the model surface

p-value greater than 0.100, accepting the null hypothesis (H_0) and concluding that the residuals are normally distributed.

With the assumptions properly tested, we concluded that the selected model is reliable and proves that the conditions of the COVID-19 pandemic influence the number of users of public transport in São Paulo. Therefore, Eq. (1) mathematically represents this statement, in thousands, according to the selected model. Graphically, Fig. 4 presents Eq. (1), represented by the grid, compared with the actual number of passengers transported, represented by the black balls. The red lines represent the difference between the actual value and the model-fitted value.

$$y = 146{,}115 - 24{,}877x_1 + 2.065x_2 + 2{,}895x_1^2 + \varepsilon \qquad (1)$$

5 Discussion

Figure 5 shows the effects of the COVID-19 pandemic on the number of passengers transported by public transit buses in São Paulo before and during the pandemic, as well as the fit model selected in this study. Despite the gradual increase during the pandemic, the demand for public transport has not returned to previous numbers yet.

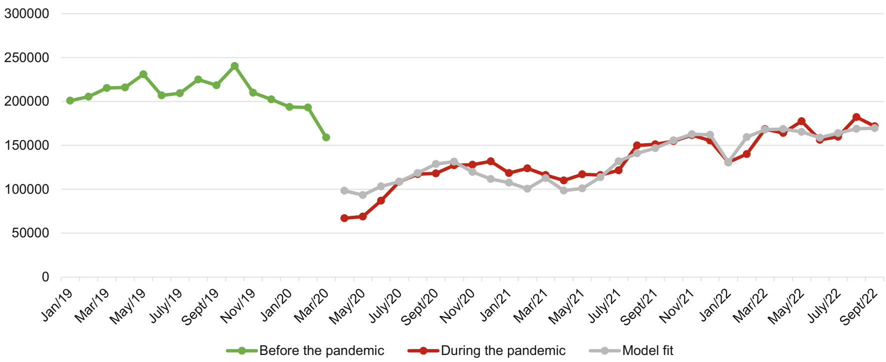

Fig. 5 Number of passengers transported, in thousands, before and during the COVID-19 pandemic

This behavior can be explained by several factors resulting from COVID-19. First, we mention the social distancing and isolation measures that, consequently, led to a reduction in the number of people attending public and private places. This had a direct impact on urban mobility, as the population was prevented from generating trips to carry out their basic and leisure activities during periods of strict restrictions. However, it is important to emphasize that, in many cases, some of these measures became routine and were extended until today, such as remote work. This may be one of the reasons that explain the lower numbers of passengers currently transported when compared to those reported in periods before the pandemic.

Another factor that impacted the population's behavior regarding the use of public transport is related to their constant concern to preserve their own safety and health during the pandemic, as well as that of people close to them. This can be explained by the high mortality rate of the new coronavirus, which was confirmed by the negative effect that the number of deaths has on the model selected in this study. In this sense, part of the population opted to stay in their houses during these periods and, when necessary, use individual vehicles for transportation. Consequently, this reduced the demand for public transport, as shown in Fig. 4.

Finally, Fig. 4 and the regression model of this study show us the positive effect of the vaccination rate on the number of passengers transported by public transit buses in São Paulo. This reflects the importance of the vaccine not only for containing the virus but also for the normality of economic and leisure activities of the population.

6 Conclusion

This paper aimed to analyze the effect of the COVID-19 pandemic on the number of passengers transported by public transit buses in the city of São Paulo, Brazil. For this purpose, a quadratic regression model was selected and adjusted, considering the number of passengers transported (y) as a dependent variable and confirmed deaths (x_1) and accumulated population fully vaccinated (x_2) as independent variables. The selected model presented high R^2 values and distributionally normalized residuals, which is reliable for the purpose of this study.

The finding results confirm that COVID-19 influences public transportation in São Paulo. As expected, the number of confirmed deaths has a negative effect on the demand for public transport. However, this demand has increased with the arrival and advancement of vaccination in the country, consequently contributing to economic and leisure activities. Therefore, these conclusions highlight the importance of social distancing and isolation measures in order to prevent deaths caused by COVID-19, in addition to the importance of vaccination, which brought greater health security to the population. Consequently, these policies encourage a brief resumption of public transport service during a pandemic.

This study has limitations that can be explored in future work. As previously discussed, the study was limited to the city of São Paulo and its generalization to another region must be accompanied by new data collection. Furthermore, as the pandemic occurred recently, it was not possible to collect a large amount of data, which could further improve the model fit. Therefore, a suggestion would be to update this data over time and monitor the model's adjustment, always updating it whenever necessary.

Despite these limitations, this paper contributes to a greater understanding of the effect that the COVID-19 pandemic has had on public transport in São Paulo. In addition, this study also benefits a better use of public transport, since, as it is a service, its underuse can bring losses to stakeholders. Therefore, we expect that the findings results can benefit decision and policymakers during possible future disasters like the COVID-19 pandemic.

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References

1. Shereen, M. A., Khan, S., Kazmi, A., Bashir, N., Siddique, R.: COVID-19 infection: Origin, transmission, and characteristics of human coronaviruses. Journal of Advanced Research 24, 91–98 (2020).
2. Brazil, Ministério da Saúde, https://covid.saude.gov.br/, last accessed: 2021/10/25.

3. Aguiar Hugo, A., Lima, R. S.: Healthcare waste management assessment: Challenges for hospitals in COVID-19 pandemic times. Waste Management and Research 39(1), 56–63 (2021).
4. Moraes, F. T. F., Gonçalves, A. T. T., Lima, J. P., Lima, R. S.: An assessment tool for healthcare waste management in Brazilian municipalities during the COVID-19 pandemic. Waste Management and Research 40(6), 625–641 (2022).
5. Aquino, E. M. L., Silveira, I. H., Pescarini, J. M., Aquino, R., de Souza-Filho, J. A.: Social distancing measures to control the COVID-19 pandemic: Potential impacts and challenges in Brazil. Ciência & Saúde Coletiva 25, 2423–2446 (2020).
6. Fatmi, M. R.: COVID-19 impact on urban mobility. Journal of Urban Management 9(3), 270–275 (2020).
7. Galeazzi, A., Cinelli, M., Bonaccorsi, G., Pierri, F., Schmidt, A., Scala, A., Pammolli, F., Quattrociocchi, W.: Human mobility in response to COVID-19 in France, Italy and UK. Scientific Reports 11 (2021).
8. Dulam, R., Furuta, K., Kanno, T.: Consumer panic buying: Realizing its consequences and repercussions on the supply chain. Sustainability (Switzerland) 13(8), 1–24 (2021).
9. Prefeitura Municipal de São Paulo, Secretaria de Mobilidade e Trânsito – Passageiros Transportados (2022).
10. Rejeb, A., Rejeb, K., Keogh, J. G.: Covid-19 and the food chain? Impacts and future research trends. Logforum 16(4), 475–485 (2020).
11. Oestreich, L., Rhoden, P. S., Vieira, J. S., Ruiz-Padillo, A.: Impacts of the COVID-19 pandemic on the profile and preferences of urban mobility in Brazil: Challenges and opportunities. Travel Behaviour and Society 31, 312–322 (2023).
12. Cui, Z. Zhu, M., Wang, S., Wang, P., Zhou, Y., Cao, Q., Kopca, C., Wang, Y.: Traffic Performance Score for Measuring the Impact of COVID-19 on Urban Mobility. Physics and Society (2020).
13. Aloi, A., Alonso, B., Benavente, J., Cordera, R., Echániz, E., González, F., Ladisa, C., Lezama-Romanelli, R., López-Parra, A., Mazzei, V., Perrucci, L., Prieto-Quintana, D., Rodríguez, A., Sañudo, R.: Effects of the COVID-19 lockdown on urban mobility: Empirical evidence from the city of Santander (Spain). Sustainability (Switzerland) 12(9) (2020).
14. Grassi, Y. S., Brignole, N. B., Díaz, M. F.: Pandemic impact on air pollution and mobility in a Latin American medium-size city. International Journal of Environmental Studies 79(4), 624–650 (2022).
15. Kellermann, R., Sivizaca Conde, D., Rößler, D., Kliewer, N., Dienel, H. L.: Mobility in pandemic times: Exploring changes and long-term effects of COVID-19 on urban mobility behavior. Transportation Research Interdisciplinary Perspectives 15 (2022).
16. Orro, A., Novales, M., Monteagudo, A., Pérez-López, J. B., Bugarín, M. R.: Impact on city bus transit services of the COVID-19 lockdown and return to the new normal: The case of A Coruña (Spain). Sustainability (Switzerland) 12(17) (2020).
17. Thombre, A., Agarwal, A.: A paradigm shift in urban mobility: Policy insights from travel before and after COVID-19 to seize the opportunity. Transport Policy 110, 335–353 (2021).
18. Alves, R., Lima, R. S., de Oliveira, L. K., de Pinho, A. F.: Conceptual Framework for Evaluating E-Commerce Deliveries Using Agent-Based Modelling and Sensitivity Analysis. Sustainability (Switzerland) 14(23) (2022).
19. dos Santos, J. B., Lima, J. P.: Quality of public transportation based on the multi-criteria approach and from the perspective of user's satisfaction level: A case study in a Brazilian city. Case Studies on Transport Policy 9(3), 1233–1244 (2021).
20. Montgomery, D. C., Lennings, C. L., Kulahci, M.: Introduction to time series analysis and forecasting. John Wiley & Sons, New Jersey (2008).
21. Enomoto, L. M., Lima, R. S.: Analysis of physical distribution and routing in a wholesaler. Production 17(1), 94–108 (2007).
22. Alves, R., Lima, R. S., de Sena, D. C., de Pinho, A. F., Holguín-Veras, J. Agent-based simulation model for evaluating urban freight policy to e-commerce. Sustainability (Switzerland) 11(15) (2019).
23. Prefeitura Municipal de São Paulo, Secretaria de Saúde – Painel COVID-19 (2022).

Analysis of Performance Indicators in Orders Pickup: Physical Volume Versus Human Factor

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Abstract One of the biggest costs of order picking is related to the wages of warehouse workers. In this sense, the indicators related to human resources need to be managed within the processes. In this research, the factors related to indicators of human resources are explained from the use of Machine Learning relating to productivity in order picking operations. From widgets with Naive Bayes, Random Forest and Logistic Regression, this study presents a robust model for related interpretations (n:682). As a result, it was given the dynamism of the volume separation process, with highly complex indicators to be evaluated. The physical indicators proved to be superior to human performance indicators. In addition, the model accuracy (Rendon Forest: 0.997) presented contributions related to wage cost in order picking. Furthermore, this study can be used in warehouses with high turnover and little automation. Generalizations must comply with the criterion of advanced automation, as the use of human strength prevailed in this research.

Keywords Performance indicators · Inventory management · Machine learning.

1 Introduction

In logistics operations, order picking is the collection of partial quantities of goods to satisfy customer orders which often accounts for more than half of the warehouse operating costs [1]. Despite the increasing automation of order picking processes, those still rely heavily on manual human work leading to high process costs [2].

Human productivity is not easy to assess, and often the indicators do not show the reality of order-picking tasks. Generally, human labor is employed in situations in which dynamism and flexibility of operation are demanded [3].

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Considering these questions, is essential to investigate the correct use of indicators for assessing performance of order picking aiming to reliability of logistics operations in warehouses. This assessment is critical when it is considered that picking, in addition to being an expensive operation, will undergo significant changes in the coming years. Order picking was identified as one of the most affected in the logistics universe when it comes to using artificial intelligence and terrestrial or aerial drones [4].

This work intends to show that the number of separated volumes and the weight of the products in separation are more robust indicators than the productivity value of each employee per hour worked. The research findings suggest that these two indicators should always be prioritized when evaluating indicators in picking operations.

Therefore, using such indicators can contribute to performance analysis by prioritizing indicators that measure volumes and weights instead of calculating human performance during working hours.

This article is structured as follows: human and physical factors are exposed through related cases; the method is described; Machine Learning widgets power analytics; conclusions are presented.

2 Human Factors and Physical Factors

In the mid-2015s a series of studies showed the importance of the human factor in the composition of the higher cost of order picking, despite the increasing automation of processes in the field of logistics [5–7]. Operational processes are typically characterized by a large amount of manual human work, especially in material handling and assembly tasks. Despite the opportunities that the automation of production and logistics systems offers, many companies still rely on human work in several areas due to their flexibility manouver and both cognitive and motor skills that machines can still not imitate economically [8].

Such studies explained why there is still significant use of a manual process in order picking, despite the irreversible arrival of robots in this segment [9, 10]. The human factor is often more flexible than automated approaches, which is especially important in the case of heterogeneous product portfolios and changes related to shortening the life cycle and increasing product differentiation in the industry [11]. due to their flexibility manouver and both motor and cognitive skills

Order picking (searching for items due to customer requests) is one of the most critical processes within warehouses. Studies suggest that about 80% of warehouses are still parts-picking systems where employees walk or move around the warehouse, picking up items from shelves [12]. Here, the flexibility of human workers – in contrast to fully automated order picking systems – has often been cited as a significant advantage.

Many companies continue to use manual order picking due to variability in SKU shape and size, demand variability, product seasonality, or the significant investment required to automate an order picking system. Therefore, it is noticeable that the attention falls on how the employee acts in the order picking operation since automation exists but still does not represent most of the order picking operations in warehouses [13].

In this context, there is a predominant need to deal more and more with social phenomena and their impact on operational performance. Future research opportunities provide an informed basis to support human-centered work design [14].

In addition to focusing on psychosocial phenomena in the order picking environment, attention is paid to human performance and cost reduction in warehouses. The critical concern is how to perform this measurement separate from automated activity [15–17].

Two could be the explanations for this idea of prioritizing indicators that measure separate volumes instead of man/hour productivity:

1. Individual productivity decreases significantly when there is high variability in lot size [18]. The consequence is that using this indicator can lead to a bias, as the variability of the lots in separation increases.
2. The financial impacts of unrecorded human factors-related effects are seen as "phantom profits" [19], where anticipated profits are eroded by the negative consequences of these human factors [20]. Most companies, however, do not fully understand the costs associated with the human factor associated with injuries and absences.

In sum, when analyzing a series of studies on performance indicators for order picking, the option focused on the performance of volumes handled is better than those oriented to man/hour productivity. This option explains the restriction of fragility, stacking, shape, size, and preferred unloading sequence [21, 22].

Examples of indicators for volume are (a) Total Weight, (b) Quantity of Volumes, which shows the average number of units separated by each separator, and (c) Quantity of Containers (container is the denomination used for the part of the load per separation area). Such indicators are preferable to the standard (d) Average Lines/Man/Hour, which represents the productivity of each employee per hour worked [14].

In this sense it is possible to add more complexity to using performance indicators by productivity in warehouses. When analyzing this indicator, there are several parameters involved, such as: work productivity [23], Income [24], workplace area [25], productivity and selection [26], goods receiving productivity [27], and turnover [25]. It can be seen that with the number of variables involved and the suggested error margin, they gain amplitude compared to volume movement and analysis.

In a study organized to place Malaysia among the most efficient countries in the region, data on storage were gathered and considered effective performance indicators for warehouses. The complexity related to the use of such indicators is perceived, given their flexibility and scope to provide reliable reports. Some points to adjust such indicators are described below:

Firstly, in reducing labor productivity failure in warehousing, the company must employ skilled workers to reduce accidents or failures caused by human error. Thus, to attract high-quality human capital, industry participants must bring about a shift in mindset among students and young job seekers, enabling and promoting warehousing career paths. The company's human resources department ensures consistency and compliance in the recruitment and selection process for hiring qualified workers in this area. In addition, the company must offer language courses and standardize the working language to English or the native language to employ foreign workers, to avoid communication problems between workers and senior management [28].

In sum, according to the Malaysian study, the indicators are aligned with subjective aspects for an accurate analysis, which ranges from qualification to raising employee awareness, ending in the knowledge of English and the Malay language. Evidence places subjective indicators in the group of weakest assessments [29]. Here it is possible to understand the complexity and fragility of using these indicators since the success of human work and its consequent measurement depend on complex variables, such as the mastery of a native language.

In addition to the subjectivity in evaluating indicators involving human work, there are studies related to fatigue and learning. This means that as an employee performs a task routinely and repeatedly, his energy is consumed and, therefore, the probability of failures and accidents increases [30]. Some studies have identified this energy consumption with a drop in the rate of circulating glucose [31–34]. The learning effect was also widely explored when it was identified that the worker often performs his task in a biased way, as he learned over time to perform his separation task outside the norms [8, 35, 36].

From the above, an important issue arises that highlights the difficulty in working with indicators that measure the human effort in the order picking process. In contrast, indicators focused on the separation of volumes are more appropriate.

3 Methods

The data used were taken from the WMS (Warehouse Management System) system of a large multinational company located in the central region of Brazil. The data (n:682) were organized into columns, where each column represents a performance indicator of the separation process, namely, Employee Enrollment, Number of Containers, Total Weight, Number of Lines, Number of Volumes, and Total Executed Time, where each line represents one working day per employee.

In a spreadsheet, the data were processed and formatted; after this step, the Line/Man/Hour indicator was calculated; the concept of lines comes from the order invoices, where each line represents an item of the order, regardless of the quantity, dividing the 'Number of Rows' column by the 'Total Executed' column. With the 'Line/Man/Hour' indicator calculated per day and employee, using the PivotTable Excel tool, an average of the period per employee was calculated for each indicator. After processing and calculating the data, the table was organized as follows:

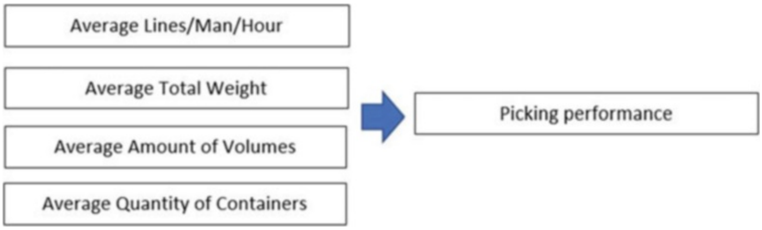

Fig. 1 General scheme of variables

(a) Employee registration, numerical identification of each employee; Average Lines/Man/Hour, which represents the productivity of each employee per hour worked. (b) Average Amount of Volumes shows the average of units separated by each separator. (c) Average Quantity of Containers, Container is the denomination used for the part of the load per separation area; the following equation can represent it. (d) Based on the average Lines/Man/Hour of all employees, the indicator's target was defined by adding 20% of this average; employees who are above average will be represented by the letter "A," and those below the average target with the letter B.

The four variables on the left of Fig. 1 are the indecent variables of the analysis model. The dependent (picking performance) on the right of Fig. 1 is the unit to be explained in the model.

4 Data Analysis

The multicollinearity analysis was the first procedure for forwarding the evaluation performed with Orange. The indicators for the variables Average Lines/Man/Hour (0.956), Average Total Weight (0.576), Average Quantity of Volumes (0.804), and Average Quantity of Containers (0.751 were adequate for the requirement [0; 1] Due to the lack of specific studies for these variables and the history of logistic regression, the 'Enter' method was used instead of the 'Conditional' and 'Wald' method.

The percentage of classifications made correctly reached 100%, considering 207 cases as 'yes' and 375 as 'no.'

The equivalent value for Linear Regression is the Wald value, also considered optimal for model adjustment. Average Lines/Man/Hour (0.002), Average Total Weight (0.002), Average Quantity of Volumes (0.003), and Average Quantity of Containers (0.015). According the condition ($H\_0{:}b = 0; H\_1{:}b \neq 0$).

It was noticed that all predicted values are different from zero, presenting statistical significance for all variables. This result is in line with recent findings predicting order picking [28, 37] that indicated the importance of considering indicators in the warehouse and picking work, including e-mail. Commerce [38].

After opening the database, the analysis of performance indicators began. The first analyzes were performed using Logistic Regression, the primary analysis of the

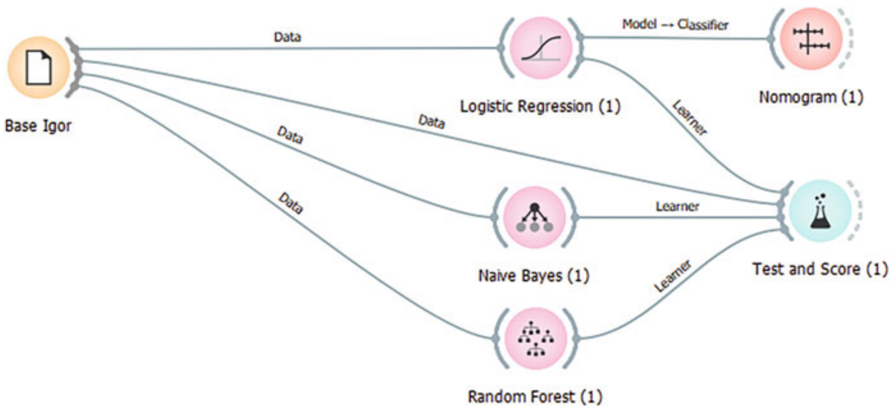

Fig. 2 Operation and analysis flow in Canvas

study in question. In Fig. 2, from left to right, the analysis plane can be seen. For example, the first widget (Base Igor) illustrates the database in Excel format. Next, from left to right, are the tools used to create the predictive model. Finally, the Test and Score Widget indicates the accuracy of the adjustment.

About the widgets used, Random Forest, Naive Bayes, and Logistic Regression, we have the following definitions:

Random Forest was chosen because it serves two purposes in the calculation logic that involves Regression: it allows prediction calculations and classification. Random Forest is based on Bootstrap Aggregation (Bagging), which provides a combination of multiple Machine Learning algorithms to obtain more accurate predictions than any individual model. The algorithm will create a structure similar to a flowchart, with "nodes" where a condition is verified, and if satisfied, the flow goes through a branch, otherwise, through another, always leading to the next node until the tree ends. With training, the algorithm looks for the best conditions and where to insert each within the flow. For more details, see Breiman [39].

Naive Bayes is considered an easy-to-use resource and has a relatively higher performance than other classifiers. Furthermore, Naive Bayes only needs a small number of test data to complete classifications with reasonable accuracy. It is considered "naive" because it disregards the variables' correlation. To perform classifications, Naive Bayes is one of the best alternatives. If a significant correlation between the factors, the feature may fail to predict the new information. For more details, see Webb [40].

Logistic Regression is a Machine Learning algorithm used for classification problems; it is a predictive analysis algorithm based on the concept of probability. Logistic Regression is essentially distinguished by the fact that the response variable is categorical. In this case, the binary variable (<5 and >5) required this algorithm to calculate the probability of the event "successful picking" to occur or not. More details can be found in Christodoulou et al. [41].

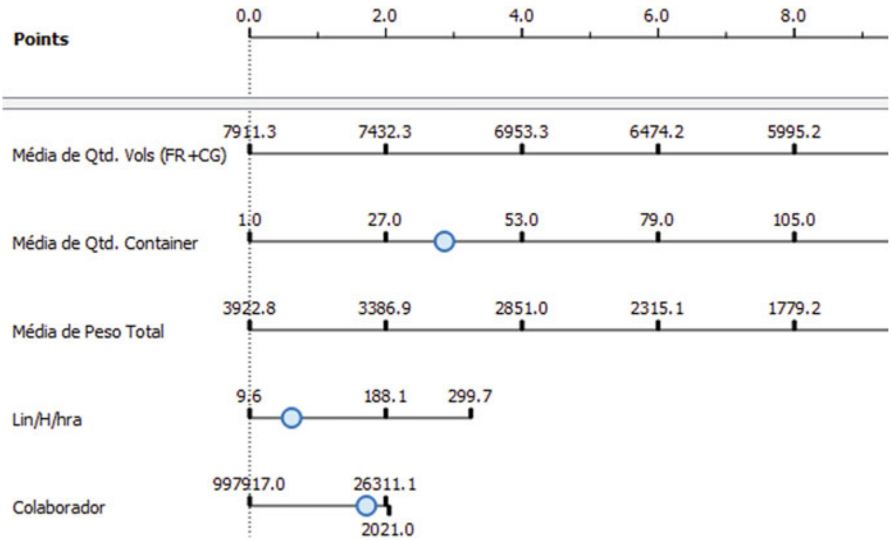

Fig. 3 Nomogram for Logistic Regression

Table 1 Predictive Model Accuracy

Model	AUC	CA	F1	Precision	Recall
Random Forrest	1000	0,997	0,997	0,997	0,997
Naive Bayes	0,977	0,900	0,901	0,904	0,900
LogisticRegression	0,925	0,868	0,869	0,874	0,868

Considering that H0: $b = 0$ and H1: $b \neq 0$, the independent variables contribute significantly to the Binary Regression model (Sig. 0.000).

The results obtained with the Logistic Regression are presented using a nomogram. The nomogram is used to graphically demonstrate equations with two or more variables, facilitating their visualization and understanding. The nomogram of the variables in question shows that the variable most related to the categorical variable, whether or not the employee meets the productivity goal, is the average amount of volumes (CG + Frac).

From Fig. 3, the three most important indicators for the picking model are related to volume movement, and the least important are aligned with human performance indicators. It is also noticeable that the Line vs man/hour and employee indicators practically do not influence the model.

Still in the Orange Canvas software, as a way of testing the reliability of the variables, considered Table 1, using the Random Forest and Naive Bayes methods. The Random Forest method obtained the best precision result, however, the 3 analysis methods obtained very satisfactory results, evidencing the reliability of the data and precision in the simulations.

Until this stage of the analysis, it is possible to infer that the model has an optimal fit, considering the use of the three Widgets. It is worth mentioning the performance of the Random Forest tool, which reached almost perfection in terms of adjustment accuracy. It is also possible to deduce that the variables related to the human factor are significant for understanding what is important to measure productivity in the picking area. It is the variables related to the volume handled that are most important for the identification of performance in the order picking system.

5 Conclusion

In this study, the number of separated volumes and the weight of the separated products were presented as more robust indicators than the value of the productivity of each employee per hour worked. The research findings suggest that these 2 indicators should always be prioritized when evaluating indicators in order picking operations. Suggests also that such indicators are more efficient for verifying order picking performance than those related to human performance. There are some theoretical and practical explanations for why this pattern is more suitable. The most accepted point is that human resource is still seen as a high cost in warehouses, nothing more natural than associating it with performance as man vs hour, and this seems to be a mistake.

Given the dynamism of the volume separation process, with numerous variables involved (batch size, operator physical stress, injuries, demand variability, seasonality and learning effect) it is highly complex to evaluate indicators seen here as subjective.

It is possible to delimit this study for use in warehouses with the characteristics of high turnover and little automation. Generalizations must obey the advanced automation criterion, as the use of human force prevailed in this research. In this case there is no use of robots, for example. It is suggested as an agenda for future research, analyzing other situations and other models of warehouses and even other organizational cultures.

References

1. S. Winkelhaus, F. Sgarbossa, M. Calzavara, and E. H. Grosse, "The effects of human fatigue on learning in order picking: an explorative experimental investigation," IFAC-PapersOnLine, vol. 51, no. 11, pp. 832–837, 2018, https://doi.org/10.1016/j.ifacol.2018.08.442.
2. E. H. Grosse, C.H. Glock & W.P. Neumann. Human factors in order picking: a content analysis of the literature. International Journal of Production Research, 55(5), 1260–1276, 2017. https://doi.org/10.1080/00207543.2016.1186296.
3. D. F. Murad, W. Ratnasari, B. Y. Saputra, and B. D. Wijanarko, "Warehouse Management System for Smart Digital Order Picking Systems," IJNMT (International J. New Media Technol., vol. 6, no. 2, pp. 74–80, Jan. 2020, https://doi.org/10.31937/ijnmt.v6i2.1215.

4. D. Loske & M. Klumpp. Smart and efficient: Learning curves in manual and human-robot order picking systems. IFAC-PapersOnLine, 53(2), 10255–10260, 2020. https://doi.org/10.1016/j.ifacol.2020.12.2757.
5. Y. Bukchin, E. Khmelnitsky, & P. Yakuel. Optimizing a dynamic order-picking process. European Journal of Operational Research, 219(2), 335–346, 2012. https://doi.org/10.1016/j.ejor.2011.12.041.
6. R. L. Daniels, J. L. Rummel & R. Schantz. A model for warehouse order picking. European Journal of Operational Research, 105(1), 1–17, 1998. https://doi.org/10.1016/S0377-2217(97)00043-X.
7. J. A. Tompkins, J.A.White, Y.A.Bozer & J. M.A.Tanchoco. Facilities planning (John Wiley & Sons (ed.)), 2010.
8. F. Sgarbossa, E.H. Grosse, W.P.Neumann, D. Battini & C.H.Glock. Human factors in production and logistics systems of the future. Annual Reviews in Control, 49, 295–305, 2020. https://doi.org/10.1016/j.arcontrol.2020.04.007
9. A. Pasparakis, J. de Vries, and M. B. M. R. de Koster, "In Control or under Control? Human-Robot Collaboration in Warehouse Order Picking," SSRN Electron. J., 2021, https://doi.org/10.2139/ssrn.3816533.
10. P. Atchade-Adelomou, G. Alonso-Linaje, J. Albo-Canals, and D. Casado-Fauli, "Qrobot: A quantum computing approach in mobile robot order picking and batching problem solver optimization," Algorithms, vol. 14, no. 7, pp. 1–27, 2021, https://doi.org/10.3390/a14070194.
11. E. H. Grosse, C. H. Glock, M. Y. Jaber, and W. P. Neumann, "Incorporating human factors in order picking planning models: framework and research opportunities," Int. J. Prod. Res., vol. 53, no. 3, pp. 695–717, Feb. 2015, https://doi.org/10.1080/00207543.2014.919424.
12. De Koster, R., Le-Duc, T., & Roodbergen, K. J. (2007). Design and control of warehouse order picking: A literature review. European Journal of Operational Research, 182(2), 481–501. https://doi.org/10.1016/j.ejor.2006.07.009.
13. C. G. Petersen and G. Aase, "A comparison of picking, storage, and routing policies in manual order picking," Int. J. Prod. Econ., vol. 92, no. 1, pp. 11–19, Nov. 2004, https://doi.org/10.1016/j.ijpe.2003.09.006.
14. T. De Lombaert, K. Braekers, R. De Koster, and K. Ramaekers, "In pursuit of humanised order picking planning: methodological review, literature classification and input from practice," Int. J. Prod. Res., pp. 1–31, Jun. 2022, https://doi.org/10.1080/00207543.2022.2079437.
15. C. Phyllis, "Determination of Performance Indicators for Warehouse Evaluation: A Case of Medium Sized Warehouses in Nakuru Town," J. Procure. Supply Chain, vol. 5, no. 2, pp. 32–38, Nov. 2021, https://doi.org/10.53819/81018102t5034.
16. N. Y. E. Sanchez, P. Y. S. Santos, G. E. M. Lastra, J. C. Q. Flores, and J. C. A. Merino, "Implementation of Lean and Logistics Principles to Reduce Non-conformities of a Warehouse in the Metalworking Industry," in 2021 10th International Conference on Industrial Technology and Management (ICITM), Mar. 2021, pp. 89–93. https://doi.org/10.1109/ICITM52822.2021.00024.
17. N. Boysen, K. Stephan, and F. Weidinger, "Efficient order consolidation in warehouses: The product-to-order-assignment problem in warehouses with sortation systems," IISE Trans., vol. 54, no. 10, pp. 963–975, Oct. 2022, https://doi.org/10.1080/24725854.2021.2004336.
18. F. Butollo, U. Jürgens, and M. Krzywdzinski, "From lean production to industrie 4.0: More autonomy for employees?," Digit. Ind. Between Domin. Emancip., pp. 61–80, 2019, https://doi.org/10.1007/978-3-030-28258-5_3.
19. L. M. Rose, U. E. Orrenius, and W. P. Neumann, "Work Environment and the Bottom Line: Survey of Tools Relating Work Environment to Business Results," Hum. Factors Ergon. Manuf. Serv. Ind., vol. 23, no. 5, pp. 368–381, Sep. 2013, https://doi.org/10.1002/hfm.20324.
20. A. Sobhani, M. I. M. Wahab, and P. W. Neumann, "Integrating Ergonomics Aspects Into Operations Management Performance Optimization Models: A Modeling Framework," IIE Trans. Occup. Ergon. Hum. Factors, vol. 4, no. 1, pp. 19–37, Jan. 2016, https://doi.org/10.1080/21577323.2016.1178190.

21. G. M. Breen & J. Matusitz. The contributions of state attorneys general to homeland security matters. Journal Of Homeland Security And Emergency Management, 5(1 WE-Social Science Citation Index (SSCI)), 2008.
22. I. Žulj, C.H. Glock, E.H. Grosse & M. Schneider. Picker routing and storage-assignment strategies for precedence-constrained order picking. Computers & Industrial Engineering, 123, 338–347, 2018. https://doi.org/10.1016/j.cie.2018.06.015
23. N. H. Karim, N. S. F. Abdul Rahman & S.F.S. Syed Johari Shah. Empirical Evidence on Failure Factors of Warehouse Productivity in Malaysian Logistic Service Sector. The Asian Journal of Shipping and Logistics, 34(2), 151–160, 2018. https://doi.org/10.1016/j.ajsl.2018.06.012
24. De Marco, A., & Mangano, G. (2011). Relationship between logistic service and maintenance costs of warehouses. Facilities, 29(9/10), 411–421. https://doi.org/10.1108/02632771111146323
25. A. Johnson, W.-C Chen & L. F. McGinnis. Large-scale Internet benchmarking: Technology and application in warehousing operations. Computers in Industry, 61(3), 280–286, 2010. https://doi.org/10.1016/j.compind.2009.10.006
26. A. Matopoulos & M. Bourlakis. Sustainability practices and indicators in food retail logistics: findings from an exploratory study. Journal on Chain and Network Science, 10(3), 207–218, 2010. https://doi.org/10.3920/JCNS2010.x179
27. F. H. Staudt, G. Alpan, M. Di Mascolo & C. M. T Rodriguez. Warehouse performance measurement: a literature review. International Journal of Production Research, 53(18), 5524–5544, 2015. https://doi.org/10.1080/00207543.2015.1030466
28. N. S. F Abdul Rahman, N. H. Karim, R. Md Hanafiah, S. Abdul Hamid & A. Mohammed. Decision analysis of warehouse productivity performance indicators to enhance logistics operational efficiency. International Journal of Productivity and Performance Management, 2021. https://doi.org/10.1108/IJPPM-06-2021-0373.
29. M. L. Domingues, V. Reis & R. Macário. A Comprehensive Framework for Measuring Performance in a Third-party Logistics Provider. Transportation Research Procedia, 10, 662–672, 2015. https://doi.org/10.1016/j.trpro.2015.09.020.
30. S. Sikström and M. Y. Jaber, "The Depletion–Power–Integration–Latency (DPIL) model of spaced and massed repetition," Comput. Ind. Eng., vol. 63, no. 1, pp. 323–337, Aug. 2012, https://doi.org/10.1016/j.cie.2012.03.005.
31. K. D. Vohs, R. F. Baumeister, and B. J. Schmeichel, "Deepening our Understanding of Depletion: New Causes, Boundaries, and Processes," J. Consum. Res., vol. 42, no. 1, pp. 215–219, 2014, https://doi.org/10.1086/429607.
32. M. Muraven and R. F. Baumeister, "Self-regulation and depletion of limited ressources: Does self-control remble a muscle?," Psychol. Bull., vol. 126, no. 2, pp. 247–259, 2000, https://doi.org/10.1037//0033-2909.126.2.247.
33. M. T. Gailliot, R. F. Baumeister, M. T. Gailliot, and R. F. Baumeister, "The Physiology of Willpower : Linking Blood Glucose to Self-Control," Personal. Soc. Psychol. Rev., vol. 11, no. 4, pp. 303–327, 2007, https://doi.org/10.1177/1088868307303030.
34. R. F. Baumeister, M. Gailliot, and C. N. Dewall, "Self-Regulation and Personality : How Interventions Increase Regulatory Success, and How Depletion Moderates the Effects of Traits on Behavior," J. Pers., no. December 2006, pp. 1774–1802, 2006, https://doi.org/10.1111/j.1467-6494.2006.00428.x.
35. S. Winkelhaus, F. Sgarbossa, M. Calzavara, and E. H. Grosse, "The effects of human fatigue on learning in order picking: an explorative experimental investigation," IFAC-PapersOnLine, vol. 51, no. 11, pp. 832–837, 2018, https://doi.org/10.1016/j.ifacol.2018.08.442.
36. D. Battini, C. H. Glock, E. H. Grosse, A. Persona, and F. Sgarbossa, "Human energy expenditure in order picking storage assignment: A bi-objective method," Comput. Ind. Eng., vol. 94, pp. 147–157, Apr. 2016, https://doi.org/10.1016/j.cie.2016.01.020.
37. A. R. Ahmadi Keshavarz, D. Jaafari, M. Khalaj, and P. Dokouhaki, "A Survey of the Literature on Order-Picking Systems by Combining Planning Problems," Appl. Sci., vol. 11, no. 22, p. 10641, Nov. 2021, https://doi.org/10.3390/app112210641.

38. S. Zhong, V. Giannikas, J. Merino, D. McFarlane, J. Cheng, and W. Shao, "Evaluating the benefits of picking and packing planning integration in e-commerce warehouses," Eur. J. Oper. Res., vol. 301, no. 1, pp. 67–81, Aug. 2022, https://doi.org/10.1016/j.ejor.2021.09.031.
39. L. Breiman. Random forests. Machine Learning, 45, 5–32, 2001. https://doi.org/10.1201/9780429469275-8.
40. G. I. Webb. Encyclopedia of Machine Learning and Data Mining. Encyclopedia of Machine Learning and Data Mining, April, 2016. https://doi.org/10.1007/978-1-4899-7502-7
41. E. Christodoulou, J. Ma, G. S. Collins, E. W. Steyerberg, J. Y. Verbakel, and B. Van Calster, "A systematic review shows no performance benefit of machine learning over logistic regression for clinical prediction models," J. Clin. Epidemiol., vol. 110, pp. 12–22, Jun. 2019, https://doi.org/10.1016/j.jclinepi.2019.02.004.

Machine Learning Applied to Industrial Assembly Lines: A Bibliometric Study

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Abstract Industrial processes have been progressively incorporating technologies such as web 2.0 communications, increased automation, the use of smart devices, and the incorporation of data obtained from such devices to improve numerous aspects of manufacturing. Recently, data-driven approaches based on Machine Learning algorithms and models have begun to be used increasingly. Given their excellent results in software-related problems, it is unsurprising that many of these technologies are being applied and tested in new products and the industrial environment. Examples can range from utilization as a core technology for self-driving cars to a complete quality assurance system for industrial plants. This study aims to perform a bibliometric analysis to investigate research related to the employment of machine learning in industrial assembly lines between the years 2017 and 2022.

Keywords Assembly Lines · Machine Learning · Bibliometric Analysis

1 Introduction

The incorporation of several new technological paradigms, such as Manufacturing 2.0, Industry 4.0, Smart Factories, and the Internet of Things, is increasing in usage due to how these concepts make the manufacturing process flexible, adaptable, customizable, and traceable [1]. Application of technologies related to these

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concepts has been increasing significantly in the last decade, but even further in the last 5 years, considering the major hit to the digital economy caused by the Covid-19 pandemic, which reduced the workforce and provoked instability in multiple supply chains.

Machine learning (ML) is a subsection of Artificial Intelligence (AI) that imparts the system the benefits of automatically learning from concepts and knowledge without being explicitly programmed [2]. The rapid development of new models and techniques in Machine Learning has given rise to numerous technologies that have been steadily being used to enhance processes in multiple areas of engineering. ML can be used both at the center of solutions or as part of their production process, increasing performance and ensuring quality, and improving the execution of less automatized tasks, even in the context of Industry 4.0.

Assembly lines are the flow oriented production systems where certain production equipment is used to perform workpiece operations. The equipment used for performing operations on workpieces in assembly lines is placed in several areas around the assembly line, called stations [3]. These lines, both automated and manual, have been incorporating data-driven approaches to improve the production of a wide set of products. It requires that assembly processes be modeled to allow a prevalent response to these problems, which can be considered optimization problems and consequently require the adoption of mathematical or computational methods to optimize their cost, efficacy, efficiency, and quality.

Specifically, machine learning methods have been demonstrably effective at analyzing complex systems in manufacturing, given that multiple tasks related to these domains match tasks for which these methods have been proposed. The matches between manufacturing tasks and machine learning methods deal with challenges that are met by production lines frequently, such as Production Planning and Control [4], quality regulations [5], quality assurance [6] fault detection [7], modeling and energy consumption optimization [8].

This article aims to find relevant theoretical frameworks and research trends, focusing on investigating the application of ML in assembly lines by developing a bibliometric study. It explores scientific research on artificial intelligence, machine learning, deep learning, and other keywords generally associated with applications in this area.

The rest of this article is divided into three sections: Sect. 2 details the methodology applied to this study, Sect. 3 presents the most relevant results obtained and discusses the main findings, and Sect. 4 concludes the paper.

2 Methodology

A bibliometric analysis consists of a review methodology usually performed to identify core research, authors, and other characteristics of interest and the relationships between them, detailing quantitative aspects of its subject of interest. It started as a statistical tool for analyzing bibliographic data made necessary by the large increase in journals and scientific papers. Only lately, due to a change of perspective, bibliometrics has become a common tool for the quantitative evaluation of scientific research [9].

This type of analysis is usually performed in a computer-assisted environment. In this specific case, two tools were used: the first one was VOSViewer (1.6.19) [10], and the second one was the R package bibliometrix (4.1.0) [11]. Both were employed to analyze, compute bibliometric relationships, structures, metrics, and to visualize data.

2.1 Platforms and Databases

The first step in a bibliometric analysis is the platform or database selection to extract a collection of scientific papers related to a subject. As such, the platforms and databases used in this article were Elsevier's Scopus and Clarivate's Web of Science databases. These databases were chosen because they are reliable sources of world-wide scientific articles and have many publications. However, they do not share a standard for describing publications. Furthermore, some fields descriptive of publications might be missing or be processed differently in both databases. Tables 1 and 2 show a summary of all parameters for each of the following subsections.

Table 1 Query and Filtering Protocol

Search Criteria	
Databases	Elsevier Scopus and Clarivate Web of Science
Timespan	2017 to 2022
Language	English, French, Spanish and Portuguese
Operators	'AND', 'OR' and "" '
Publication Type	Articles, Conference Papers
Search Fields and Keywords	
Search Fields	TITLE - ABSTRACT - KEYWORDS
Terms	assembly, ergonomics, "deep learning", "machine learning", "artificial intelligence", "engineering", "analytics".
Final String	TITLE-ABS-KEY (assembly OR ergonomics) AND ("deep learning" OR "machine learning" OR "artificial intelligence") AND ("engineering" OR "analytics")

Table 2 Total documents after exclusion

Filtered corpus for analysis	
Total documents found in both bases:	741
Duplicated documents (appeared in both databases)	67
The final amount of documents	**674 documents**

2.2 Query Protocol

Following the platform and database selection, defining a query string that relates keywords associated with the subject of interest is essential. It is also done through the search engines made available by selected platforms. Then this query string is constructed by assembling a set of words connected to operators (AND, OR, among others). The resulting constructed query string was:

(assembly OR ergonomics) AND ("deep learning" OR "machine learning" OR "artificial intelligence") AND (engineering OR analytics).

Given that this study is interested in models, tasks, techniques, and applications, these were not specified. Also, double quotes were used to restrict specific keywords to their exact meaning, while other keywords were left without quotes so that similar keywords could be returned. Also, the keywords: assembly, ergonomics, engineering, and analytics were employed to indirectly focus the search on applications because the other keywords often return theoretical advances in Computer Science and Artificial Intelligence.

2.3 Filtering

The resulting string search totalized 741 documents after the timespan, and publication type filters were applied. A hundred and fifteen of these documents were from the Scopus database, and six hundred and twenty-six from Web of Science, with sixty-seven duplicated documents excluded from the collection. Table 2 shows the number of filtered documents as well as the remaining documents after the process.

2.4 Bibliometric Processing

After the search is applied to the databases and all the filters selected, we could extract data about the documents containing details about each publication, such as year of publication, number of citations, and title of publication, among many others. This extract was then formatted to the Web of Science format and loaded onto VOSViewer. Afterwards, multiple bibliometric analyses available in this software were applied to the extracted data, namely: visualization of the bibliometric network, analysis of authorship, co-authorship, bibliographic coupling, analyses by country, and co-citation. The results from these analyses are presented in the following section.

3 Results

The main findings related to the proposed methodology are discussed in this section. From the 626 documents obtained, an overview of the research being developed can be ascertained.

3.1 Evolution of Publications by Year

As can be observed in Fig. 1, there has been a steady linear increase in the number of publications from 2017 to 2022, which suggests evidence of a trend in research of machine learning usage due to research interest in manufacturing 4.0, smart manufacturing, and other directly connected concepts.

It is also interesting to note the significant increase in publications in 6 years, considering that 2017 had 17 publications and 2022 had 197. It accumulated an increase of 1129.41%, which suggests that these subjects remain of great academic relevance.

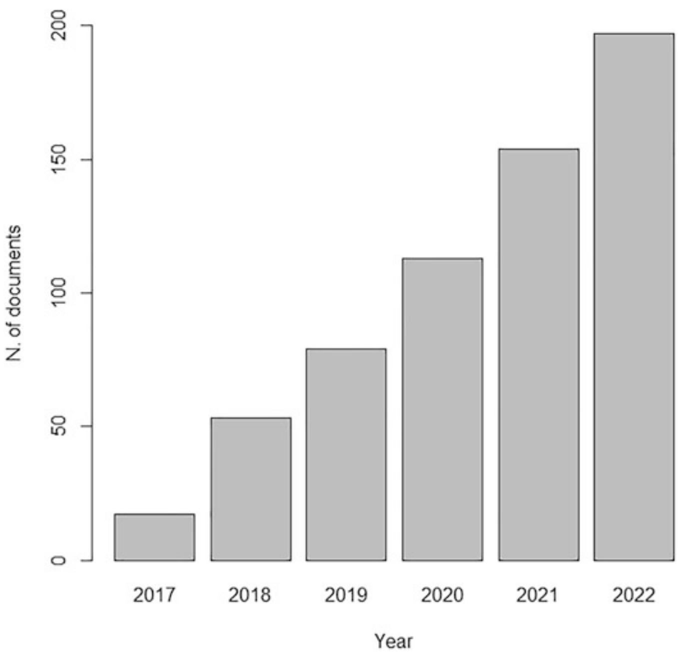

Fig. 1 Number of publications between 2017–2022

3.2 Most Cited Papers

The top 10 most cited papers correspond to almost 30% of all citations in the collection. Table 2 details these documents. The observed metrics associated with each paper are shown in Table 3.

It is interesting to note that there are multiple bases in this most cited set of documents and articles that perform a range from basic to applied research. The most cited article, basic research, leverages Machine Learning/Deep Learning algorithms such as convolutional neural networks to solve a high-complexity problem in

Table 3 Top 10 most cited documents in the collection

Authors	Title	N. Citations	Publication	JCR
Carrasquilla, J. and Melko, R. G. (2017)	Machine Learning Phases of Matter	764	Nature Physics	19.252
Li, L. Z. et al. (2018)	Deep Learning for Smart Industry: Efficient Manufacture Inspection System with Fog Computing	208	IEEE Transactions on Industrial Informatics	10.680
Wang, L. et al. (2019)	Symbiotic Human-Robot Collaborative Assembly	136	CIRP Annals-Manufacturing Technology	4.072
Syafrudin, M. et al. (2018)	Performance Analysis of IoT-based sensor, Big Data Processing and Machine Learning Model for Real-time Monitoring System in Automotive Manufacturing	124	Sensors	3.190
Musil, F. et al. (2018)	Machine Learning for the Structure-Energy-Property Landscapes of Molecular Crystals	115	Chemical Science	9.529
Gasparrini A. J. et al. (2019)	Persistent Metagenomic Signatures of Early-Life Hospitalization and Antibiotic Treatment in the Infant Gut Microbiota and Resistome	97	Nature Microbiology	30.755
Zheng, W. et al. (2019)	Deep-Learning Contact-map Guided Protein Structure Prediction in CASP13	95	Proteins-Structure Function and Bioinformatics	3.629
Steele, A. J. et al. (2018)	Machine Learning Models in Electronic Health Records can Outperform Conventional Survival Models for Predicting Patient Mortality in Coronary Artery Disease	87	PLoS One	3.608
Yao, Z. P. et al. (2021)	Inverse Design of Nanoporous Crystalline Reticular MAterials with Deep Generative Models	86	Nature Machine Intelligence	25.401
Song, W. C. et al. (2019)	Prophage Hunter: an Integrative Hunting Tool for Active Prophages	86	Nucleic Acids Research	18.338

condensed-matter physics, a type of usage widely similar to the other articles in the collection [12].

3.3 Publications by Country

To identify the top 10 countries with more publications about the subjects of this analysis, Fig. 2 presents a bar chart with the number of publications by country. The three most productive countries are the United States, China, and the United Kingdom, responsible for 53.35% of all articles in the collection. The remaining 46.65% is divided between other countries: Korea, Italy, Germany, Canada, Japan, India, Australia, Czech Republic, Greece, Hungary, Malaysia, Poland, Ireland, Israel, Russia, Sweden, Switzerland, France, Portugal, Romania, Singapore, Austria, Belgium, Brazil, Colombia, Saudi Arabia, Serbia, Denmark, Slovakia, Turkey, Bangladesh, Egypt, Netherlands, Pakistan, Slovenia, Spain, Finland, Ghana, Lithuania, Luxembourg, Norway, Peru, South Africa, and Vietnam.

The United States leads the chart with 24.6% of all articles (154), followed by China with 19.96% (125), and the United Kingdom with 8.78% (55).

Brazil has published four articles, which amounts to 0.638% of the total production in the collection, focusing on basic research. However, there are examples of Brazilian researchers declared as other nationalities in the collection, which means these researchers work outside the country.

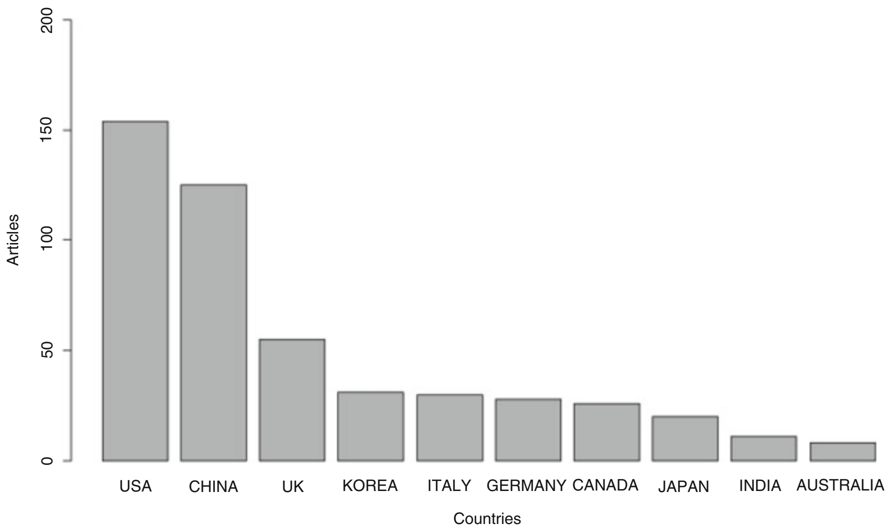

Fig. 2 Number of publications by country (author's country of origin)

3.4 Keyword Occurrence

A keyword co-occurrence map is built using the data collected to find the most frequent keywords that are correlated to the terms applied in the initial search. This keyword co-occurrence map was built with a minimum number of occurrences of a keyword set to 5 and used the keywords chosen by the authors.

From this map, a reconstruction of the most frequently used author keywords can be obtained, detailing mainly the query search terms described in Sect. 2.2 and keywords often used alongside them, revealing current research trends and topics of interest.

These keywords were selected from their presence in documents. The filtering criterion was a presence in at least five documents, and the search query keywords were omitted. The related keywords can be divided into two groups. The first corresponds to tasks in which machine learning is applied to achieve meaningful results in specific industrial assembly tasks. The second group is composed of keywords related to areas, models and technologies, as presented in Table 4.

From the components of each cluster, we can summarize their general concepts: there is a group of keywords related to general applications with a focus on assurance and quality control, there are multiple applications in robotics and Industry 4.0 technologies, and finally, there are also multiple computer science and software engineering concepts.

The relatedness of each keyword is based on the number of documents in which they occur together. Related areas are presented with stronger links, and keywords with high occurrence have nodes with greater radius. Thus, low-occurrence keywords related to high-occurrence keywords represent new directions in research, like Machine Learning and human-robot collaboration.

Table 4 Clustered keywords in Fig. 3

Groups	Keywords by Cluster
Tasks	Cyan Cluster: simulation, classification, decision support, quality control. Blue Cluster: manufacturing, production, data analytics, automation, scheduling, and robotics. Green Cluster: human-robot collaboration, collaboration, task analysis, service robots, robots, and robotic assembly. Yellow Cluster: training and feature extraction. Orange Cluster: safety and fault detection. Red Cluster: prediction, assembly line, smart factory, augmented reality, industry 4.0, industry 4, 0. Purple Cluster: self-assembly
Areas, Models, and Technologies	Green Cluster: transfer learning Yellow Cluster: convolutional neural networks, data models, predictive models Orange Cluster: random forest Red Cluster: digital twin, internet of things Brown Cluster: neural network, computer vision Purple Cluster: neural networks, big data, support vector machine, and data science.

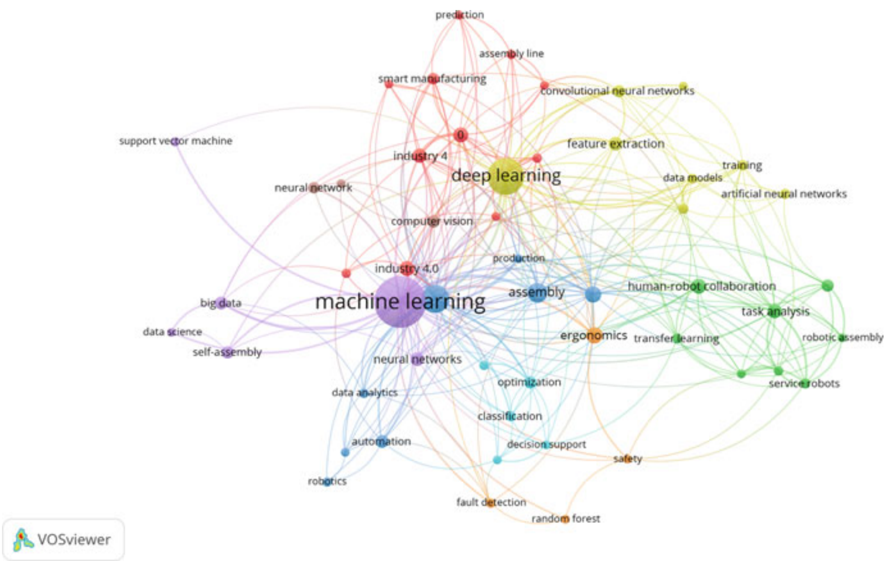

Fig. 3 Author keywords Co-occurrence map

3.5 Bibliographic Coupling

A bibliographic coupling chart shows when two works reference a third work. It is an indication that there is a probability that they treat a related or the same subject. This bibliographic coupling used five as the minimum threshold for the number of citations, which selected 257 documents and divided them between 55 clusters. The map in Fig. 4 evidences the biggest cluster among them, containing 192 documents.

It can be seen that distinct groups have been colored according to the degree of coupling between documents. For example [12], despite having the largest number of citations, this paper does not couple well with other documents signaling that it doesn't share subjects with other documents in the collection as its total number of links is 14. For comparison, papers [13] and [14] have a significantly lower number of citations but possess 35 and 36 links, respectively.

3.6 Author Co-Citation

Author co-citation has often been analyzed to ascertain the structure of a research domain. It provides a contrasting assessment of bibliography coupling as the first is forward-thinking and the second retrospective. It is also a metric that does not penalize authors over the chosen timespan of this study. To build the co-citation network, we have restricted the minimum citation number to 20 to obtain the widely most cited authors and investigate their relationships. Figure 5 below shows the resulting network.

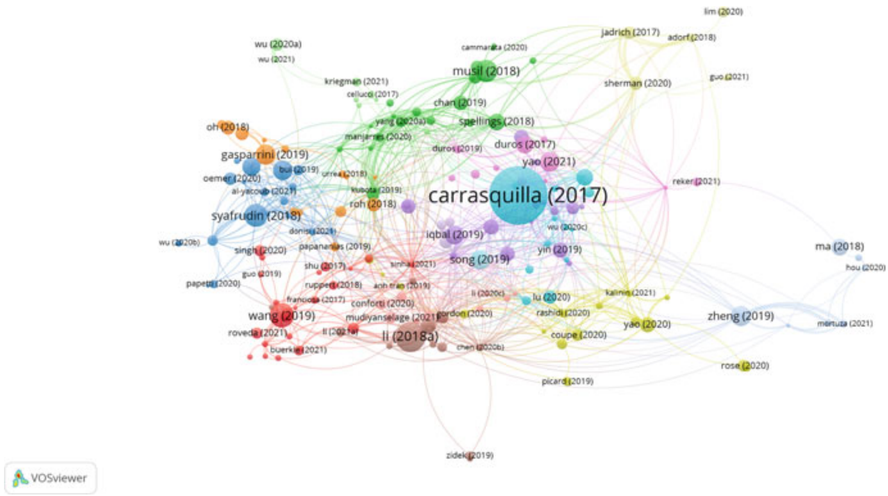

Fig. 4 Largest cluster in bibliographic coupling for documents with at least 5 citations

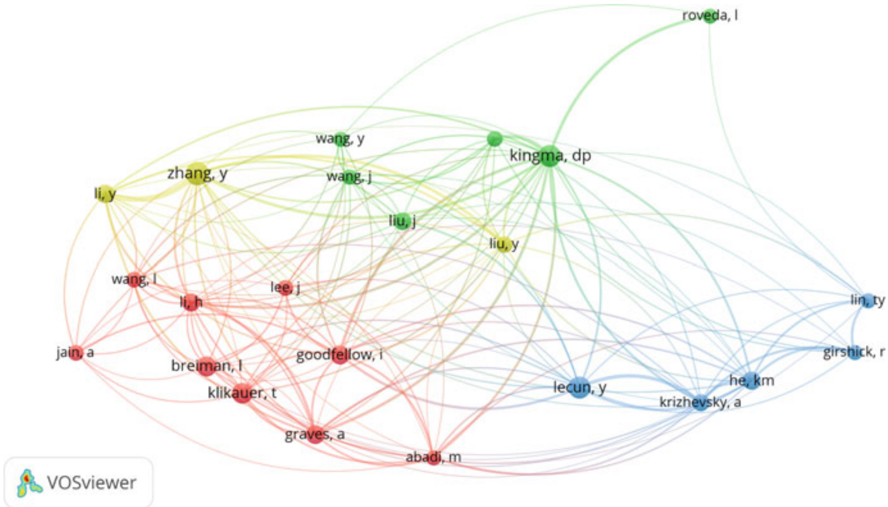

Fig. 5 Co-citation network of authors with at least 20 citations

In this analysis, it can be seen that multiple famed authors in Statistics, Machine Learning, and Deep Learning, such as Leo Breiman, who is known for Bagging algorithm and extensions of the Random Forest algorithm. Yann Lecun is also in this set. He is famous for making extensive advances in deep neural networks (DNN). Ian Goodfellow created generative adversarial neural networks (GANN). Alex Krizhevsky, the creator of AlexNet, the convolutional neural network that won the large-scale ImageNet competition. Finally, Diederik Kingma created the Variational Autoencoders and OpenAI. These authors are widely cited and co-cited among themselves.

4 Conclusion

This article presented a bibliometric study, which identified major and related publications about the application of ML and similar approaches in the Industrial context, focusing on Assembly Lines and Ergonomics. It also identified the most frequently used keywords related to those of the main query, mapping recent research and related areas of interest as well as challenges and approaches currently under investigation by academia. It provides opportunities for addressing openings in research areas in their first steps and evidences the greatest contributions so far.

Additionally, this study identifies the main researcher's country-wise. It ascertains a dramatic growth in the research topics, validating the need for further research both in breadth and depth for such a promising field of study.

Furthermore, it highlighted important contributions to basic and applied research both with regards to advances in theory and new practical developments.

Moreover, by observing the extent to which the research subject has progressed, it consolidates the research boundaries, which will guide the direction of future works.

References

1. Luque, A., Peralta, M. E., de las Heras, A., & Córdoba, A.: State of the Industry 4.0 in the Andalusian food sector. Procedia Manufacturing, Volume 13, 1199–1205 (2017)
2. Dargan, S., Kumar, M., Ayyagari, M.R., Kumar, G.: A Survey of Deep Learning and Its Applications: A New Paradigm to Machine Learning. Archives of Computational Methods in Engineering **27**, 1071–1092 (2020)
3. Saif, U., Guan, Z., Jahanzaib, M., Wang, B.: Survey of Assembly Lines and its Types. Frontiers of Mechanical Engineering, 9, (2014)
4. Cadavid, J. P. U., Lamouri, S., Grabot, B., Pellerin, R., Fortin, A.: Machine learning applied in production planning and control: a state-of-the-art in the era of industry 4.0. Journal of Intelligent Manufacturing, 31 (6), 1531–1558, 2020.
5. Ngo, Q. H., Schmitt, R.: A Data-based Approach for Quality Regulation. 1st edn. Universitätsbibliothek der RWTH Aachen, Aachen, Germany (2016)
6. Thamm, S., Huebser, L., Adam, T., Hellebrandt, T., Heine, I. Barbalho, S., Velho, S. K., Becker, M., Bagnato, V. S., Schmitt, R. H.: Concept for an augmented intelligence-based quality assurance of assembly tasks in global value networks, Procedia CIRP, Volume 97, 423–428. (2021)
7. Zhang, D., Xu, B., Wood, J.: Predict failures in production lines: A two-stage approach with clustering and supervised learning, In: 2016 IEEE International Conference on Big Data, Washington DC, USA, 2070–2074, (2016).
8. Golkarnarenji, G., Naebe, M., Badii, K., Milani, A.S., Jazar, R. N., Khayyam, H.: Production of Low Cost Carbon-Fiber through Energy Optimization of Stabilization Process. Materials 2018, 11, 385. (2018)
9. Salini, S.: An Introduction to Bibliometrics. In: Research Methods for Postgraduates (eds T. Greenfield and S. Greener). (2016).
10. van Eck, N. J., Waltman, L.: VOSViewer: Visualizing Scientific Landscapes [Software]. (2010). Available from https://www.vosviewer.com, last accessed 2023/01/31

11. Aria, M., Cuccurullo, C.: bibliometrix: An R-tool for comprehensive science mapping analysis, Journal of Informetrics, 11(4), pp 959–975, Elsevier. (2017)
12. Carrasquilla, J., Melko, R.: Machine learning phases of matter. Nature Physics 13, 431–434. (2017)
13. Sinha, S., Franciosa, P., Ceglarek, D.: Object Shape Error Response using Bayesian 3D Convolutional Neural Networks for Assembly Systems with Compliant Parts, 2020 IEEE 18th International Conference on Industrial Informatics (INDIN), Warwick, United Kingdom, 104–109. (2021)
14. Tao, W., Leu, M. C., Yin, Z.: Multi-modal recognition of worker activity for human-centered intelligent manufacturing, Engineering Applications of Artificial Intelligence, Volume 95. (2020)

Barriers, Enablers and Base Industry 4.0 Technologies of Digital Transformation in Supply Chains: An Inter-Country Comparison

Lia Denize Piovesan, Rodrigo Goyannes Gusmão Caiado, Renan Silva Santos, and Antônio Márcio Tavares Thomé

Abstract This paper aims to analyse the barriers and enablers of digital transformation in supply chains (SC) and discuss the relationships between these barriers and enablers to contribute to theory and practice in the industry 4.0 (I4.0) theme. A mixed-method approach was adopted, first adopting a tertiary review to identify key barriers and enablers associated with the digital transformation of SC. Then, a prioritisation was carried out with experts to refine and classify the identified barriers and enablers. Finally, they were sent for ranking by I4.0 specialists in Brazil and Germany. With the results, the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method was applied to obtain the interrelation of barriers and facilitators for the digital transformation of SC. The survey results show eight barriers, five enablers and their respective cause-and-effect relationships, which should help managers and decision-makers to better understand and implement I4.0 in their SCs in the context of both developed and developing economies. This article addresses the need for studies examining digital transformation in developing and developed economies. It is one of the first to examine barriers and enablers using combined tertiary analysis and the DEMATEL approach. Most studies analyse barriers and enablers on a sole basis. Those who analyse jointly do not use multicriteria methods for analysis.

Keywords Barriers · Enablers · Digital transformation · DEMATEL

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1 Introduction

The transformation that some industries have faced since the beginning of the twenty-first century led to the conception of the term Fourth Industrial Revolution (I4.0), characterised by the combination of physical and digital technologies, such as artificial intelligence, cloud computing, advanced robotics, augmented reality, additive manufacturing and Internet of Things (IoT) [1]. In today's dynamic business environment, digital transformation is no longer a choice for companies; it is imperative for survival [2]. The first three industrial revolutions profoundly transformed manufacturing [3]. The First Industrial Revolution arose due to mechanisation, the Second Industrial Revolution was driven by electricity, and the Third Industrial Revolution was motivated by information technology [4]. This paper analyses enablers, barriers, and the bases of I4.0 in Brazil and Germany.

Changes related to the I4.0 Revolution include a more ubiquitous mobile internet, smaller and more powerful sensors, and artificial intelligence and machine learning [5]. In Germany, discussions are focused on I4.0 and the impacts caused by the evolution of technologies in managing global value chains [5].

However, the limited adoption of digital technologies in companies [6, 7] may be related to barriers faced by digital transformation. According to Bag et al. [2] (p. 1), a question remains: "what might be the underlying reasons for the low adoption rate and unsustainability of Industry 4.0 projects?"

Since organisations must design digital transformation in the long term [8], analysing the barriers and enablers of I4.0 provides a starting point for governments and organisations to establish strategies to expand the adoption of digital technologies.

Barriers discourage companies from changing, as the need for I4.0 has been widely recognised. Several factors drive the transition to I4.0, and understanding these factors is significant in managing I4.0 [9]. Obiso et al. [9] analyse barriers and enablers and suggest a multicriteria decision-making approach, causal modelling and learning algorithms, among others, to expand the research. In addition, they suggest that a theoretical model of the structural relationships of enablers or barriers in elucidating the implementation of I4.0 be carried out in future work [9]. The prioritisation of enablers and barriers is also an important future agenda [9], as an ordering can support managerial decisions on resource allocation, financial and personnel, and strategy formulation, among others. Since adoption enablers and barriers offer insights for efficient and effective strategies to expedite I4.0 implementation, analysing them becomes crucial for management [9] (p. 215).

Chauhan and Singh [10] present barriers and enablers as emerging themes for I4.0 in SC Management. Raj et al. [11] study the barriers to implementing I4.0 and propose that the enabler factors should be studied in addition to the barriers. Among others, Kumar, Vrat and Shankar [12] use multi-criteria decision-making (MDCM) methods. The SWARA-WASPAS method was used to analyse barriers and propose strategies for implementing I4.0 in the context of a manufacturing facility in India.

The authors propose that the barriers be analysed in other countries and sectors in addition to applying other methods of multicriteria analysis [12].

Even with being a relatively current topic (the I4.0 term was created in 2011), there are several literature reviews on I4.0 [13]. In this way, it will be possible to carry out a tertiary review of the barriers and enablers of digital transformation. After the tertiary review, an MCDM method will be applied to analyse the relationships between barriers and enablers for adopting Industry 4.0. DEMATEL is applied to build a network relationship design to examine the internal relationship between attributes [14], being useful in the analysis of cause-and-effect relationships between the components of a system [15]. This method not only converts the interdependence relationships into a cause-and-effect group through matrices but also finds the critical factors of a complex structure system with the help of an impact relationship diagram [15].

Despite the extant literature on I4.0 enablers and barriers, there is a recurrent call for understanding the policies and strategies created in developing and developed countries, the differences in the diffusion processes of the adoption of new technologies [16], the contrasting paths of technological advancement in different countries [11]. Addressing this gap in the comparative analysis of I4.0 will contribute to advancing the state of knowledge in the field. With the backdrop of the dynamic capabilities [17] and structural contingency [18] theories, this study posits that I4.0 technologies are a competitive advantage for the companies implementing the adequate fit between the context they operate in and the structural arrangements to enhance the enablers and inhibit the barriers to I4.0 deployment.

Thus, this article aims to analyse, through a tertiary literature review, followed by a multicriteria analysis, how the barriers and enablers of digital transformation are related and thus answer two research questions:

RQ1: What are the barriers and enablers companies face in adopting Industry 4.0?
RQ2: What are the causalities and dependencies between these barriers and enablers and the hierarchical levels between them?

This study contributes to the extant literature on I4.0 digital transformation by identifying the most critical enablers and barriers and contrasting experts' perceptions of developed and emerging economies. It suggests the path to a smooth transition that is context-dependent and is expected to vary in Brazil and Germany, based on the theoretical lenses of dynamic capability and contingency theories. In addition, applying the DEMATEL method offers an orderly, objective and verifiable approach to identifying the cause-effect relationships between enablers and barriers, with practical implications for practitioners and policymakers alike.

The article is organised as follows: after this Introduction, in Sect. 2, related works and a literature review are presented. Section 3 describes the methodology used for the tertiary analysis of barriers and enablers and the multicriteria analysis method to analyse the interrelationships between barriers and enablers. The multicriteria analysis of barriers and enablers is presented in Sect. 4. Finally, Sect. 5 presents the conclusion, discussions, research gaps, implications for practitioners, and directions for future research.

2 Related Works

2.1 Theoretical Background

This research is engrained in the dynamic capabilities and the structural contingency theories. It posits that the digital transformation carried out by the I4.0 revolution is a differentiation factor in today's SC competitive scenario. Companies and their SC could innovate in new business models developing their dynamic capabilities by exploitation (with the incremental change of the existing capabilities) or exploration (with radical and disruptive new capabilities) [19]. For Teece [17] (p. 680), "dynamic capabilities are the skills, procedures, organisational structures, and decision rules that firms utilise to create and capture value. Managers must be able to sense opportunities, craft a business model to capitalise on them, and reconfigure their organisations, and sometimes their industries, as the business environment and technology shift." In this sense, the enabling factors and barriers for the digital transformation of companies and their SC are paramount for I4.0 technologies to become a dynamic capability fostering competitive advantages. The systems view of the structural contingency theory informs that performance results from the fit between the organisational context (i.e., firm size, country of origin, technology) and organisational structure [18, 20]. Inversely, a context-structure misfit is detrimental to performance. The trajectories for competitiveness are thus context-dependent. It is expected that enablers and barriers would not be perceived and interact in the same direction in different contexts, like in countries such as Brazil and Germany. Therefore, their perceptions and path to transform I4.0 technologies, organisation, processes, and decision-making rules into a dynamic capability enabling competitive advantages might differ.

2.2 Industry 4.0

In Germany, in 2011, at the Hannover fair, the term "Industry 4.0" was coined [5]. Terms such as digital transformation and advanced manufacturing are similarly used to describe the transformation that is taking place in organisations. However, the fourth industrial revolution describes a change that is not just about smart, connected machines and systems but has a much broader scope. Transformations, from genetic sequencing to nanotechnology, renewable energies to quantum computing, have driven the fourth revolution. And what makes this revolution different from previous ones is the fusion of these technologies and the interaction between the physical, digital, and biological domains [5]. Therefore, implementing the I4.0 vision will involve an evolutionary process that will progress at different rates in individual companies and sectors [4].

Industry 4.0 in the Supply Chain Management

With the rise of digital technologies, traditional SC can transform into digital SC. This transformation will bring efficiency and connection from product development, purchasing, manufacturing, logistics, and suppliers to delivering products or services to customers [21].

The digital transformation in SC is brought about by the convergence of two distinct lines of change. On the one hand, technologies and applications, such as cloud computing, intelligent sensors and cyber-physical systems, and IoT, which drive digital transformation, are increasingly being researched, tested and applied in real environments. But on the other hand, high expectations on the part of the agents involved (suppliers, customers, employees) encourage companies to develop more reliable and receptive SC [22].

In the digital SC, there is potential for interactions of each link with all other points in the network, allowing connectivity between areas that previously did not exist. In this model, communications are multidirectional, with digitisation being the network's core. Thus, the interconnection between processes traditionally disconnected from the CS is generated [23].

However, the lack of technical skills makes companies unaware of the potential of technologies. A study in Germany suggests that the autonomous ability to plan, organise and act, combined with the experience of the company and the workers, are crucial for the organisation's success [24]. In the early stages of transformation, companies tend to focus on individual technologies to improve operations [25]. In companies with digital maturity, that is, companies where digitisation has transformed processes, there is engagement, business models and digital strategies aimed at business transformation [25]. The digital strategy considers implementing technologies focused on business transformation, not just individual technologies with an operational focus [25]. In other terms, digitally mature companies have developed a dynamic capability to operate in the I4.0 environment.

A holistic approach to digital transformation in SC, based on a digital strategy and a digital operating model, will result in successful execution, enabling the development of capabilities and improved operational performance. In addition, digital SC offers broad information availability and integration, resulting in greater reliability, agility and effectiveness [26].

Such a reinvented SC is a next-generation SC: smart, connected and agile, with the customer at the centre. This SC is also the foundation of a smart business, which embraces constant technological change and profits from it [27].

The digitalisation of SC contributes to the management of the complexity of the SC. Furthermore, it accelerates the responsiveness to the market, with better performance of the flow of products and information, constituting a key factor for the SC to gain a competitive advantage [27]. Therefore, internal data integration and external integration with suppliers, customers and partners through digital technologies will be important at SC [28].

2.3 Technologies of Digital Transformation

I4.0 digital technologies allow the integration of data and information from different sources and locations to drive the production and distribution of goods and services [23]. The convergence of information and communication technologies with other technologies leverages digital transformation, even in traditional sectors such as manufacturing and agriculture [24]. The enabling technologies, such as Big Data Analytics, cloud computing, and the IoT, are foundational. Table 1 presents the main base technologies of I4.0.

The IoT, big data and cloud computing were considered digital enablers [9].

2.4 Enablers of the Industry 4.0 Adoption

Obiso [9] states that 'soft' enablers (e.g., social, economic, regulatory, organisational, and inter-organizational factors) are complex and structurally integrated within an organisation. Therefore, a better understanding of these enablers gives managers and practitioners insights into decision-making. Table 2 presents the tertiary analyses' enablers of the I4.0 adoption results.

Table 1 Technologies of Industry 4.0

Technology	Description	Code if enablers	Code if barriers
Big Data Analytics	Big Data Analytics involves the statistical examination and analysis of data that goes beyond gathering intelligence from generic data to uncover deep, actionable insights and make predictions autonomously or semi-autonomously [29].	C6	C9
Internet of Things (IoT)	IoT is an amalgamation of advanced software, cost-effective sensors, and network connectivity that allow objects to interact digitally. IoT involves connecting machines, facilities, fleets, networks, and even people to sensors and controls and feeding sensor data into advanced analytics applications and predictive algorithms [29].	C7	C10
Cloud Computing	A model that allows convenient, universal network access to a shared pool of computing resources that can be provisioned and released with minimal management effort or service provider interaction. Processing and storage resources are provided as utilities and can be granted and released by users via the Internet on demand.	C8	C11

Table 2 Enablers of the Industry 4.0 adoption

Enablers	Papers	Code
New business models	[9, 30]	C1
Cost reduction	[30]	C2
Government policies and regulations	[2, 31]	C3
Dynamic capabilities	[9, 32]	C4
Transformational leadership	[32]	C5

The descriptions of the enablers are in Appendix A

Table 3 Barriers to Industry 4.0 adoption

Barriers	Papers	Code
Lack of trained and qualified workforce	[11, 37–39]	C1
Lack of support from top management	[11, 30, 37, 38]	C2
Economic risk barriers	[9, 38, 39]	C3
Resistance to changing organisational culture	[11, 30, 38, 39]	C4
Unclear economic benefits	[9, 11, 30, 37]	C5
Lack of coordination between vertical and horizontal supply chain members	[9, 11, 38]	C6
Lack of support and government support	[37]	C7
Interoperability issues	[9, 32]	C8

The descriptions of the barriers are in Appendix A

2.5 Barriers to Industry 4.0 Adoption

The benefits of adopting I4.0 technologies are widely quoted in the literature, but more needs to be reported about its implementation and management guidelines [9]. In the context of Brazil, a study by the CNI (the Brazilian acronym for the National Confederation of Industries) [33] presents the main industry barriers to the adoption of digital technologies, namely: (i) implementation cost, (ii) difficulty in quantifying the return on investment, (iii) difficulty to integrate new technologies and software; and (iv) structure and culture of the organisation. Some studies bring barriers to I4.0 in isolation. Uncertainties about the return on investment are barriers to adopting I4.0 [24, 34, 35]. Barriers related to the skills of human resources and management support are presented in studies on the application of technologies in companies [36]. Table 3 presents the barriers resulting from the tertiary analysis.

3 Research Methodology

The research was carried out in two stages. In the first stage, a tertiary analysis was carried out to extract the barriers and enablers for I4.0 adoption from the literature. In the second stage, a multicriteria analysis of barriers and enablers was carried out based on the response of specialists, academics and professionals.

3.1 Tertiary Analysis of the Literature

The eight steps suggested by Thomé et al. [40] were followed with necessary adaptations to carry out the tertiary analysis of the literature. The research planning and formulation of the problem, step one of the literature review proposed by Thomé et al. [40], are presented in the introduction. In step two, the terms and databases to conduct the searches were defined. In addition, other terms were included to analyse the concept of I4.0 to expand the search results. Thus, aiming to analyse I4.0 broadly, we chose to use the related terms that characterise the digital transformation of SCs (Digital Transformation, I4.0, supply chain 4.0 and logistic 4.0).

To perform the tertiary review, only primary reviews were sought. Thus, according to Thomé et al. [41], the keywords that return literature reviews were used. Thus, the keywords used were: ((barrier*) OR (enabler*)) AND ("digital transformation" OR "industry 4.0" OR "logisti* 4.0" OR "supply chain* 4.0") AND ("research synthesis" OR "systematic review" OR "evidence synthesis" OR "research review" OR "literature review" OR "meta-analysis" OR "meta-synthesis" OR "mixed-method synthesis" OR "narrative reviews" OR "realist synthesis" OR "meta-ethnography" OR "state-of-the-art" OR "rapid review" OR "critical review" OR "expert review" OR "conceptual review"). Searches were limited to English-language articles and reviews. No time limit was adopted. The searches were conducted in titles, abstracts and keywords in the Scopus, Web of Science and Dimensions databases. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) were used to provide transparency for the literature review. This report was designed to transparently state why the review was carried out, how it was carried out, and the results found [42]. Figure 1 presents the PRISMA survey report.

In step three – data gathering, the barriers and enablers presented from the selected studies were extracted and grouped according to their occurrence. Then, the CRITIC method [43] was applied to rank the most cited barriers and enablers in the papers retrieved based on the Scopus number of citations. The result was a list of 54 barriers and 80 enablers.

The lists of barriers and enablers were then analysed by experts (academics and consultants) who selected the most significant ones from those listed, thus resulting in a list with eight barriers and five enablers. These eight barriers and five enablers will be used for multicriteria analysis.

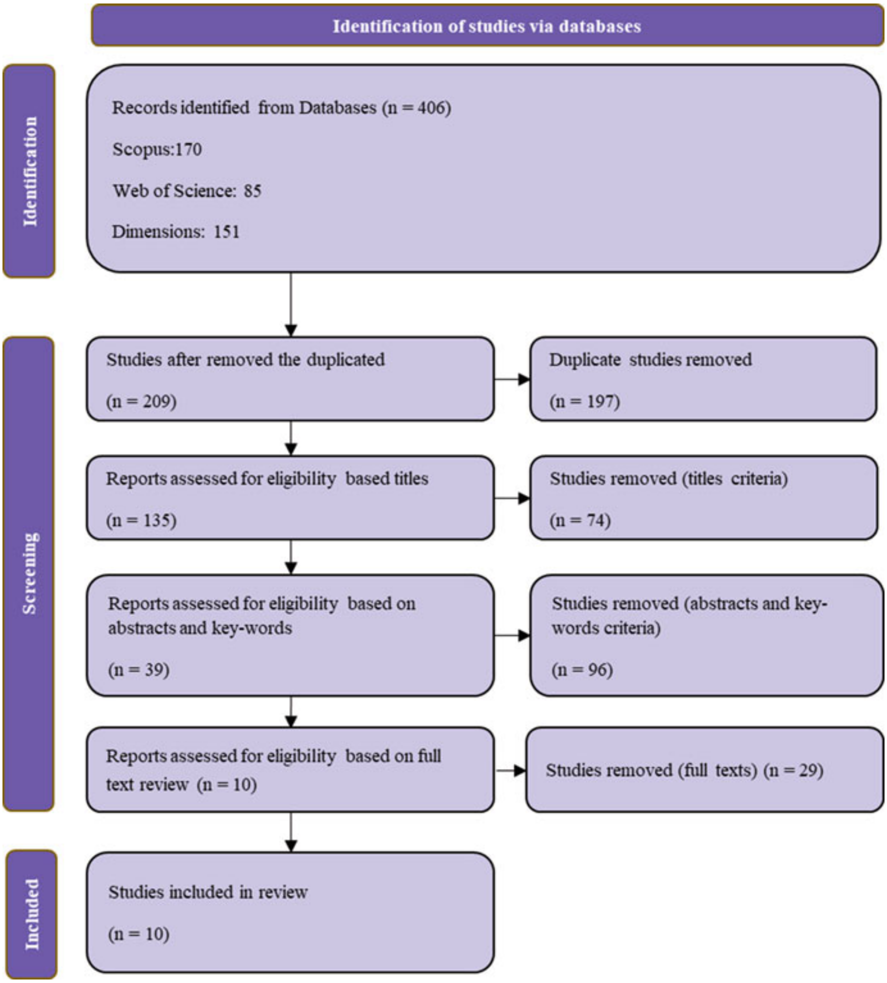

Fig. 1 Study obtained from the PRISMA perspective. (Adapted from PRISMA [42])

Step four, quality evaluation, was reinforced by including peer-reviewed articles only to gauge the quality of reviews selected for the tertiary review. Steps five and six, data analysis, synthesis and interpretation, are described in Sects. 3.2 and 4 of this paper. Step seven, presenting results, corresponds to this study. Finally, step eight of Thomé et al.'s [40] guidelines, updating the review, was deemed out of the scope of the tertiary review.

3.2 Multicriteria Analysis Using the DEMATEL Approach

For the MCDM analysis, the DEMATEL method was used. DEMATEL was first developed in 1971 by the Geneva Research Centre of the Battelle Memorial Institute, by Fonetla and Gabus, and is mainly used to study complex global issues [14, 15, 44]. The steps of the DEMATEL method used in this work are presented below [14]:

Step 1: Calculate the average matrix. Respondents were asked to indicate the direct influence they believe each barrier or driver has on each other according to a full scale ranging from 0 to 6. A higher score by a respondent indicates that element i exert a strong direct influence on element j. From the group of direct matrices of the respondents, it is possible to derive an average matrix M. Each element of this average matrix will, in this case, be the average of the same elements in the different direct matrices of the respondents.

Step 2: Calculate the Normalized Direct Relation Matrix. Equation 1 is used to normalize the direct relation matrix, and the k-index value is obtained using Eq. 2.

$$D = k.M \tag{1}$$

$$k = \max_{i,j}\left\{\frac{1}{\max\limits_{i}\sum\limits_{j=1}^{n}\left|m_{ij}\right|} \middle| \frac{1}{\max\limits_{j}\sum\limits_{i=1}^{n}\left|m_{ij}\right|}\right\} \tag{2}$$

Step 3: Calculate the total relation matrix. Equation 3 is used to calculate the attribute's total penetration value. When the $\lim X^l = [0]_{nxn}$ e 1 $l \to \infty$ as:

$$\begin{aligned} T &= D + D^2 + D^3 + \ldots + D^l \\ &= D\left(I + D + D^2 + D^3 + \ldots + D^{l-1}\right)(I - D)(I - D)^{-1} \\ &= D\left(I - D^l\right)(I - D)^{-1} \end{aligned} \tag{3}$$

In Eq. 3 (I) is the identity matrix. The total relation matrix is represented by Eq. 4:

$$T = D(I - D)^{-1} \tag{4}$$

Step 4: Calculate cause and effect values. In this step, calculations are made using the values of r and c, representing the sum of row and column values determined from Eqs. 5 and 6.

$$r = [r_i]_{nx1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{nx1} \quad ; i = 1, \ldots, n \tag{5}$$

$$c = [c_j]'_{nx1} = \left[\sum_{i=1}^{n} t_{ij}\right]'_{nx1} \quad ; j = 1, \ldots, n \tag{6}$$

Where t_{ij} indicates the amount of direct relationship for attribute i in attribute j.

In Eq. 6, $[c_j]'$ indicates the transposition of the value of column j, c_j represents the sum of the values of column j, indicating the effect of attribute j on other attributes, and r_i denotes the sum of values of line i, indicating the cause of attribute i in other attributes.

If $i = j$, the horizontal vector $(r_i + c_i)$ indicates the effect and impact of the ith attribute. In other words, when the $(r_i + c_i)$ value is greater, the attribute has more interaction with other attributes. The vertical vector $(r_i + c_i)$ indicates the influence and power of the ith attribute. If $(r_i + c_i)$ is positive, it is a cause variable and it is considered as an effect if the value is negative.

Step 5: Calculate the threshold value. The threshold value must be determined to draw the interrelationship map. Only equations whose values in the total relationship matrix are greater than the threshold value are plotted on the interrelation map. The threshold value is calculated by averaging the elements of the total ratio matrix according to Eq. 7.

$$a = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij}}{N} \tag{7}$$

Step 6: Build the interrelationship map. In this step, the interrelationship map is drawn for proper analysis of the final solution with the values of $(r_i + c_i)$ and $(r_i - c_i)$ for each attribute in relation to the value limit.

Step 7: Final classification of attributes. A possible structure and ordering of the factors are obtained using the interrelation map and arranging the values $(r_i + c_i)$ *and* $(r_i - c_i)$ in descending order, as depicted in Fig. 2.

4 Results

The respondents were separated by the country where they carried out their activities. Figure 3 presents the enablers and barriers identified together.

Figures 4, 5, 6, and 7 depict the cause-and-effect diagrams of respondents from Brazil and Germany on barriers and enablers of digital transformation in SCs.

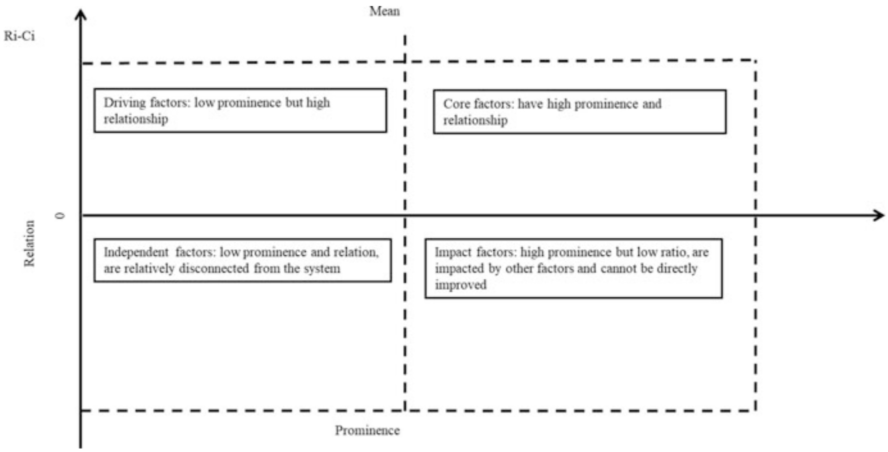

Fig. 2 Interrelationship Map of DEMATEL. (Adapted from [15])

Enablers

	C1	C2	C3	C4	C5	C6	C7	C8
C1	0.00	3.70	4.38	5.03	5.36	4.89	4.80	4.91
C2	4.15	0.00	3.74	3.42	4.22	3.06	3.59	3.85
C3	3.72	3.35	0.00	2.99	2.88	2.99	3.13	3.12
C4	5.38	3.77	2.99	0.00	5.11	4.20	4.61	4.51
C5	5.20	4.61	2.90	5.14	0.00	3.97	4.48	4.48
C6	5.45	4.30	3.85	4.80	4.07	0.00	5.14	5.24
C7	5.48	4.63	3.58	4.46	4.33	4.87	0.00	5.01
C8	5.24	4.73	3.48	4.31	3.95	5.22	5.07	0.00

0.00
1.00
2.00
3.00
4.00
5.00
6.00

Barriers

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1	0.00	4.43	4.73	5.03	4.13	4.33	2.68	4.22	4.33	4.56	4.36
C2	5.38	0.00	4.33	5.28	4.46	4.84	3.08	4.56	4.14	4.36	4.54
C3	3.73	4.56	0.00	3.92	5.36	4.01	4.04	2.68	2.63	3.02	3.02
C4	4.21	5.68	3.36	0.00	3.44	4.46	2.73	3.98	3.91	3.91	3.91
C5	3.56	4.98	4.25	3.81	0.00	3.81	3.35	3.13	4.00	3.65	3.95
C6	3.54	3.80	4.20	3.88	4.66	0.00	2.41	5.18	3.93	4.10	4.10
C7	3.42	3.40	4.18	3.12	3.48	2.79	0.00	2.92	3.06	3.06	3.06
C8	2.65	3.66	3.22	3.38	3.28	4.56	2.27	0.00	4.56	4.98	4.64
C9	3.91	3.80	3.25	3.82	3.31	3.84	2.83	4.59	0.00	5.07	4.87
C10	3.80	3.27	3.38	3.73	3.10	3.65	2.79	4.69	4.87	0.00	4.78
C11	4.07	3.69	3.58	3.73	3.50	4.07	2.99	4.49	4.76	4.78	0.00

0.00
1.00
2.00
3.00
4.00
5.00
6.00

Fig. 3 Enablers and Barriers of digital transformation in SC

The combined results of the two countries were analysed to understand if there was a difference in the responses. Figures 8 and 9 show the barriers and enablers interrelation map for all respondents.

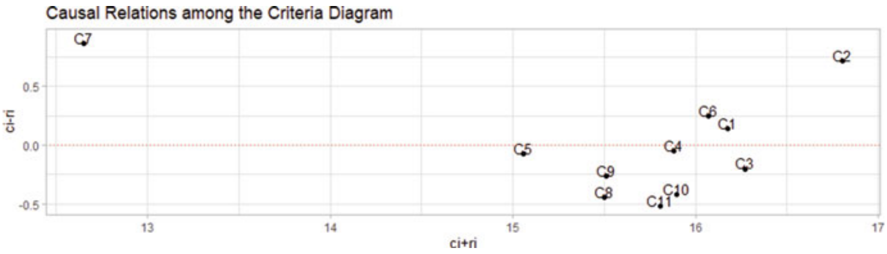

Fig. 4 Cause-Effect Diagram of Barriers from Brazil

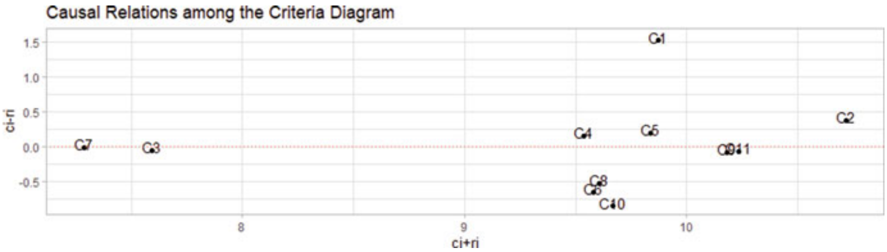

Fig. 5 Cause-Effect Diagram of Barriers from Germany

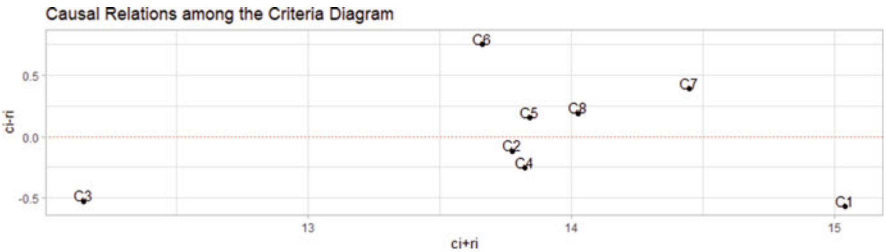

Fig. 6 Cause-Effect Diagram of Enablers from Brazil

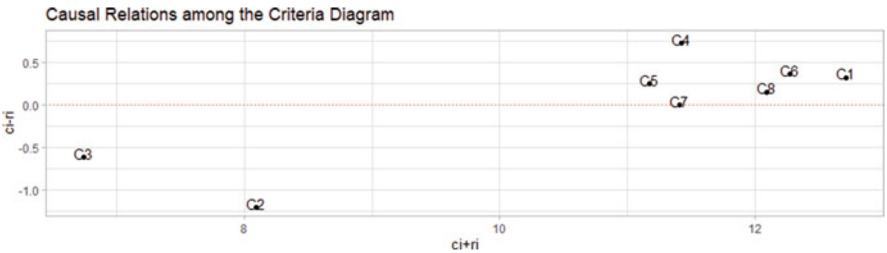

Fig. 7 Cause-Effect Diagram of Enablers from Germany

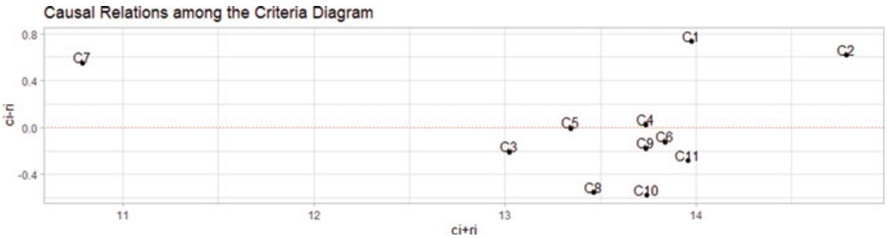

Fig. 8 Cause-Effect Diagram of Barriers Combined

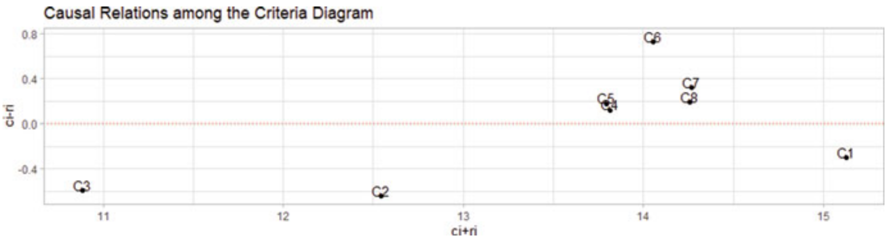

Fig. 9 Cause-Effect Diagram of Enablers Combined

Table 4 The DEMATEL map discussion for Barriers

Barriers	Brazil	Germany	Combined country
Core factors	C2, C6, C1	C1, C2, C4, C5	C1, C2, C4
Driving Factors	C7	None	C7
Impact factors	C3, C4, C5, C8, C9, C10, C11	C6, C8, C9, C10, C11	C5, C6, C3, C8, C9, C10, C11
Independent factors	None	C3, C7	None

Table 5 The DEMATEL map discussion for Enablers

Enablers	Brazil	Germany	Combined country
Core factors	C7, C6, C5, C8	C1, C4, C5, C6, C8, C7*	C4, C5, C6, C7, C8
Driving Factors	None	C7*	None
Impact factors	C1, C4, C2	None	C1
Independent factors	C3	C2, C3	C2, C3

Note: C7: it is impossible to define the barrier's position

Tables 4 and 5 present the results of the barriers and enablers, respectively, divided according to the classification by Si et al. [15].

For respondents in Brazil, the factors causing barriers were: Lack of trained and qualified workforce, Lack of support from top management, and Lack of coordination between vertical and horizontal SC members. For respondents in Germany, the first two factors were the same. Still, for them, the barrier Lack of coordination between vertical and horizontal SC members is not a causative factor, with

Resistance to changing organisational culture and Unclear economic benefits as a causative barrier.

There are digital technologies as an effect of the barriers in both analyses. Interoperability issues are an effect in the aggregation analysis by country and also in the combined analysis. Lack of government support appears with low prominence in all analyses, a driving factor for respondents in Brazil and the combined analysis and an independent factor for respondents in Germany.

For enablers, respondents in Brazil identified Transformational leadership and Big Data Analytics, the Internet of things and cloud computing as causal factors and new business models, Cost reduction and Dynamic capabilities as effects. For respondents in Germany, in addition to digital technologies, Dynamic capabilities and Transformational leadership are also considered a cause. For these respondents, the new business models are the effect of the other enablers. Government policies and regulations are an independent factor in all analyses.

New business models are an effect both for respondents in Brazil and for the combined analysis. For German respondents, new business models are a causal factor. Government policies and regulations are an independent factor; that is, it is a potentially disconnected enabler of the system.

Based on the analysis of the results, some propositions were created:

(i) Government policies and regulations as an enabler appear to be partially disconnected from the other barriers and enablers.
(ii) Lack of government support as a barrier has a high relationship with other barriers.
(iii) Enabling digital technologies are the cause of digital transformation.
(iv) New business models, Cost reduction and Government policies and regulations are effects of the enablers.

5 Conclusion

Despite extensive research on I4.0 in the SC, literature reviews on barriers and enablers still need to be completed. Analysis of barriers and enablers in the two countries showed differences in respondents' perceptions, allowing for some conclusions. Cost reduction is an effect for respondents in Brazil but an independent factor for respondents in Germany. The level of development of the two economies may explain this difference.

Lack of support and government support as a barrier and Government policies and regulations as an enabler appear with low prominence being partially disconnected from the other barriers and enablers. Interoperability issues are an effect in all the analyses. This result presents the barrier's characteristic, which is necessary to evaluate the barriers that cause interoperability problems.

This is the first article that jointly analyses barriers and drivers of digital technologies, to the authors' best knowledge. The study created the potential to analyse the relationship between barriers and enablers with digital enabling technologies, providing a deeper understanding of existing connections and their potential to trigger dynamic capabilities fostering competitive advantages differently in the perception of experts from the two countries.

This research is limited to only two countries. Another limitation is the restriction of the interviewees to academics and consultants. For future research, the analysis can be expanded to additional countries, and the survey can be expanded to practitioners working in the companies.

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Appendix A

Enablers	Definition
New business models	Refers to new value propositions through data-driven products and services, including increased customer orientation and service-based business models [9, 30].
Cost reduction	The cost reduction driven by I4.0 is manifested in reducing production costs, transaction costs in negotiating with suppliers and customers, logistical costs for transportation and storage of products, and contract administration.
Government Policies and Regulations	Government Policies and Regulations can drive I4.0 through incentives (e.g., fees, taxes) and funding, enhanced cybersecurity and electronic transactions in cloud computing, the internet of things, and large-scale analytics data [2, 31].
Dynamic Capabilities	Dynamic Capability is the company's ability to integrate, build and reconfigure internal and external competencies to deal with rapidly changing environments [45].
Transformational leadership	The ability of senior management to lead the transformation of digitalization processes involving different employees of different cultural profiles, technical training, and located in different departments of the company, as well as to lead change processes in the supply chain.

Barriers	Definition
Lack of Trained and Skilled Manpower	Industry employees and workers need training and development to update their technical skill sets. A successful application of new technologies requires a specialized workforce [11, 37–39]
Lack of support from top management	Top management may be reluctant to support I4.0 transformations due to a lack of vision or funding, leading to ineffective management of change

(continued)

Barriers	Definition
	processes inside and outside the company with partners in the supply chain [11, 37]. I4.0 changes are fast and require high support from top management for skills development, training, and cross-functional collaboration [30, 38].
Economic risk	The barriers related to economic risk are due to the low perception of productivity and economic gains, the high costs of digital transformation (people and equipment), and a perception that the returns on investment may not compensate for the transformation effort [9, 39]
Resistance to changing organizational culture	Cultural resistance to change can come from (i) the inertia of traditional operational performances, (ii) the aversion to change itself, (iii) the lack of knowledge of technologies and the gains of I4.0, (iv) the lack of skills and training to deal with big data and I4.0 technologies, (v) the cultural background of employees (employees and managers) [11, 30, 38, 39].
Unclear economic gains	Investors may be uncertain about the expected return on the large investments required in infrastructure and innovations by I4.0 technologies, with little clarity on digitization's cost-benefits and monetary gains [9, 11, 30, 37].
Lack of vertical and horizontal coordination between supply chain members	It refers to the difficulty of breaking down silos between departments in the company and between partners in supply chains. Vertical coordination takes place between factories, markets, and sales, while horizontal coordination is intra and inter-organizational [9, 11, 38].
Lack of government support	It specifically refers to the lack of government support in the form of funding and incentives (e.g., fees, taxes) for automating processes with I4.0 technology [37]
Interoperability issues	Interoperability refers to the ability of a system or product to perform the function properly when there are changes in machinery and equipment, even from different manufacturers [9]. The central idea behind interoperability is integration, which is also the main point of IoT and CPS technologies [46].

References

1. A. Ustundag and E. Cevikcan, *Managing The Digital Transformation*. Switzerland: Springer, 2018.
2. S. Bag, A. Telukdarie, J. H. C. Pretorius, and S. Gupta, "Industry 4.0 and supply chain sustainability: framework and future research directions," *Benchmarking*, vol. 28, no. 5, pp. 1410–1450, 2018.

3. S. Sivri and B. Oztaysi, "Data Analytics in Manufacturing," in *Managing The Digital Transformation*, Switzerland: Springer, 2018, p. 285.
4. H. Kagermann, W. Wahlster, and J. Helbig, "Recommendations for implementing the strategic initiative INDUSTRIE 4.0," Frankfurt, 2013.
5. K. Schwab, *The Fourth Industrial Revolution*. Cologny: World Economic Forum, 2016.
6. CNI, "Relatório Síntese da Pesquisa de Campo: Análise agregada dos resultados," Brasília, 2017.
7. N. Szozda, "Industry 4.0 and its impact on the Functioning of Supply Chains," *Sci. J. Logist.*, vol. 13, no. 4, pp. 401–414, 2017.
8. A. Scheer, "Whitepaper - Industry 4 . 0 : From vision to implementation," no. September, 2015.
9. J.-J. A. Obiso *et al.*, "Management of Industry 4.0-reviewing intrinsic and extrinsic adoption drivers and barriers," *Int. J. Technol. Manag.*, vol. 81, no. 3–4, pp. 210–257, 2019.
10. C. Chauhan and A. Singh, "A review of Industry 4.0 in supply chain management studies," *J. Manuf. Technol. Manag.*, vol. 31, no. 5, pp. 863–886, 2019.
11. A. Raj, G. Dwivedi, A. Sharma, A. B. Lopes de Sousa Jabbour, and S. Rajak, "Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective," *Int. J. Prod. Econ.*, vol. 224, pp. 1–17, 2020.
12. V. Kumar, P. Vrat, and R. Shankar, "Prioritization of strategies to overcome the barriers in Industry 4.0: a hybrid MCDM approach," *OPSEARCH*, vol. 58, no. 3, pp. 711–750, 2021.
13. J. Barata, "The fourth industrial revolution of supply chains: A tertiary study," *J. Eng. Technol. Manag. - JET-M*, vol. 60, no. February, 2021.
14. A. Alinezhad and J. Khalili, "DEMATEL Method," in *New Methods and Applications in Multiple Attribute Decision Making (MADM)*, vol. 277, Switzerland: Springer Nature Switzerland AG, 2019, pp. 103–108.
15. S. L. Si, X. Y. You, H. C. Liu, and P. Zhang, "DEMATEL Technique: A Systematic Review of the State-of-the-Art Literature on Methodologies and Applications," *Math. Probl. Eng.*, vol. 2018, no. 1, 2018.
16. S. L. Parente and E. C. Prescott, "Barriers to technology adoption and development," *J. Polit. Econ.*, vol. 102, no. 2, pp. 298–321, 1994, https://doi.org/10.1086/261933.
17. D. J. Teece, "Technological innovation and the theory of the firm: the role of enterprise-level knowledge, complementarities , and (dynamic) capabilities," in *Handbook of the Economics of Innovation*, 1st ed., vol. 1, no. 10, Elsevier B.V., 2010, pp. 679–730.
18. L. Donaldson, *The contingency theory of organizations*. SAGE, 2001.
19. B. S. Silvestre, M. E. Silva, A. Cormack, and A. M. T. Thome, "Supply chain sustainability trajectories: learning through sustainability initiatives," *Int. J. Oper. Prod. Manag.*, vol. 40, no. 9, pp. 1301–1337, 2020.
20. R. Drazin and A. H. Van De Ven, "Alternative Forms of Fit in Contingency Theory," *Adm. Sci. Q.*, vol. 30, no. 4, pp. 514–539, 1985.
21. M. Brettel, N. Friederichsen, M. Keller, and M. Rosenberg, "How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective," *Int. J. Mech. Aerospace, Ind. Mechatron. Manuf. Eng.*, vol. 8, no. 1, pp. 37–44, 2014.
22. S. Schrauf and P. Berttram, "How digitization makes the supply chain more efficient, agile, and customer-focused," *Strategy&*, p. 31, 2016.
23. A. Mussomeli, D. Gish, and S. Laaper, "The Rise of the Digital Supply Chain," *Deloitte*, vol. 45, no. 3, pp. 20–21, 2015.
24. A. Gurría, "The Next Production Revolution," OECD Publishing Press, 2017.
25. G. C. Kane, D. Palmer, A. N. Phillips, D. Kiron, and N. Buckley, "Strategy, not Technology, Drives Digital Transformation.," *MIT Sloan Management Review*, 2015.
26. M. Raab and B. Griffin-Cryan, "Digital Transformation of Supply Chains: Creating Value – When Digital Meets Physical," 2011.
27. D. Schulman, M. Hajibashi, R. Narsalay, and S. Sreedharan, "Is your supply chain in sleep mode?," Accenture, 2018.

28. R. Schmidt, M. Möhring, R.-C. Härting, C. Reichstein, P. Neumaier, and P. Jozinović, "Industry 4.0 -Potentials for Creating Smart Products: Empirical Research Results," *Int. Conf. Bus. Inf. Syst.*, 2015.
29. S. Laaper, G. Yauch, P. Wellener, and R. Robinson, "Embracing a digital future How manufacturers can unlock the transformative benefits of digital supply networks," 2018.
30. A. Ghadge, M. Er Kara, H. Moradlou, and M. Goswami, "The impact of Industry 4.0 implementation on supply chains," *J. Manuf. Technol. Manag.*, vol. 31, no. 4, pp. 669–686, 2020.
31. J. C. Franceli and S. N. Z. Turri, "Adoption Factors of Enabling I4.0 Technologies and Benefits in the Supply Chain," *Comput. Sci. Inf. Technol.*, pp. 81–96, 2021.
32. E. Machado, L. F. Scavarda, R. Goyannes, G. Caiado, A. Márcio, and T. Thomé, "Barriers and Enablers for the Integration of Industry 4 . 0 and Sustainability in Supply Chains of MSMEs," vol. 0, 2021.
33. CNI, "Sondagem especial," 2016.
34. J. Bughin, L. LaBerge, and A. Mellbye, "The case for digital reinvention," *McKinsey Q.*, vol. 2017, no. 1, pp. 26–41, 2017.
35. E. Hofmann and M. Rüsch, "Industry 4.0 and the current status as well as future prospects on logistics," *Comput. Ind.*, vol. 89, pp. 23–34, 2017.
36. Z. X. Guo, E. W. T. Ngai, C. Yang, and X. Liang, "An RFID-based intelligent decision support system architecture for production monitoring and scheduling in a distributed manufacturing environment," *Int. J. Prod. Econ. J.*, vol. 159, pp. 16–28, 2015.
37. P. Kumar, R. K. Singh, and V. Kumar, "Managing supply chains for sustainable operations in the era of industry 4.0 and circular economy: Analysis of barriers," *Resour. Conserv. Recycl.*, vol. 164, Jan. 2020.
38. V. S. Narwane, R. D. Raut, V. S. Yadav, and A. R. Singh, "Barriers in sustainable industry 4.0: a case study of the footwear industry," *Int. J. Sustain. Eng.*, vol. 14, no. 3, pp. 175–189, 2021.
39. A. Calabrese, M. Dora, N. L. Ghiron, and L. Tiburzi, "The Management of Operations Industry's 4 . 0 transformation process : how to start , where to aim , what to be aware of," *Prod. Plan. Control*, pp. 1–21, 2020.
40. A. M. T. Thomé, L. F. Scavarda, and A. J. Scavarda, "Conducting systematic literature review in operations management," *Prod. Plan. Control*, 2016.
41. A. M. T. Thomé, L. F. Scavarda, A. Scavarda, and F. E. S. de S. Thomé, "Similarities and contrasts of complexity, uncertainty, risks, and resilience in supply chains and temporary multi-organization projects," *Int. J. Proj. Manag.*, vol. 34, no. 7, pp. 1328–1346, 2016, https://doi.org/10.1016/j.ijproman.2015.10.012.
42. M. J. Page *et al.*, "The PRISMA 2020 statement: An updated guideline for reporting systematic reviews," *BMJ*, vol. 372, 2021.
43. D. Diakoulaki, G. Mavrotas, and L. Papayannakis, "Determining objective weights in multiple criteria problems: The critic method," *Comput. Oper. Res.*, vol. 22, no. 7, pp. 763–770, 1995, https://doi.org/10.1016/0305-0548(94)00059-H.
44. W. W. Wu, L. W. Lan, and Y. T. Lee, "Exploring decisive factors affecting an organization's SaaS adoption: A case study," *Int. J. Inf. Manage.*, vol. 31, no. 6, pp. 556–563, 2011.
45. D. J. Teece, G. Pisano, and A. Shuen, "Dynamic Capabilities and Strategic Management," *Strateg. Manag. J.*, vol. 18, no. 7, pp. 509–533, 1997.
46. L. Da Xu, E. L. Xu, and L. Li, "Industry 4.0: State of the art and future trends," *Int. J. Prod. Res.*, vol. 56, no. 8, pp. 2941–2962, 2018, https://doi.org/10.1080/00207543.2018.1444806.

Project Management Office and Teaching and Learning Center: A Comparative Literature Review

Eric Alberto Quinaglia and Marco Aurélio de Mesquita

Abstract The competency-based education and the digital transformation we are experiencing today have posed significant challenges for engineering schools. To face these challenges, some engineering schools worldwide have a team to support teachers' activities, usually called Teaching Learning Centers (TLC). This article aims to map the Project Management (PM) and Engineering Education (EE) literature to help design a typology of TLC, benchmarking the Project Management Offices (PMO). We used the systematic literature review method and, based on the PM literature, established five dimensions to characterize the types of PMO and TLC. The results show that the EE literature does not delve into the typology of TLC. On the other hand, the PM literature has a more detailed description of PMOs' goals, functions, and autonomy, which contributes to a better understanding of TLC configuration alternatives. This research has limitations inherent to the systematic review method, such as article selection and data collection exclusively from the literature. The study presents originality and value for contributing to the specification of a typology for TLC.

Keywords Teaching · Learning · Project Management · Engineering Education

1 Introduction

Higher education institutions (HEI) have been seeking to modernize their teaching and learning practices along with the review of curricula, exploring potentialities in the advancement of information and communication technologies. Marbach-Ad et al. [1] point out that, previously, higher education professors were required only to master the contents of the disciplines. Currently, they are also charged for pedagogy, particularly for mastering active teaching and learning methodologies.

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To accompany these transformations and reconcile teaching activities with research, extension, and management, without generating competition between activities, Kim et al. [2] point out that professors and coordinators of higher education institutions need support in the preparation of courses, elaboration of didactic activities and evaluation.

The need to support teaching activities has led some higher education institutions to idealize project offices dedicated to developing teaching and learning practices. In the perception of [3], these offices arise based on the belief that a professor's didactics resulted from experience and maturity over time and that certain support systems are necessary to accelerate this evolution. The Teaching and Learning Center (TLC) seek, through direct contact with the teaching staff, to support them in their teaching activities to improve higher education.

Schumann et al. [4] indicate that few teaching institutions have implemented TLCs and, as the value delivered in their functions is not clear, the interest in structuring these centers is not awakened by other institutions. In addition, the stakeholders have difficulty starting implementation, and current TLCs point out problems to improve and bring changes with innovation to the pedagogical models.

Although TLCs are not a new concept, there are still few studies in the literature. The increase in publications coincides with the period of the Covid-19 pandemic, which led to forced migration to remote teaching, a challenge for a large contingent of teachers. Schlesselman [5] comments that this year, universities around the world had to change quickly and empirically to remote teaching, and this change highlights the lack of academic support for professors.

In addition to research on TLC, there is another concept more developed in the literature that also offers a support structure for professional development and project coordination to acquire improvements, the Project Management Offices (PMO). With more applications in the business environment, PMOs offer support in project management, portfolio administration, monitoring and control [6].

Based on the premise of the relevance of TLCs, this article aims to map the Project Management and Engineering Education literatures and compare the PMO and TLC typologies. To achieve this objective, we review the literature to understand how the typologies of these offices and centers are defined and how the PMO literature can contribute to the construction of TLC typology. Therefore, we seek to answer three research questions:

RQ 1: What are the types of PMO in the Project Management literature?
RQ 2: What are the types of TLC in the Engineering Education literature?
RQ 3: How does the PMO literature can contribute to defining TLC typologies?

This article is structured into five sections. In Sect. 2, we discuss the literature review method. In Sect. 3, we present the literature review on PMO and TLC. Then, in Sect. 4, we perform a comparative analysis of PMO and TLC typologies based on the literature. Finally, in Sect. 5, we conclude the article with the synthesis, limitations and developments.

2 Methodology

This section introduces the research method. The systematic literature review process is described in detail in Sect. 2.1, and the conceptual framework for comparative analysis of typologies is presented in Sect. 2.2.

2.1 Conducting the Literature Review

As outlined by [7], the systematic literature review process was adopted to ensure a replicable, scientific, and transparent approach. We followed a 3-step process that included (i) locating studies, (ii) study selection, and (iii) analysis and synthesis. These three steps are presented below.

Locating studies, the first step, consists of finding relevant studies to help answer the research questions [7]. Two databases were selected for the research: Web of Science and Scopus. These databases cover most journals of interest in operations management, organizational management, and social sciences [8]. The following strings were used in search engines: "project management office*" for PMO and "teaching and learning cent*" for TLC. The strings were included in the abstract, title, and keyword to include documents that focus their studies on PMO and TLC and exclude articles that secondarily mention them. Additionally, a search was done with the term "business process management office* OR "business process management cent* of excellenc*", which did not result in a significant number of scientific studies; therefore, it was decided to proceed to the next step of the systematic review.

Study selection, the second step, requires transparency and a set of explicit selection criteria to assess the relevance of each study [7]. Figure 1 demonstrates the identification and selection process obtained in the systematic literature review. The following exclusion filter criteria were applied to the documents and to the reading of titles, abstracts, and keywords:

(i) Document types: Based on this criterion, the following categories were excluded: "conference paper", "early access", "editorial materials", and "book chapter".
(ii) Languages: In this criterion, only the following languages were accepted: English and Portuguese.
(iii) Year of publication: To analyze the most recent scenario of published articles, the filter of articles published in the last 10 years was applied.
(iv) Duplicate documents: Articles on both databases were kept only once.
(v) Adherence to the study: Based on this criterion, articles that did not treat project management as an office or center in an organizational or academic structure and that did not bring characteristics of its design were excluded.

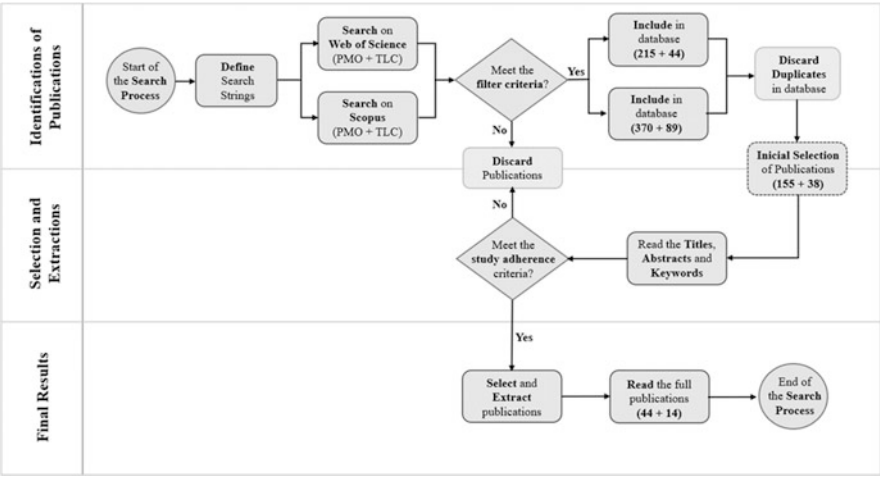

Fig. 1 Process to Identify and Select the Articles

Analysis and synthesis, the third step, consists of breaking down the studies into their constituent parts and describing how each relates to the research questions [7]. In the first part of the analysis, the articles were submitted to a temporal analysis based on the year of publication, which is summarized in Sect. 3. Then, the content analyzes were carried out.

Both analyzes are guided by questions RQ1 and RQ2, which are discussed in Sects. 3.1 and 3.2. Based on the content analysis, the results are synthesized to respond to RQ3, which was discussed in Sect. 4.

2.2 Conceptual Framework to Compare Literature Reviews

To analyze how the literature addresses the typology of PMOs and TLCs, a conceptual framework was used to explore various dimensions of the typology and be applicable and replicable in both cases. The conceptual structure adopted, which was based on reference [9], considers five dimensions for typology: (i) goals, (ii) functions, (iii) structure, (iv) positioning and (v) autonomy. Table 1 summarizes the conceptual framework that was applied in this study.

Table 1 Conceptual framework for analysis of a PMO

Dimension	Description
(1) Goals	For the success of the office, a clear definition of goals is necessary, which must be aligned with the organization's strategy.
(2) Functions	They can range from providing project management support to directly managing one or more projects.
(3) Structure	Typically, it is a team made up a few full-time professionals.
(4) Positioning	Usually, report to the top leadership of the organization.
(5) Autonomy	It varies depending on the degree of control and influence over the projects, such as support control and direction.

Adapted from [9]

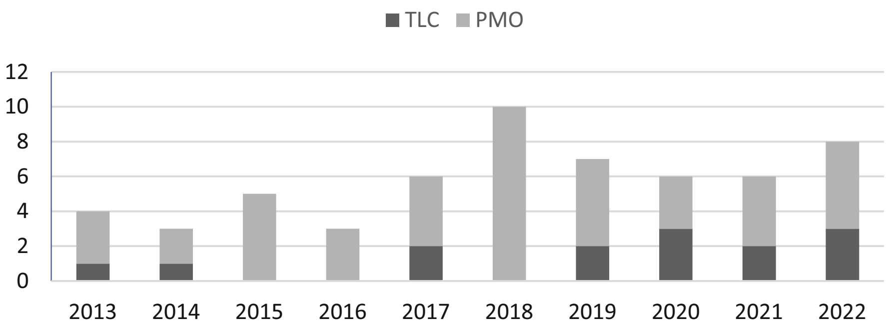

Fig. 2 Temporal analysis of articles (PMO/TLC) (N = 58)

3 Literature Survey and Analysis

The analysis results are presented in this section. First, a temporal literature analysis is performed, followed by content analysis to answer the questions about PMO and TLC typologies, which are presented in Sects. 3.1 and 3.2. These results provide answers to questions RQ1 and RQ2.

Temporal analysis of the articles presented in Fig. 2 demonstrates that all 58 articles were published between 2013 and 2022, 44 articles on PMO and only 14 on TLC, showing a lack of academic research on pedagogical project offices.

3.1 Analysis of PMO Articles

Here we approach our first literature analysis to answer the first research question: how the structure of a PMO is formed based on the literature. Our study seeks to identify the structure in previous studies, following the criteria: (a) goals, (b) functions, (c) structure, (d) positioning and (e) autonomy.

The goals are characteristics of the PMO that an organization is expected to meet. Such expected goals differ as much as the organizations to which the PMO belongs. However, [10] state that even in project offices with different segments, certain goals and main functions are very similar.

According to [11], the PMO's implementation is intended to increase the organization's maturity in project management and the success of its projects, thus contributing to its strategic objectives. In the view of [12], the PMO aims to integrate all project management activities through the organization's hierarchy or network. Alves et al. [13] points out that PMOs assume the purpose of acting as a management cell where dynamic structures in the company are articulated as means to implement organizational goals through projects to maximize value. In another way, the purpose of a PMO can be seen as a corporate strategy tool to integrate project-oriented organization assets and create value for the organization.

The PMO functions can vary from providing project management support functions to the effective responsibility for direct project management, according to [9]. This scope will reflect in the PMOs' goals. In the analysis of [14], the PMO's attributions are linked to providing internal consulting experience, knowledge of project management and application of a clear set of performance standards for project execution. Aubry and Brunet [15] point out that one of the main goals of a PMO is to improve the efficiency of project management. Jalal and Koosha [16] add that this improvement can be achieved through the following functions:

(i) Develop and implement standards on project management methods with a repository of documented project management knowledge.
(ii) Monitor and control project performance with status reporting.
(iii) Develop a management system to coordinate projects.
(iv) Provide support and assistance to the project manager and his team using project management methodologies.
(v) Train project managers in project management tools software and promote project management within the organization.
(vi) Monitor and control the performance of the PMO.

The structure of project offices lists the composition of the team that participates in the process of managing, implementation and controlling projects, describing the roles and responsibilities of everyone. In the study by [10] through a review and analysis of the literature, the authors identified two main classes of agents and ten roles are part of the team participating in project management. The roles and responsibilities of Funding and Performance agents are described below.

1. **Funding**

    (i) Funder: Senior executive who approves and allocates resources, including manpower for the project. A project can have multiple funders.
    (ii) Champion: Leads the development of the business case, presents it to the Funder for approval, and may become the Project Owner.
    (iii) Project Owner: Senior manager who runs the business case on behalf of the Funder, seeking to ensure their interests are met.

(iv) Project Steering Committee: Strategic group ensuring the project aligns with the plan and that the business case is realized. Typically chaired by the Project Owner and not applicable for small projects.
(v) Users: Individuals who utilize the project's outputs. Users can be internal or external to the funding organization.

2. **Performing**

(i) Project Manager: Responsible for delivering the project's outputs according to the plan and reporting to the Project Owner.
(ii) Project Team: Team members who produce the project's outputs.
(iii) Program Manager: Responsible for overseeing interconnected projects and their Project Managers. This role is only applicable to projects that are part of a program.
(iv) Sponsor: Senior manager who supports the project and provides political and top management support for the Project Manager and their team.
(v) Project Management Office (PMO): The group responsible for standardizing the project-related governance processes and supporting Project Managers with methodologies, tools, and project management techniques.

According to [10], the PMO's scope varies according to each organization's needs. A PMO can also be established within the funding scope. The PMO may not apply to organizations that do not undertake enough projects to justify the necessary costs.

The positioning of the PMOs operates according to the needs and goals of the organization. Therefore, each project office is structured differently, and there is no consensus on the hierarchical level that the PMOs report to and may be linked to more strategic levels of the organization, as well as at tactical levels. However, based on research that used case studies to analyze the functioning of PMOs in companies, the studies of [17–19] point out that most of the investigated PMOs report directly to top leadership executives.

As for autonomy, PMOs can vary according to their degree of control and influence in the organization, exercising this autonomy over programs, and portfolios of projects [9]. Müller et al. [14] used a multi case study to identify different levels of autonomy applied in the configuration of PMOs. Three levels of autonomy were identified: serve, control and partner. PMOs assume a serve autonomy when they operate as a service unit to internal and external teams, project leaders, and project workers. PMOs assume a control autonomy when they work as management units on projects under their domain. PMOs assume a partner autonomy when they imply lateral communication between a PMO and other equally qualified or equally commissioned project leaders or project workers.

3.2 Analysis of TLC Articles

Here we approach our second literature review to answer the second research question: how the structure of a TLC is formed based on the literature. Our analysis seeks to identify the structure in previous studies, following the criteria: (a) goals, (b) functions, (c) structure, (d) positioning and (e) autonomy.

The goals of TLC are to improve the quality of higher education and accelerate the learning process [20]. According to [21], one of the goals of these offices is to support the development of teachers who are experts in their subject area and typically seek knowledge about teaching practices from their resources and personal considerations. Kolomitro and Anstey [22] add that there is a tendency in universities to promote and overestimate research to the detriment of teacher training, giving incentives and developing a primary identity as researchers and not as teachers. In this context and considering that the teacher's experience alone is not enough to guarantee student learning, the purpose of the centers becomes relevant.

To delve deeper into the purpose and goals of TLCs, [23] carried out a case study in three centers in Southeast Asia, where they could identify the following objectives: The center (a) was established to provide a student support system through consulting, mentoring, and e-learning, as well as to support faculty in improving their teaching strategies through the latest educational technology. Center (b) was founded to meet the needs of the faculty using research-based teaching methodologies. It also aims to use the research results to improve student learning outcomes. Center (c) was established to enhance teaching strategies and develop faculty research skills and support students' learning needs.

The functions consider programs and services offered by the TLCs, in which it was revealed by the case study of [23] that the programs offered by the center (a) include faculty development, learning development, e-learning support and management of the educational performance. At center (b) programs include, but are not limited to, professional development, teaching assistants' program, scholarship writing course, faculty workshops, student consultations, teaching enhancement fellowships, publications, research, and teaching evaluations. Finally, at center (c) programs are limited to in-service training and various student support programs.

It could be observed that, among the three centers investigated by [23], center (a) has a more balanced approach in providing support for the needs of teachers and students. In center (b) the focus is more on the professional development of faculty members and on the other hand, in center (c), the programs offered were limited to in-service training and some student support activities.

The structure that makes up the team provides clarity regarding who does what and identifies roles and responsibilities for the programs and services offered. In the view of [23], most organizations fail not because of their programs, but because of the team's unclear structure of roles and responsibilities. This is the case for center (c). Since the role of developing teaching and learning processes are only ancillary functions of different trades, and there is rarely a separate and unique center dedicated to them, most of the results were far from promising. This is the opposite about centers (a) and (b), which have more success stories in the implementation of their programs and services.

In center (a), the team composition comprises professionals with exclusive dedication and their organizational structure, including the director, assistant, president of the program and other support staff. Center (b) is very similar to center (a) and only differs using a shared organizational structure. In center (c), the team composition is mainly informal and usually linked to different offices, such as the Faculty of Education, Guidance Office, or Research Development, not having a separate organizational structure.

The positioning was a dimension that, although not found in the literature for those reporting TLCs in the academic structure, the study by [23] points to the effectiveness of programs and services, which are primarily influenced by how much or how little the availability of financial support, considering the sources that finance the investigated centers. In centers (a) and (b), the programs offered are funded by combined resources from the public and private sectors and student fees. However, in center (c), they are mainly funded through student fees. The availability of funds affects the breadth of services and programs that the center can offer to students and faculty; the smaller the funds, the more limited the services provided. Therefore, we can consider that there is a reporting relationship between the centers and the funding sources.

The autonomy regarding the influence that TLCs exert in the academic environment is represented by the study of [24], which presents the PROF-XXI structure that describes competencies that TLCs must consider defining strategies and actions according to their autonomy and that allow supporting innovation in teaching and learning. The PROF-XXI structure organizes the autonomy of the TLCs into five levels that refer to institutional interests and influence how programs and services are offered in the centers.

(i) Teacher support refers to competencies related to teacher support directly affecting the institution's teachers.
(ii) Student support refers to competencies related to student support directly affecting the institution's students.
(iii) Leadership, Culture and Transformation refer to the competencies necessary to lead and promote cultural transformations in the institution by defining new policies and actions that affect its current processes.
(iv) Technology at the service of Learning refers to the competencies that an institution must have to manage educational initiatives supported by technology, including the definition of processes and technological infrastructures.
(v) Evidence-Based Practice refers to the necessary competencies related to initiatives that aim to collect data and information to understand the effect of transformations and initiatives carried out in education.

4 Discussion

Here we approach the synthesis of the literature analyzes to respond to RQ3. Our analysis seeks to identify gaps in the TLC literature, which the PMO literature can contribute based on its typology.

The goals identified in the literature are influenced according to the organizational or academic needs and contexts in which the PMOs and TLCs are installed. The first goal aims to raise the organization's maturity and efficiency in project management and articulates the implementation and achievement of organizational goals. The second goal is supporting the faculty's development, providing a support system for students learning needs and improving teaching strategies.

The functions that different authors address begin to show gaps in the TLC literature that can receive contributions from the PMO literature. By presenting a scarcer base of authors, the TLC literature presented only a single author who comments on the attributions of teaching and learning centers. Unlike the PMO literature that points out six more detailed attributions to improve the efficiency of projects, the TLC literature comments more comprehensively on programs that these centers can offer to support the needs of teachers and students.

The structure is another aspect where we find gaps in the TLC literature that can receive contributions based on the PMO literature. Like the previous one, the TLC literature presented only a single author who deals with the composition of the team that is part of the teaching and learning centers. Unlike the PMO literature, where each of the ten roles and responsibilities of agents participating in project management is presented, the TLC literature addresses only a macrostructure formed by the presidency, directors, and support staff, but without specifying their roles and responsibilities for programs to function and meet their goals.

The positioning is an aspect where gaps were found in both literatures. To identify to whom the PMOs and TLCs report in the hierarchy where they are installed, no studies were found that worked on this aspect. In the PMO literature, it is estimated that these offices report to the top leadership, but do not detail this hierarchical reporting level. In the TLC literature, no works related to a hierarchical report of these centers were found. Still, a study was found reporting different sources of funding for these centers that we can describe as a direct report of the programs and services offered by the center.

Autonomy is a dimension of the typology where different configurations of autonomies and influences of PMOs and TLCs have been identified in the literature. According to the organizational and academic needs of teaching, we found different levels of these offices. Basically, three levels of PMOs were found: service, control, and partnerships. As for the TLCs, five levels presented by a single author, were found: teacher support; student support; leadership, culture, and transformation; technology at the service of learning and evidence-based practices.

Table 2 summarizes the synthesis of the comparative analysis of the literature that helps to design a typology of TLC, having as benchmarking the PMO characteristics.

Table 2 Summary of the comparative analysis of the literature

Typology	TLC	PMO
(1) Goals	Improve the quality of education, teaching and learning.	Raise the maturity and efficiency of the project management team.
(2) Functions	Few references address the aspect of attributions. It does not present details about the functions of a center; it only lists programs that can be offered.	Six main attributions are described that are essential to achieve the goals of the PMO. These assignments connect what will be done with the purpose and goal of the office.
(3) Structure	Few references address the team aspect. Absence of surveys that relate the composition of each team member with their roles and responsibilities.	Two main scopes are described (financing and performance). Ten functions are described that can help direct roles and responsibilities.
(4) Positioning	No studies were found that deal with reporting, although one of them commented on the sources of funding.	No studies were found that address the aspect of reporting, although they consider, in most cases, reporting to senior leadership.
(5) Autonomy	Teacher support; student support; leadership and transformation; technologies for learning and research practices.	Service, control, and partnerships

5 Conclusions

This article mapped the Project Management (PM) and Engineering Education (EE) literature to help design a TLC typology, benchmarking the Project Management Offices (PMO). We used the systematic literature review method and, based on the PM literature, we established five dimensions to characterize the types of PMO and TLC: goals, functions, structure, positioning and autonomy.

The results show that the EE literature does not delve into the typology of TLC. On the other hand, the PM literature has a more detailed description of PMOs' goals, functions, and autonomy, which contributes to a better understanding of TLC configuration alternatives.

The results showed that the PMO literature was sufficient to characterize four of the five dimensions of the types and produce an answer to the first research question of this study. Except for the positioning dimension, which did not bring a clear answer to who the offices should report to in project-oriented organizations, the other dimensions got more precise answers to the characterization of PMO types.

The results also showed that although the TLC literature has contributed to design its typology and answer the second research question, the dimensions of functions, structure and autonomy were identified in only one research, limiting the source of information to understand these dimensions. Like the PMO literature, the positioning dimension was not found in the selected articles. However, a survey presented sources that finance these centers that approach the positioning dimension.

Finally, we present a comparative analysis of the literature to understand which characteristics of PMOs identified in the PM literature can contribute to the definition of a TLC typology and thus produce an answer to the third question of this study. The results showed that the characteristics found in the dimensions of functions and structures in the PMO literature could contribute to the typologies of TLC. The PMO articles present a more detailed roadmap of activities performed to achieve the goals in the functions dimension and a more organized scope of roles and responsibilities in the team's dimension.

This research has limitations inherent to the systematic review method, such as article selection criteria and data collection exclusively from the literature. A natural outcome of the work would be to replicate the five dimensions of types explored in this study in the application of empirical methods such as a survey or a case study that can contribute to the understanding of how these structures should be organized from the perspective of the functioning of a PMO or TLC in practice. The study presents originality and value for contributing to the specification of a typology for TLC.

References

1. Marbach-Ad, G., Eagan, L., & Thompson, K. (2015). A discipline-based teaching and learning center. NY: Springer Publications.
2. Kim, A. S., Popovic, C., Farrugia, L., Saleh, S. A., Maheux-Pelletier, G., & Frake-Mistak, M. (2021). On nurturing the emergent SoTL researcher: responding to challenges and opportunities. International Journal for Academic Development, 26(2), 163–175.
3. Frantz, A. C., Beebe, S. A., Horvath, V. S., Canales, J., & Swee, D. E. (2004). 5: The roles of teaching and learning centers. *To improve the academy*, *23*(1), 72–90.
4. Schumann, D. W., Peters, J., & Olsen, T. (2013). Cocreating value in teaching and learning centers. New directions for teaching and learning, 2013(133), 21–32.
5. Schlesselman, L. S. (2020). Perspective from a teaching and learning center during emergency remote teaching. American Journal of Pharmaceutical Education, 84(8).
6. Singh, R., Keil, M., & Kasi, V. (2009). Identifying and overcoming the challenges of implementing a project management office. *European journal of information systems*, *18*(5).
7. Denyer, D., & Tranfield, D. (2009). Producing a systematic review.
8. Thomé, A. M. T., Scavarda, L. F., & Scavarda, A. J. (2016). Conducting systematic literature review in operations management. Production Planning & Control, 27(5), 408–420.
9. PMI Publications. (Ed). (2021). Project management body of knowledge (pmbok® guide). In Project Management Institute (7th, pp. 42–50).
10. Zwikael, O., & Meredith, J. R. (2018). Who's who in the project zoo? The ten core project roles. *International Journal of Operations & Production Management*.
11. Fernandes, G., Pinto, E. B., Araújo, M., & Machado, R. J. (2020). The roles of a Programme and Project Management Office to support collaborative university–industry R&D. *Total Quality Management & Business Excellence*, *31*(5-6), 583–608.
12. Otra-Aho, V. J., Iden, J., & Hallikas, J. (2019). The impact of the project management office roles to organizational value contribution. *International Journal of Information Technology Project Management (IJITPM)*, *10*(4), 79–99.

13. Alves, R. O., Costa, H. G., Quelhas, O. L. G., Silva, L. E. D., & Pimentel, L. B. (2013). Best practices in project management office implementation: development of success reference. *Production*, *23*, 582–594.
14. Müller, R., Glückler, J., & Aubry, M. (2013). A relational typology of project management offices. *Project Management Journal*, *44*(1), 59–76.
15. Aubry, M., & Brunet, M. (2016). Organizational design in public administration: Categorization of project management offices. *Project Management Journal*, *47*(5).
16. Jalal, M. P., & Koosha, S. M. (2015). Identifying organizational variables affecting project management office characteristics and analyzing their correlations in the Iranian project-oriented organizations of the construction industry. *International Journal of Project Management*, *33*(2), 458–466.
17. Bredillet, C., Tywoniak, S., & Tootoonchy, M. (2018). Exploring the dynamics of project management office and portfolio management co-evolution: A routine lens. *International journal of project management*, *36*(1), 27–42.
18. Wedekind, G. K., & Philbin, S. P. (2018). Research and Grant Management: The Role of the Project Management Office (PMO) in a European Research Consortium Context. *Journal of Research Administration*, *49*(1), 43–62.
19. Barbalho, S. C. M., Carlos de Toledo, J., & Cintra Faria, A. C. (2022). Transitions in Project Management Offices: A Framework Relating Functions, Success Factors and Project Performance in a High-Technology Company. *Engineering Management Journal*, *34*(3), 357–373.
20. Ellis, D. E., Brown, V. M., & Tse, C. T. (2020). Comprehensive assessment for teaching and learning centres: a field-tested planning model. International Journal for Academic Development, 25(4), 337–349.
21. Jerez Yàñez, Ó., Aranda Càceres, R., Corvalán Canessa, F., González Rojas, L., & Ramos Torres, A. (2019). A teaching accompaniment and development model: possibilities and challenges for TLC. International Journal for Academic Development, 24(2), 204–208.
22. Kolomitro, K., & Anstey, L. M. (2017). A survey on evaluation practices in teaching and learning centres. *International Journal for Academic Development*, *22*(3), 186–198.
23. Nam, J. K., & Dipasupil, S. R. (2019). The Status of Teaching and Learning Centers in Higher Education: An Asian Perspective. *International Journal of Learning and Teaching*, 262–265.
24. Pérez-Sanagustín, M., Kotorov, I., Teixeira, A., Mansilla, F., Broisin, J., Alario-Hoyos, C., & Gonzalez Lopez, A. H. (2022). A Competency Framework for TLIC for the 21st Century: Anticipating the Post-COVID-19 Age. Electronics, 11(3), 413.

Main Musculoskeletal Disorders in Virtual Modality Students

César Corrales, Wilmer Atoche, and Jonatan Rojas

Abstract Musculoskeletal disorders are injuries and symptoms that affect any part of the body, mainly the locomotor system (bones, muscles, joints, tendons, ligaments, nerves mainly), from prolonged exposure to a certain activity and caused by the type of task, postures, required physical strength, use of work equipment, environment where it is developed and work organization, among others. It is one of the most frequent occupational diseases and the one that has increased the most in recent years and also encompasses people's daily activities. The appearance of the COVID-19 pandemic has motivated that activities that were usually carried out in person, are now carried out virtually, in many cases using domestic environments and not designed for such purposes. This has been particularly important among university students who have had to study from home, using computer equipment and modifying their routine of daily activities, with the almost exclusive use of computer equipment. This situation has generated different musculoskeletal disorders among students, which usually occurred at older ages. The objective of this study was to determine the main musculoskeletal problems present among students in virtual mode. For this, a study sample was taken among students of the Industrial Engineering specialty and the so-called Nordic Kuorinka Questionnaire was applied, an evaluation instrument that allowed to establish these problems. The results will allow measures to be taken to reduce musculoskeletal disorders among students.

Keywords Musculoskeletal disorders · COVID 19 pandemic · Ergonomics

1 Introduction

In Peru, as in all countries of the world, musculoskeletal disorders are one of the most important causes of ailments among the adult population, both at work and at home. An important sector that has not been taken into account is the educational

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sector, given that, as it is mainly composed of young people and children, the probability of presenting this type of problems is not very high. However, the conditions generated by the COVID-19 pandemic have forced the closure of educational facilities and have led to work from home, with conditions that, in many cases, are not adequate because they have not had ergonomic considerations for their implementation.

The latter has generated, among young people, the appearance or increase of musculoskeletal disorders that are not known and deserve to be taken into account.

The objective of this work is to present in a preliminary way the details of some problems of the upper limbs, as well as to measure the degree of intensity of the discomfort, among engineering students of a private university in Peru.

2 Literature Review

Musculoskeletal disorders (MSDs) are one of the most common health problems of people worldwide [1]. Work-related MSDs, describe a wide range of inflammatory and degenerative diseases and maladies. Particularly, work-related MSDs of the neck and upper extremities are a significant problem within the European Union, related to poor health, productivity and associated costs, and these conditions cause pain and functional disablement, although work is not the sole determinant [2] and these can affect the neck, shoulders, elbows, forearms, wrists and hands. MSDs develop slowly over time, affecting nerves, tendons, ligaments and joints, and are caused by the physical stress of workers, leading to tissue breakdown that at an early stage, are presented as fatigue, discomfort, and pain [3]. Cumulative disorders of the body, magnify over time through constant and frequent exposures [4].

Globally, from 1990 to 2019, the number of people requiring any rehabilitation treatment for health conditions experiencing difficulties in, for example, mobility, vision or cognition, is estimated to have increased by 63%, and the disease area contributing most to prevalence was musculoskeletal, with low back pain (LBP) being the most prevalent condition in 134 of 204 countries analyzed [5].

Contemporary lifestyles, which have become hypokinetic in the last two decades, have resulted in worsening fitness and work performance, as well as an increase in various diseases, including MSDs, the worsening of which has also been caused by coronavirus [6]. The COVID-19 pandemic appeared in late 2019 and spread worldwide in early 2020, and was then declared a pandemic by the World Health Organization [7].

With the COVID-19 pandemic and due to restrictions and quarantine, people have remained inactive at home, continuing in many cases with their intense work schedules but in an unfamiliar and unergonomic environment, resulting in musculoskeletal and psychosocial problems [8]. The alarming condition of the presence of musculoskeletal pain in a young population stands out [9].

Due to the COVID-19 pandemic, telecommuting has been implemented with increased psychological demands and stress, the main risk factors being no physical activity, non-compliance with ergonomic recommendations and stress, generating MSDs, which mostly originate back pain followed by neck pain and low back pain, and psychosocial problems [8, 10]. MSDs, following the spread of the virus in most organs, have increased significantly, especially in the back, neck and knees [11]. Neck pain has always been a major problem in modern society [12].

The confinement by the COVID-19 pandemic has taken many educational institutions by surprise and has warranted an abrupt migration from offline to online learning. This has resulted in an educational shift, without time for due consideration, as to its impact on MSDs in students given that the hours of online learning spent per day and the level of frustration with online classes online were positively associated with MSD symptoms in various parts. of the body [13]. The global pandemic of 2020 led most schools and universities to prepare and start adapting digital education by offering full online classes to students in the comfort of their homes, however, the home environments of the surveyed students are still not ergonomically friendly and postural risk and body discomfort are also evident [14]. While each university adapted as best it could to the new situation, in general the usual schedule was maintained, with the previously established workload, with distance, virtual and video classes, and encouraging the use of more autonomous learning methods by students [15].

During the COVID-19 pandemic, several countries changed their teaching programs to e-learning, where students spend long hours using electronic devices, which is associated with various MSDs among students, considering that most students use the sitting position with the back leaning forward while using the device [16]. The use of computers at work has increased rapidly in recent decades and has been associated with various MSDs, which are now the most commonly diagnosed occupational diseases in Estonia, with a high prevalence of MSDs observed in the neck, lower back, wrist/arm and shoulder among Estonian, computer users [17]. Computer use is associated with pain complaints, but it is not yet clear whether this association is causal [18].

lIt is necessary to mention that sitting posture is not at all favorable for human anatomy, since the loading effects on the spine and attachments are much greater when sitting than when lying down or walking; in this sense, it can be indicated that animals do not suffer back and neck pain as much as humans due to their horizontal spine compared to the human vertical spine [19]. While it is true that sitting position was not directly associated with the risk of developing LBP, however, sitting for more than half a working day, in combination with whole body vibration and/or awkward postures, increases the likelihood of having LBP and/or sciatica, and it is the combination of these risk factors that leads to the greatest increase in LBP, which has been identified as one of the most costly disorders among the world's working population [20].

In that sense, the furniture on which college students spend most of their time in a day with any of the furniture such as table, chair, bookcase, etc., are responsible for many types of physical problems, such as back pain, because of the posture that has to be adopted to use them [21].

3 Methodology

3.1 Population Data and Determination of the Number of Samples

The research focuses on 1800 Industrial Engineering students enrolled at the selected university during the academic semester of 2021. Subsequently, the number of samples is determined according to the described formula in Eq. (1). Thus, to prepare the sample, the number of students needed for the research is 75 (n = 74.52). However, to strengthen the analysis, it was planned to add a 10% of surveys which lead to show surveys from 83 students. Therefore, the data of 102 students were processed.

$$n = \frac{Z_{1-\frac{\alpha^2}{2}} N \sigma^2}{(N-1)E^2 + Z_{1-\frac{\alpha^2}{2}} \sigma^2} \tag{1}$$

Where:

n = Number of students needed.
σ = Standard deviation (4.5 students).
N = Total number of Industrial Engineering students (1750 students).
Z = Confidence level 95% = 1.959 (95% + α/2).
E = Permissible error (1 student)

3.2 Nordic Questionnaire

To collect the information we used part of the Kuorinka Nordic Questionnaire [22] which is applied for the detection and analysis of musculoskeletal symptoms that are relevant in the context of ergonomic or occupational health studies; so as to detect the existence of initial symptoms that have not yet been identified as a disease or have not led people to consult a doctor. The questions focus on most of the symptoms that are most frequently detected in different economic activities, mainly in the upper limbs.

Tables 1 and 2 show part of what was sent to the students for their response. It should be noted that the initial survey included more items, but these tables are the ones used for this study.

Table 1 Discomfort location

Neck		Dorsal or lumbar		Shoulder		Elbow or lower arm		Wrist or hand	
Yes	No	Yes	No	Yes	Left	Yes	Left	Yes	Left
				No	Right	No	Right	No	Right
							Both		Both

Table 2 Discomfort intensity

Neck	Dorsal or lumbar	Shoulder	Elbow or lower arm	Wrist or hand
1	1	1	1	1
2	2	2	2	2
3	3	3	3	3
4	4	4	4	4
5	5	5	5	5

3.3 Application of the Instrument

Once the sample was defined and the tables to be considered from the Nordic Questionnaire were determined, a survey was applied virtually to the students in the sample (https://forms.gle/fiy3pBCgRpZdt53d9), which was answered based on what each student felt or knew about it.

4 Results

The following important results were obtained from the students' answers to the questionnaire. In relation to the frequency of the affected body part, the results are shown in Figs. 1 and 2.

Low back pain is present in 86.3% of the respondents and neck pain in 79.4% of the respondents; this infers that the majority of students present both complaints. Shoulder pain is present in at least 70.6% of respondents, wrist pain in 64.7% of respondents, and elbow or forearm pain was present in only 35.3%. The most frequent pains can occur due to inadequate working postures or equipment during long study and work days.

If we separate these same data by gender, F: Female and M: Male, we have the results in Figs. 3 and 4.

Neck pain occurs more frequently in female students than in male students. However, back pain does not show significant gender differences. Shoulder discomfort is greater in female students than in male students. It can be seen that elbow and wrist discomfort do not present significant differences by gender.

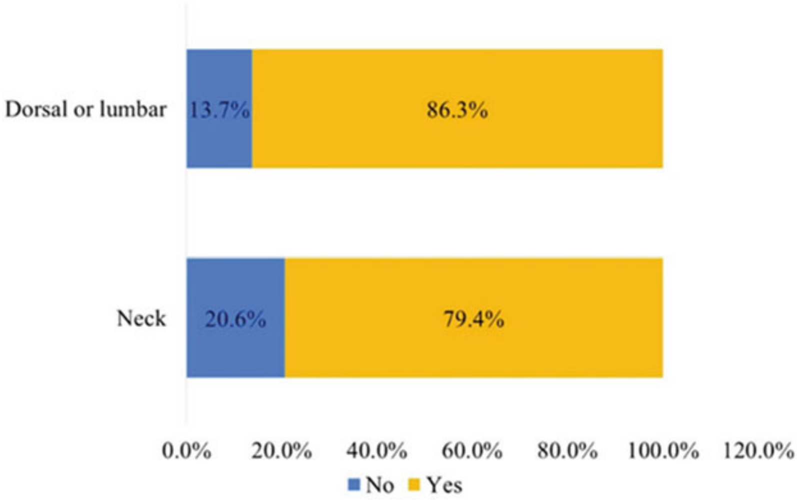

Fig. 1 Frequency of affected body part per student

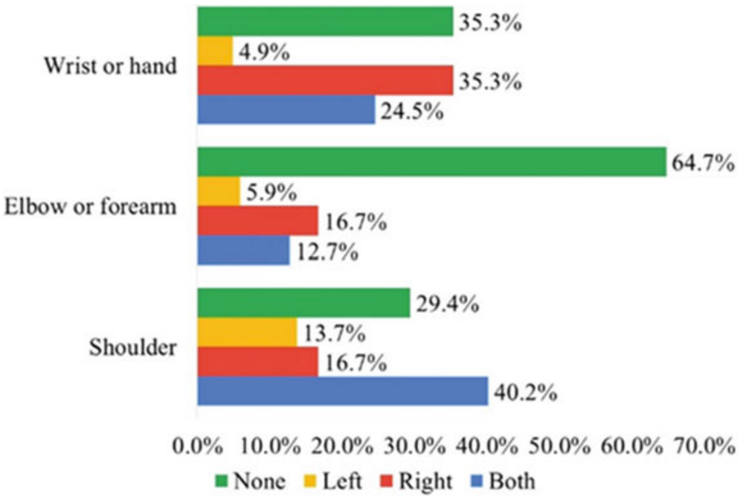

Fig. 2 Frequency of body part affected per student

If we analyze shoulder, elbow and wrist pain in male students, it can be seen that shoulder pain is more frequent, followed by wrist pain and the least frequent is elbow pain. If we analyze shoulder, elbow and wrist pain, in female students, it can be appreciated that shoulder pain is more frequent, followed by wrist pain and the least frequent is elbow pain.

The next aspect that was evaluated was the intensity of the discomfort felt by the students. Also in this case it was done, in addition to the separation by body part

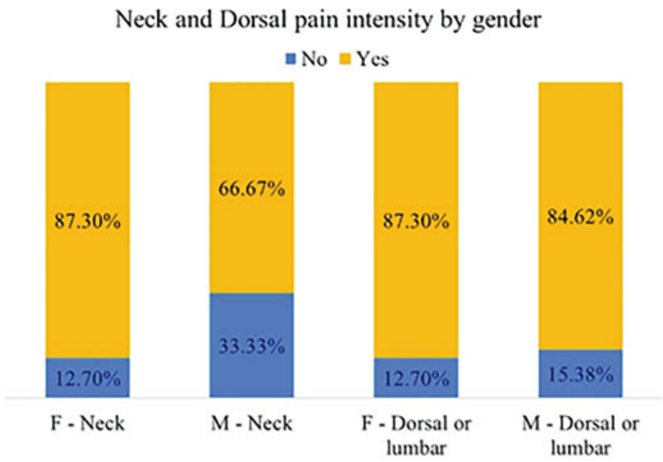

Fig. 3 Neck and back discomfort by gender

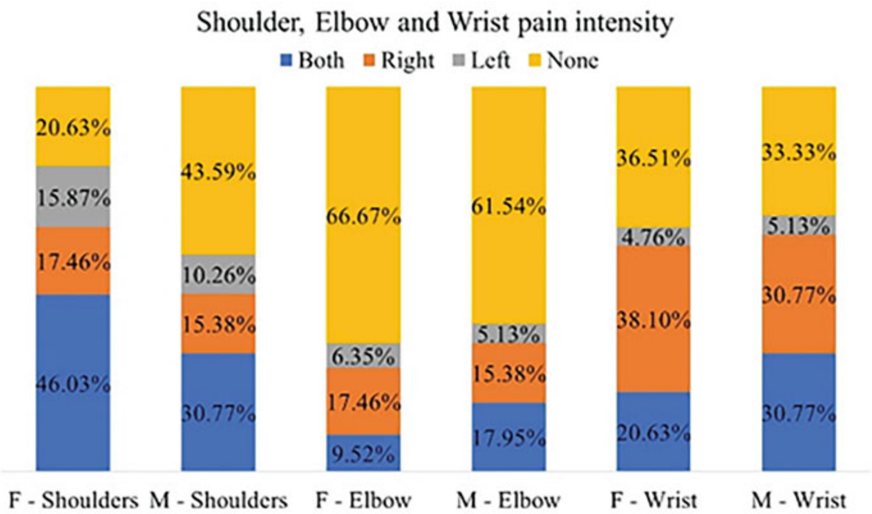

Fig. 4 Shoulder, Elbow and Wrist Discomfort

affected, by the gender of the students, i.e. F: female and M: male. The results of these segmentations are shown in Figs. 5, 6, 7, 8, and 9.

It can be noted that the average perceived neck discomfort in females is 3.08 and in males it is 2.53. The average of the perception of shoulder discomfort in women is 2.64 and in men is 1.97. The average of the perception of low back discomfort in women is 3.18 and in men is 2.88. The average perceived elbow or forearm discomfort in women is 1.67 and 1.91 in men. The average perceived hand or wrist discomfort in females is 1.93 and in males is 2.08.

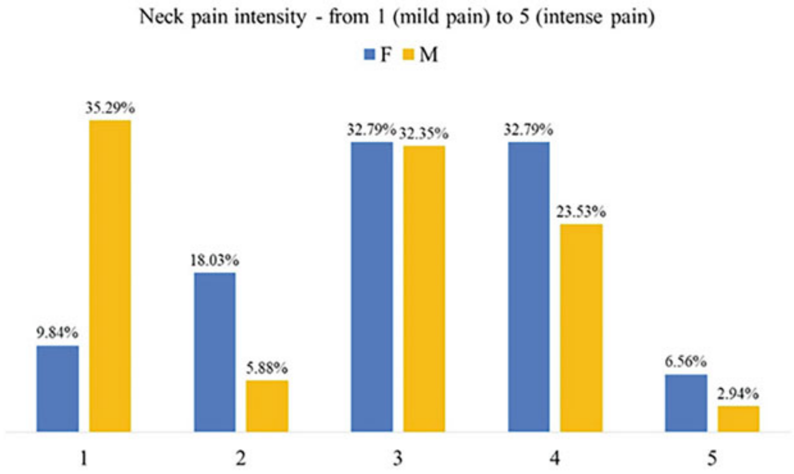

Fig. 5 Intensity of neck discomfort - 0 (no discomfort) - 5 (very strong discomfort)

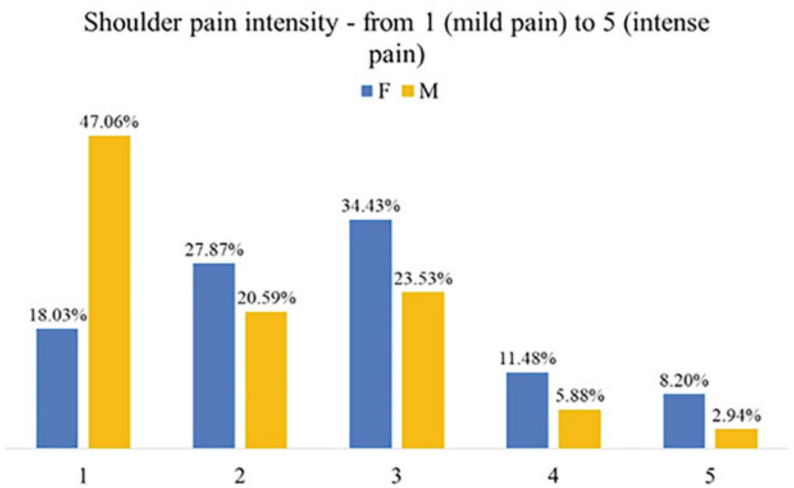

Fig. 6 Intensity of shoulder discomfort - 0 (no discomfort) - 5 (very strong discomfort)

The values also indicate that the greatest discomfort is in the neck and in the lumbar or dorsal area, with the neck having more discomfort for women and the dorsal or lumbar area for men.

Figure 10 shows a global graph of the results, which confirms what was previously indicated as a result of observing the values and graphs presented.

Lumbar discomfort is the one that presents high pain indexes, neck discomfort and shoulder discomfort present medium pain indexes, wrist and elbow discomfort are the ones with the lowest pain indexes.

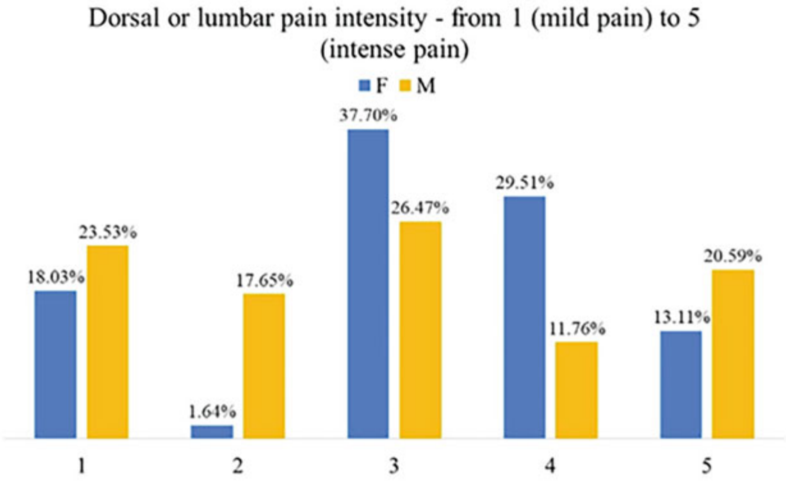

Fig. 7 Intensity of back or lumbar discomfort - 0 (no discomfort) - 5 (very strong discomfort)

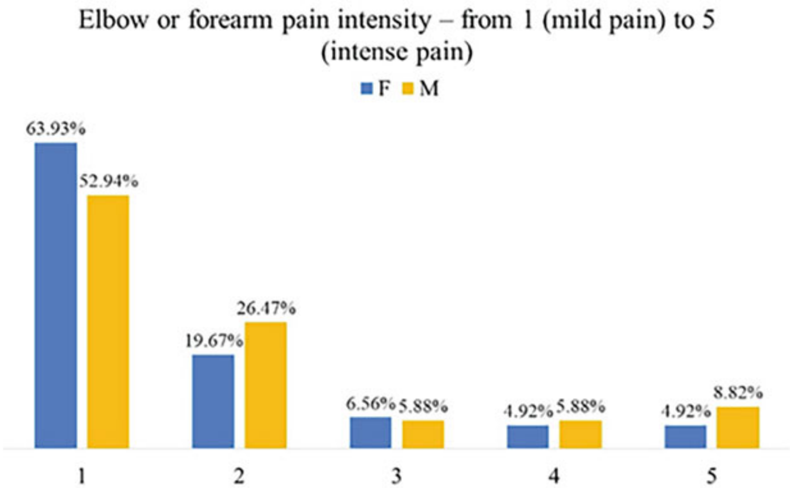

Fig. 8 Intensity of elbow or forearm discomfort - 0 (no discomfort) - 5 (very strong discomfort)

5 Conclusions

The main result is that almost 100% of students manifest some type of musculoskeletal discomfort in the upper part of the body. Only in the dorsal or lumbar pain we have almost 90% of students, if we see that there are four other parts of the body that can be affected we can reach this conclusion.

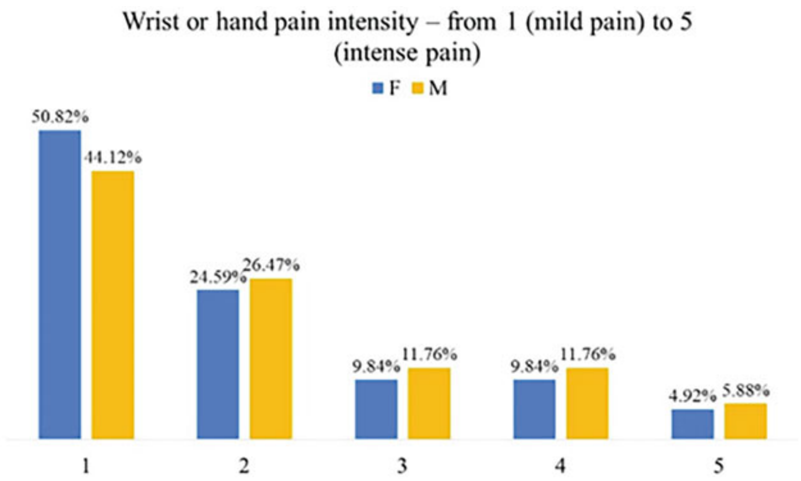

Fig. 9 Intensity of wrist or hand discomfort - 0 (no discomfort) - 5 (very strong discomfort)

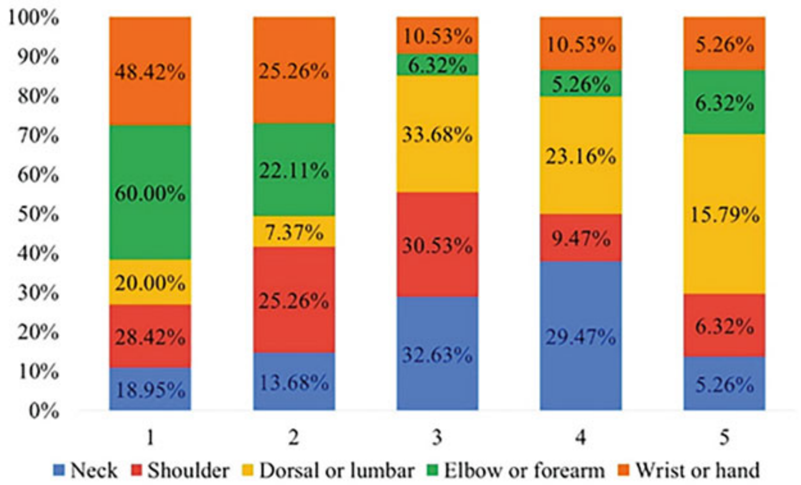

Fig. 10 Global graph of the discomfort score

The values also indicate that the greatest discomfort is in the neck and in the lumbar or dorsal area, being the neck with more discomfort for women and the dorsal or lumbar area for men.

Neck pain occurs more frequently in female students than in male students. However, dorsal pain does not present significant gender differences.

If we analyze shoulder, elbow and wrist pain, in male students, it can be seen that shoulder pain is more frequent, followed by wrist pain and the least frequent is elbow pain. If we analyze shoulder, elbow and wrist pain in female students, it can be seen that shoulder pain is more frequent, followed by wrist pain and the least frequent is elbow pain.

It is therefore very important to identify the causes mainly of neck pain in women and lumbar or dorsal pain in the shoulders. According to previous studies, the causes may be the use of non-ergonomic furniture that generates incorrect postures, the use of computers and their screens, the use of cell phones and the posture for their use.

A next step would be to carry out a study of students' perceptions of the causes that they believe originate these discomforts. In this way it would be possible to validate in some way incorrect attitudes on the part of the students or problems with the devices or furniture used and other causes that theoretically lead to such discomfort.

In the same way, the other data obtained from the Nordic Questionnaire can be used.

References

1. Osborne, A., Blake, C., Fullen, B., Meredith, D., Phelan, J., McNamara, J., Cunningham, C.: Prevalence of musculoskeletal disorders among farmers: A systematic review. American Journal of Industrial Medicine 55(2), 143–158 (2012).
2. Buckle, P., Devereux, J.: The nature of work-related neck and upper limb musculoskeletal disorders. Applied Ergonomics 33(3), 207–217 (2002).
3. Delin, P., Roja, S., Karthika, S.: Analysis of Occupational Risk Factors for Ergonomic Design of Construction Work Systems. International Research Journal of Engineering and Technology (IRJET) 7(8), 3577– 3581 (2020).
4. Reid, C., Bush, P., Cummings, N., McMullin, D., Durrani, S.: A review of occupational knee disorders. Journal of Occupational Rehabilitation 20(4), 489–501 (2010).
5. Cieza, A., Causey, K., Kamenov, K., Hanson, S. W., Chatterji, S., Vos, T.: Global estimates of the need for rehabilitation based on the Global Burden of Disease study 2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet 396 (10267), 2006–2017 (2020).
6. Bendíková, E., Palaščáková Špringrová, I.: Online Teaching of Physical and Sports Education During the Covid-19 Pandemic in Relation To Pain in the Musculoskeletal System of Female Students (Pilot Study). In: INTED2021 on Proceedings, pp. 10674–10681 (2021).
7. Cucinotta, D., Vanelli, M.: WHO declares COVID-19 a pandemic. Acta Biomed. 91(1), 157–160, Published online (2020).
8. Kayabınar, E., Kayabınar, B., Önal, B., Zengin, H. Y., Köse, N.: The musculoskeletal problems and psychosocial status of teachers giving online education during the COVID-19 pandemic and preventive telerehabilitation for musculoskeletal problems. Work 68(1), 33– 43 (2021).
9. Roggio, F., Trovato, B., Ravalli, S., Di Rosa, M., Maugeri, G., Bianco, A., Palma, A., Musumeci, G.: One year of COVID-19 pandemic in Italy: Effect of sedentary behavior on physical activity levels and musculoskeletal pain among university students. International Journal of Environmental Research and Public Health 18(16) (2021).
10. Prieto-González, P., Šutvajová, M., Lesňáková, A., Bartík, P., Buľáková, K., Friediger, T.: Back pain prevalence, intensity, and associated risk factors among female teachers in Slovakia during the COVID-19 pandemic: A cross-sectional study. Healthcare 9(7), 860 (2021).
11. Jafari-Nodoushan, A., Bagheri, G., Mosavi Nodoushan, F.: Effect of COVID-19 virus on Prevalence of Musculoskeletal Disorders of Faculty Members of Yazd University. Iranian Journal of Ergonomics 8(3), 1–12 (2020).

12. Ariëns, G., van Mechelen, W., Bongers, P., Bouter, L., van der Wal, G.: Physical risk factors for neck pain. Scandinavian Journal of Work, Environment & Health 26(1), 7–19 (2000)
13. Karingada, K., Sony, M.: Demonstration of the relationship between MSD and online learning during the COVID-19 pandemic. Journal of Applied Research in Higher Education 14(1), 200–222 (2022).
14. Vallespin, B., Tri Prasetyo, Y.: Posture Analysis of Students doing Online Class at Home during COVID-19 Pandemic. In: 7th IEEE International Conference on Engineering Technologies and Applied Sciences (ICETAS) on Proceedings, pp. 1–6. Kuala Lumpur (2020).
15. Leirós-Rodríguez, R., Rodríguez-Nogueira, Ó., Pinto-Carral, A., Álvarez-Álvarez, M., Galán-Martín, M., Montero-Cuadrado, F., Benítez-Andrades, J.: Musculoskeletal pain and non-classroom teaching in times of the covid-19 pandemic: Analysis of the impact on students from two Spanish universities. Journal of Clinical Medicine *9*(12), 1– 12 (2020).
16. Yaseen, Q., Salah, H.: The impact of e-learning during COVID-19 pandemic on students' body aches in Palestine. Scientific Reports 11(1), 1–9 (2021).
17. Oha, K., Animägi, L., Pääsuke, M., Coggon, D., Merisalu, E.: Individual and work-related risk factors for musculoskeletal pain: A cross- sectional study among Estonian computer users. BMC Musculoskeletal Disorders 15(1), 1–5 (2014).
18. Andersen, J., Fallentin, N., Thomsen, J. F., Mikkelsen, S.: Risk factors for neck and upper extremity disorders among computers users and the effect of interventions: An overview of systematic reviews. PLoS One 6(5) (2011).
19. Bakhtiar Choudhary, M., Choudary, A., Jamal, S., Kumar, R., Jamal, S.E.: The Impact of Ergonomics on Children Studying Online During COVID-19 Lockdown. Journal of Advances in Sports and Physical Education 3(8), 117–120 (2020).
20. Lis, A. M., Black, K. M., Korn, H., Nordin, M.: Association between sitting and occupational LBP," European Spine Journal, 16(2), 283–298 (2007).
21. Bhuiyan, T., Hossain, M.: University hall furniture design based on anthropometry: An artificial neural network approach. International Journal of Industrial and Systems Engineering 20(4), 469–482 (2015).
22. Kuorinka, I., Jonsson, B., Kilbom, A., Vinterberg, H., Biering-Sørensen, F., Andersson, G., Jørgensen, K.: Standardised Nordic questionnaires for the analysis of musculoskeletal symptoms. Applied Ergonomics 18(3), 233–237 (1987).

The PMOs' Roles on Reaching the Brazilian's Sanitation Universalization Goals

Felipe Góes and Marina Bouzon

Abstract Project Management Offices (PMOs) play an important role in connecting the corporative strategy and the projects that are executed. In the current context, where organizations compete in a volatile, uncertain, complex, and ambiguous (VUCA) environment, their use and exploitation among organizations that conduct projects are necessary. Moreover, for public services, in which other interests must be considered besides the organization's, the achievement of sustainable and fair public results must be considered success factors. The Brazilian sanitation scenario passed recently for a change in one of its main norms, which, among other changes, established the universalization achievement by 2033, which means water access to 99% and sewage collection to 90% of its population. The present scenario, mainly related to sewage collection, is distant from the goals defined by the norm revision, bringing the necessity to change the current status quo regarding planning and executing infrastructure projects for sanitation services. This study aims to uncover the PMO roles, considering the project management literature, for the achievement of Brazilian's goals of sanitation universalization. As a result, many responsibilities and strategies are recommended that could be assigned to organizations that manage sanitation systems by using PMOs as catalysts in the universalization process.

Keywords Brazil · Sanitation · PMO

1 Introduction

Although it is a fundamental right recognized by the United Nations (UN), billions of people worldwide still do not have access to quality sanitation [1]. Despite the advances, Brazil still has great deficiencies in water supply and sewage collection

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and treatment services, which, in turn, present great regional, state, and municipal disparities [2, 20]. Regarding sewage collection, a little more than half of the Brazilian population is served, totaling about 60% [3, 7], and of these, only 78,5% are properly treated before returning to nature [7, 21]. The universalization of sanitation services in Brazil is one of the greatest challenges of the twenty-first century.

In Brazil, contracts for the provision of basic sanitation public services should define universalization goals that ensure that 99% of the population is served with drinking water and 90% of the population is served with sewage collection and treatment by December 31, 2033 [5, 18, 19]. Although there is an effort through norms for such indexes to be reached, some authors consider that the quality of the services provided and the mismatch between the numerous public agents may be barriers to achieving the goals [4, 6, 7, 17]. Moreover, considering the universalization of sanitation as a project that potentially presents multiple external requirements for success, these should be very well defined - in addition to the traditional internal requirements for success: scope, schedule, and cost [11, 24]. The implementation of a Water Supply and Sanitation system (WSS), due to its high implementation costs (also called Capital Expenditures - CAPEX), its considerable structural complexity, and its high logistic mobilization, is considered a capital project [40]. The fact that capital projects move massive resources of organizations is one of the main factors that justify that such projects must add maximum value to these organizations; that is, they must be connected to the cooperative strategy [26, 27, 40].

Considering the need to observe the corporate strategy to have an effective project management process [9, 10], Project Management Offices (PMOs) have been used to lead organizations to achieve their strategic objectives [8, 15, 25]. However, there are several roles that PMOs have played in various markets over the past few years [9, 10, 12, 13]. Thus, which type of PMO would be more adequate for the public objective of universalizing sanitation services in Brazil is addressed. Therefore, this paper aims to suggest the role that PMOs can play in the universalization of sanitation in Brazil.

2 Literature Review

Considering the objective of this work, this item aims to gather the necessary concepts to enable the collection of results for further analysis. Concepts related to Brazilian basic sanitation and the different PMOs reported in the literature over the past few years are presented.

2.1 The Brazilian Sanitation Scenery

The Brazilian Association of Sanitary Engineering (ABES) published an instrument to analyze Brazilian sanitation in 2021 called ABES Ranking of Sanitation

Table 1 KPIs to Brazilian sanitation as defined by ABES [22]

KPI	Description	Source
Water supply (R1)	Index of the population covered with water supply services	SNIS, IN055_AE
Sewage collection (R2)	Index of the population covered with sewage collection services	SNIS, IN056_AE
Sewage treatment (R3)	Index of the population covered with sewage treatment services	SNIS, IN046_AE
Residue collection (R4)	Index of the domestic solid residue collection services in relation to the total population of the municipality	SNIS, IN015_RS
Adequate destination of the residue (R5)	Index of solid residues generated by the municipality that are adequately disposed	SNIS, UP080; UP025; UP003

Table 2 Municipalities efforts classification as defined by ABES [22]

Category	Criteria
Towards universalization (C1)	Over 489.00
Commitment to the universalization (C2)	450.00–489.00
Diligence to the universalization (C3)	200.00–449.99
First steps to the universalization (C4)	Under 200.00

Table 3 KPIs results by ABES [22]

Category	Amount cities	R1	R2	R3	R4	R5	Total
C1	119	99.51	98.41	99.69	98.06	100.00	495.67
C2	253	93.79	88.41	95.61	93.33	99.68	470.82
C3	1.106	82.10	55.82	50.43	85.86	60.87	335.07
C4	192	53.68	17.56	14.66	64.05	6.84	156.79

Universalization 2021 [22]. In this document, five KPIs were defined and analyzed, which have as a source the National Sanitation Information System (SNIS) from its standardized indicators (IN and UP), arranged in Table 1. These indicators derive from a self-assessment that municipalities do and make data available in the system.

Among the 5570 Brazilian cities, 1670 participated in the survey, equivalent to 30% of the total. However, in terms of population concentration, this amount totals 69% of the Brazilian population. The absence of the other cities is justified by the incomplete presentation of all the indicators shown in Table 1. The participating municipalities were classified into small to medium sizes (up to 100 thousand inhabitants). Based on the result in relation to the sum of the performance of the indicators (500.00 being the maximum result), the municipalities were classified with regard to the distance to the universalization of their sanitation, according to Table 2.

Based on the data informed by the municipalities themselves in the SNIS, ABES [22] built Table 3 with the results of its research.

In an analogous study, Oliveira, Scazufuca and Sayon [23] carried out a work to update the Brazilian Sanitation Ranking published since 2007. This ranking

Table 4 Sanitation services KPIs researched by Oliveira, Scazufuca and Sayon [23]

Dimension	KPI	Source
Service Level	Total Water Supply (ITA)	IN055
	Urban Water Supply (IUA)	IN023
	Total Sewage Collection (ITE)	IN056
	Urban Sewage Collection (IUE)	IN024
	Total Sewage Treatment (ITR)	IN046/IN056

considers the one hundred largest Brazilian municipalities from the population estimate performed by the Brazilian Institute of Geography and Statistics (IBGE) in 2020. In this study, six KPIs were considered, which were also based on SNIS data, as shown in Table 4.

2.2 *The Evolution of PMOs and Their Role in Capital Projects*

Capital projects are the structures and equipment that, when deployed, represent the most valuable part of the final project delivery [40]. Capital projects involve the construction/expansion of a plant and/or equipment facilities to produce a new product and maintain/expand operating capacity [40, 41].

Considering portfolio management as more than a set of norms and procedures but rather a cultural process inherent to organizations [11], the need for good practices and standard procedures dissemination is crucial. Therefore, project management offices (PMOs) are considered the entity responsible for deploying, keeping, and supplying the organization's needs regarding project management [28, 29]. PMOs are also known as management structures that standardize project-related governance processes [14, 38], by providing a wide variety of portfolio management capabilities [25] and executing them in a professional form [26]. These aspects should not only be linked to economic-financial considerations but also other factors, such as corporate risks and eligible benefits [36]. Another aspect in the literature, which deals with the strategic change of organizations and their ecosystem, concerns the co-evolution processes of PMOs and the organizational strategy to which they are linked to [13, 16, 33, 35–37]. As an entity traditionally related to the portfolio management of certain organizations, PMOs participate in the process of unfolding corporate strategy into projects [10, 30, 34, 37] so that they become attentive to the strategic needs of the organization to which they belong. This effort demands a dynamic corporate communication system; an efficient deployment of the organization's key processes; and active participation and engagement of employees [31, 32]. There are numerous types of PMOs in the literature. Although there are plenty of them, they all possess different degrees of the characteristics described above. Table 5 shows different conceptions of PMOs in the literature.

Table 5 Examples of PMOs types

PMO Types	Author
Supporter (A1); Controller (A2); Coordinator (A3)	Unger, Gemunden, and Aubry [42]
Project Control Office (B1); Business Unit Project Office (B2); Strategic Project Office (B3)	Crawford [43]
Project Control Office (C1); Business Unit PMO (C2); Strategic/Enterprise PMO (C3)	Dinsmore and Cabanis-Brewin [50]
Functional Project Office (D1); Customer Group Project Office (D2); Corporate Project Office (D3)	Kerzner [49]
The Supporter (E1); The Information Manager (E2); The Knowledge Manager (E3); The Coach (E4)	Desouza and Evaristo [46]
Center of Excellence (F1); Project Support Office (F2); Project Management Office (F3); Program Management Office (F4); Accountable Project Office (F5)	Verzuh [45]
Project Repository (G1); Coach (G2); Enterprise (G3); Deliver Value Now (G4)	Kendall and Rollins [48]
Project Control Office (H1); Project or Program Office (H2); Project Management Center of Excellence (H3); Strategic Project Office (H4)	Englung, Graham and Dinsmore [44]
Control Tower (I1); Weather Station (I2); Resource Pool (I3)	Casey and Peck [47]

3 Data and Methodology

This study uses data available in the literature to seek to link the use of PMOs to the achievement of the goals of universalization of basic sanitation in Brazil. This link is made from a narrative literature review, an appropriate method for discussing the development of a given subject from the author's theoretical point of view [39].

Although the research makes use of some quantitative data, especially those related to the Brazilian sanitation scenario, this study is considered to be qualitative, since the aforementioned quantitative data will be considered to qualify a situation, in the same way that the findings and their discussions will be qualitative, to establish parallels and opportunities for the use of PMOs in the universalization of sanitation.

For the literature research regarding WSSs and PMOs, the databases Scopus, Google Scholar, and IEEE were consulted, as well as some books that traditionally figure among those cited by the literature in the databases [9–11, 14, 25–28, 43, 49–51]. The string used to locate the literature related to PMOs on the databases considered the terms "Project Management Office" and "PMO", resulting in 229 studies on Scopus, 11,300 on Google Scholar, and 30 on IEEE, giving a total amount of 11,559. In the WSS research related to WSSs, the terms "Water and Sanitation Systems" and "Brazil" were used, resulting in 2 studies on Scopus, 1840 on Google Scholar, and zero on IEEE, giving the total amount of 1842. In both scenarios, the 20 studies classified as most relevant were selected for this study, bringing the final amount of 40 studies considered within the databases.

Regarding the Brazilian WSS scenario, the studies that supported the findings and discussions were mainly based on the results of studies conducted by ABES [22] and Oliveira, Scazufuca and Sayon [23], which were selected for this work because: (i) both are contemporary; (ii) both make use of SNIS data; and (iii) both are considered traditional sources in the area of Brazilian sanitary engineering. This study method was listed to establish the degree of relevance of the theme and encourage other related studies to be conducted.

Finally, regarding the multiple PMOs' classifications, all listed in Table 5, this study considered these different definitions, aiming to compare them in the face of the PMOs' traditional goals and responsibilities. Therefore, this study attempts to indicate the most appropriate PMO framework for the Brazilian WSS scenario and objectives.

4 Findings and Discussion

The studies performed by ABES [22] and Oliveira, Scazufuca and Sayon [23] do not share the same context since, while ABES [22] considered all the municipalities that properly responded to the data in SNIS (totaling 1670 cities), Oliveira, Scazufuca and Sayon [23] considered the hundred largest Brazilian cities in estimate populational terms. Referring to the study conducted by ABES [22], Fig. 1 shows the cities distribution among Categories C1, C2, C3, and C4.

While a minority of the municipalities participating in the survey (about 7%) appear in the most favorable scenario for the universalization of sanitation, about 78% are far from this achievement. Figure 2 explores the cities distributing them among the Brazilian regions.

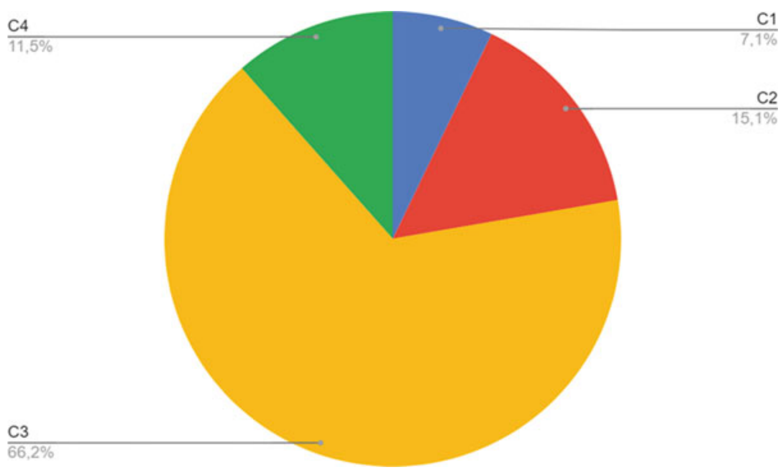

Fig. 1 Cities' distribution among the Categories

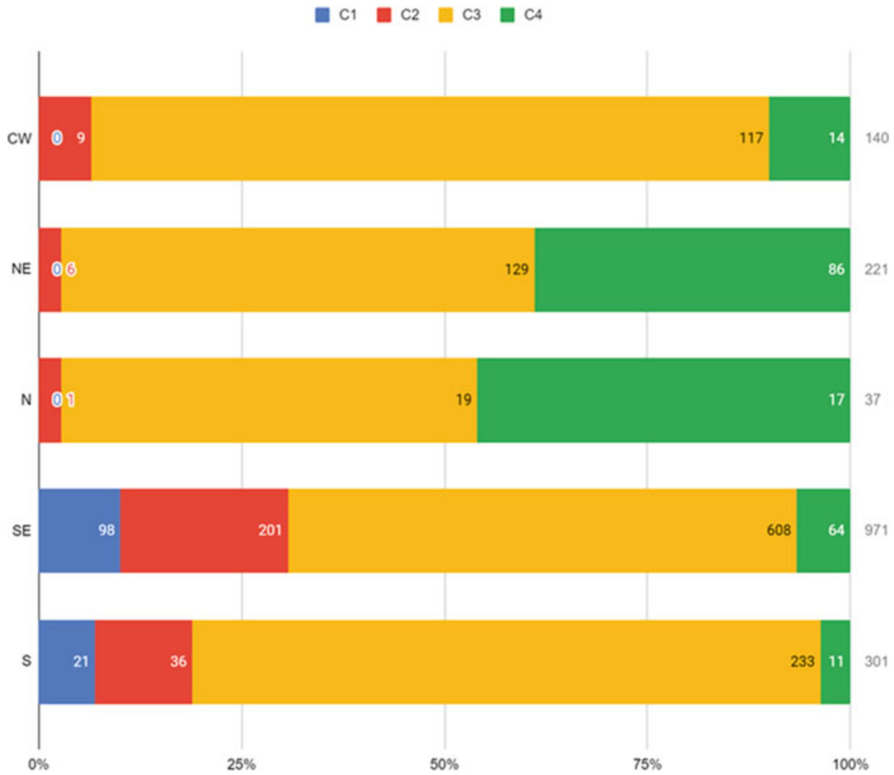

Fig. 2 Distribution of the cities among the Brazilian regions and their categories

The KPIs listed in Table 5 were calculated and materialized in Fig. 3, generating different possibilities for analysis.

It can be seen that 90% of the hundred largest Brazilian municipalities are served with drinking water (ITA) and that a small part of them (5%) is served between 20.1 and 59.9% of their population. The study shows that attendance in the urban context (IUA), isolating the rural part of these cities, follows the same trend. Regarding sanitary sewage (ITE), the study shows that 53% of the hundred largest cities of Brazil present total sewage attendance and that 35% of the municipalities present coverage between 40 and 59.9%. This scenario is similar to the urban context (IUE). Finally, the result regarding the treated sewage index in relation to water consumption (ITR) is noteworthy as it presents a practically uniform distribution among the hundred largest Brazilian municipalities. Specifically, in the Total Sewage Collection and Urban Sewage Collection (ITE and IUE, respectively), it can be seen that the sewage coverage in the one hundred largest Brazilian cities is still far from the value targeted by the New Sanitation Regulatory Framework (90% by the year 2033). The Service Level, as supported by Oliveira, Scazufuca and Sayon [23], consists of KPIs related to the availability of services, without mentioning their quality.

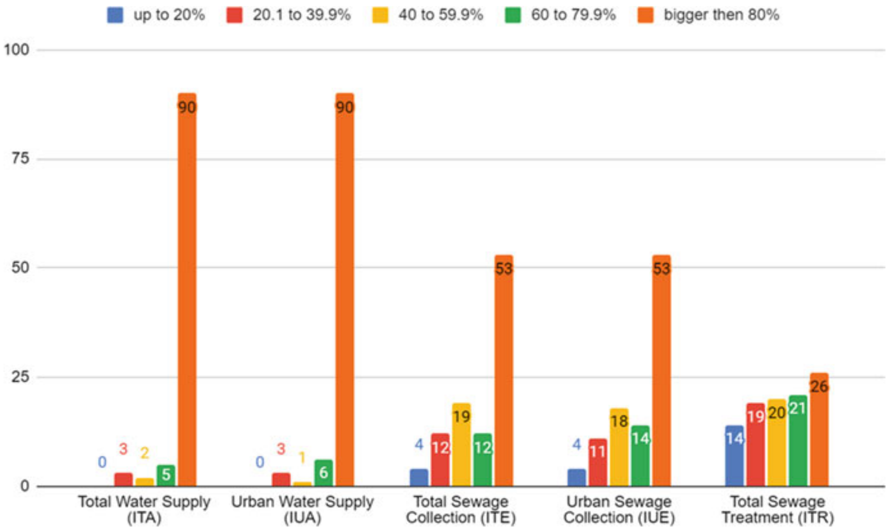

Fig. 3 KPIs results for the Service Level

In this sense, based on the results of the studies conducted by Almeida [26], Barcaui [27], Verzuh [51], and Hobbs and Aubry [52], the different types of PMOs presented in the literature were considered and classified according to their responsibilities and roles within organizations, as shown in Table 6.

As can be seen in Table 6, the literature search resulted in 32 different types of PMOs. Given the different ways in which PMOs traditionally act, it can be seen that, depending on the role considered, whether they can properly play it or not.

Considering that WSS projects (for being mostly understood as capital projects) consume a considerable amount of organizational resources, it is necessary that the structure built to manage such projects provides validation processes of the projects according to their economic-financial profitability, corporate risks and adherence to its business portfolio. With correct execution of the projects, there is an increase in the organization's value. In this sense, based on Barcaui [27] and Prado [40], governance is an essential feature to conduct the work of a PMO under these conditions, since governance represents the set of best practices applied by senior management to guide the decision-making process assertively against the complexity of internal and external factors to organizations.

Thus, PMOs B3, C3, D3, F5, and H4 are the only ones that play the governance level, providing these characteristics to the organizational structure to which they belong. In the case of PMO H2, which partially plays the governance role, it is necessary to investigate whether the level reached by it satisfies the different and complex needs of authority, control, and management that capital projects usually require.

Table 6 Roles associated with the types of PMOs according to the references

	Unger et al. [42]			Crawford [43]			Dinsmore and Cabanis-Brewin [50]			Kerzner [49]			Desouza and Evaristo [46]				Verzuh [45]					Kendall and Rollins [48]				Englund, Graham and Dinsmore [44]				Casey and Peck [47]		
Variable	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3	E1	E2	E3	E4	F1	F2	F3	F4	F5	G1	G2	G3	G4	H1	H2	H3	H4	I1	I2	I3
Governance	–	–	–	–	–	x	–	–	x	–	–	x	–	–	–	–	–	–	–	–	x	–	–	–	–	–	o	–	x	–	–	–
Portfolio Management	–	–	o	–	–	x	–	–	x	–	–	x	–	–	–	–	–	–	–	x	x	–	–	–	o	–	x	–	x	–	–	–
Benefits Management	–	–	x	–	x	x	–	x	x	–	–	x	–	–	–	–	–	–	–	x	x	–	–	–	x	–	x	–	x	–	–	–
Resources Management	–	o	x	o	x	x	o	x	x	o	–	x	–	–	–	x	–	–	–	x	x	–	–	–	x	–	x	o	x	–	–	x
Budget Control	o	x	x	x	x	x	x	x	x	x	o	o	o	o	o	x	–	–	o	o	x	–	o	x	x	x	o	o	o	–	o	o
Schedule Control	o	x	x	x	x	x	x	x	x	x	o	o	o	o	o	x	–	–	x	x	x	–	o	x	x	x	o	o	o	–	o	o
Support	x	x	x	x	x	x	x	x	x	x	x	o	x	x	x	x	o	x	x	x	x	o	x	x	x	x	x	x	o	x	x	x
PM Methods	–	x	x	x	x	x	x	x	x	x	o	o	x	–	x	x	x	x	x	x	x	–	x	x	x	x	x	x	o	–	o	x
PMIS	x	x	x	x	x	x	x	x	x	x	x	–	x	x	x	x	–	–	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Training	x	x	x	x	x	x	x	x	x	x	x	–	o	–	x	x	o	o	o	o	o	o	x	x	x	–	–	x	–	o	x	x
Label	x = Play fully the role										o = Play partially the role										– = Don't play the role											

Urban infrastructure works have a considerable CAPEX cost. Given the high financial amount, projects for this type of work should be managed to add maximum value to the beneficiary organization, reducing the mapped risks, in addition to being in good financial health and connected to the organization's strategic objectives. Considering the roles traditionally played by PMOs, one realizes that their use by sanitation organizations can be beneficial, both in terms of maintaining and expanding the service portfolio (internal success factors) and in terms of development structures that effectively cooperate in the development of the local population (external success factors). To this end, it is recommended to use PMOs whose roles are linked to the organization's senior management and strategy.

Given the urgency established by the New Sanitation Regulatory Framework, which establishes 2033 as the deadline for universalizing sanitation in Brazil, the efficient use of cooperative capital when running WSS should be a central objective. The chances of achieving this goal tend to increase with the adoption by the organization of a PMO that operates in the deployment of corporate strategy in projects.

5 Conclusions

This study explored the current Brazilian sanitation scenario, especially regarding drinking water distribution services and sanitary sewage collection and treatment. Based on surveys carried out by renowned sources in the area, this scenario enabled the recognition of the areas furthest from reaching the universalization of sanitation, considering where they are today in terms of efforts to achieve it. Likewise, KPIs were recognized referring to the availability of WSS in Brazilian municipalities, indicating that the services referring to water, in an average perspective, are close to universalization. Regarding sewage services, the scenario is the opposite. Given that only 53% of the sample municipalities have a sewage collection percentage equal to or higher than 80%, one can see that it is a great effort to transform the reality of those municipalities that still do not have sewage collection services. The challenge becomes even bigger when one realizes that most of these municipalities lacking WSS are located in regions with unfavorable social and economic indexes, such as the north and northeast regions of Brazil. Therefore, the presence of PMOs that prioritize projects that are feasible to be executed and operated, as well as more chances of serving the largest number of people in a satisfactory level of quality, is essential for organizations that operate WSS. Finally, it was noted that capital projects require a governance role from the PMOs they are linked to, seeing that the multiple different agents related to these projects need to be involved in the decision-making process.

Along the development of this work, some limitations were perceived: due to the fact that the theme of this article (the link between PMO and WSS) is not extensively treated in academic literature, the authors needed to refer to the specialized literature of each one of the components to create a solid theoretical foundation, which makes difficult the process of gathering knowledge in a defined number of pages. Likewise, it is understood that another limitation of this work is linked to the fact that the literature review was not carried out systematically, making it difficult for other authors to reproduce it and reach the same results.

For future studies, we recommend the characterization of existing PMOs in sanitation organizations, whether public or private, and their adherence to the types of PMOs existing in the literature. It is also recommended to apply MCDA tools to understand the variables' relation and prioritization presented in Table 6 to the WSS scenario. Finally, we recommend running a survey to measure the PMO impact in WSS organizations.

References

1. Naylor, K., Gordon, B.: Learning from history: sanitation for prosperity. World Health Organization, https://www.who.int/news/item/19-11-2020-learning-from-history-sanitation-for-prosperity, last accessed 2022/12/12.
2. Ferreira, J. G., Gomes, M. F. B., Dantas, M. W. A.: Desafios e controvérsias do novo marco legal do saneamento básico no Brasil. Brazilian Journal of Development 7(7), 65449–65468 (2021).
3. Pereira, L. H. C.: O desafio da universalização do saneamento básico no Brasil e a contribuição da participação popular para a sua efetividade. In: Dissertação de Mestrado na Universidade Presbiteriana Mackenzie, São Paulo (2021).
4. Coutinho, C. C.: Proposta de PMO para racionalização de recursos de uma empresa de saneamento básico. In: Dissertação de Mestrado na Universidade Federal Fluminense, Rio de Janeiro (2021).
5. Brasil: Lei nº 14.026, de 15 de julho de 2020. Dispõe sobre a atualização do Marco Legal do Saneamento Básico. http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2020/lei/l14026.htm, last accessed 2022/12/13.
6. Kresch, E. P., Walker, M., Best, M. C., Gerard, F., Naritomi, J.: Sanitation and property tax compliance: Analyzing the social contract in Brazil. Journal of Development Economics 160, 1–12 (2023).
7. Borges, M. C. P., Abreu, S. B., Lima, C. H. R., Cardoso, T., Silvia, M. Y., Araujo, W. D. V., Silva, P. R. S., Machado, V. B., Moraes, V., Silva, T. J. B., Reis, V. A., Santos, J. V. R., Reis, M. L., Canamary, E. A., Vieira, G. C., Meireles, S.: The Brazilian National System for Water and Sanitation Data (SNIS): Providing information on a municipal level on water and sanitation services. Journal of Urban Management 11(4), 530–542 (2022).
8. Patanakul, P.: How to Achieve Effectiveness in Project Portfolio Management. IEEE Transactions on Engineering Management 69(4), 987–999 (2022).
9. Dinsmore, P. C.: Winning business with enterprise project management. AMACOM, New York (1998).
10. Rabechini Jr., R., Carvalho, M. M.: Gerenciamento de Projetos na Prática. 1st edn. Atlas, São Paulo (2010).
11. Kerzner, H.: Gestão de Projetos: As melhores práticas. 2nd edn. Bookman, Porto Alegre (2006).
12. Aubry, M., Lavoie-Tremblay, M.: Organizing for the management of projects: The project management office in the dynamics of organization design. In: Cambridge Handbook of Organizational Project Management (2017).
13. Hobbs, B., Aubry, M., Thuillier, D. The project management office as an organizational innovation. International Journal of Project Management 26(5), 547–555 (2008).

14. Project Management Institute: A guide to the Project Management Body of Knowledge PMBOK Guide. 7th edn. Project Management Institute, Newton Square (2021).
15. Sanz, M. M. M., Ortiz-Marcos, I.: Dimensions of knowledge governance in a multi-PMO project context. International Journal of Managing Projects in Business 13(7), 1423–1441 (2020).
16. Pinto, G. O., Mello, L. C. B. B., Spiegel, T.: Melhores práticas na implantação de um escritório de Gerenciamento de Projetos: uma revisão sistemática da literatura. Sistemas & Gestão 14(4), 448–463 (2019).
17. Galvão, A. C., Paganini, W. S.: Aspectos conceituais da regulação dos serviços de água e esgoto no Brasil. Engenharia Sanitária e Ambiental 14(1), 78–88 (2009).
18. Ribeiro, B. C., Bin, A., Serafim, M. P.: Innovation dynamics of the state basic sanitation companies. Engenharia Sanitária e Ambiental 27(2), 305–314 (2022).
19. Brasil: Lei no 14.026/2020. Dispõe sobre o Novo Marco Legal do Saneamento. http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2020/lei/l14026.htm, last accessed 2022/12/14.
20. Brasil: Plano Nacional de Saneamento Básico (PLANSAB) (2019). https://www.gov.br/mdr/pt-br/assuntos/saneamento/plansab/Versao_Conselhos_Resoluo_Alta__Capa_Atualizada.pdf, last accessed 2022/12/13.
21. Borja, P. C.: Política pública de saneamento básico: uma análise da recente experiência brasileira. Saúde Sociedade 23(2), 432–447 (2014).
22. Associação Brasileira de Engenharia Sanitária (ABES): Ranking ABES da Universalização do Saneamento (2021). https://abes-dn.org.br/wp-content/uploads/2021/06/Ranking_2021_1917_7_compressed.pdf, last accessed 2022/12/13.
23. Oliveira, G., Scazufuca, P., Sayon, P. L.: Ranking do Saneamento 2022 - Instituto Trata Brasil (SNIS 2020). https://tratabrasil.org.br/wp-content/uploads/2022/09/Relatorio_do_RS_2022.pdf, last accessed 2022/12/13.
24. Lundin, R. A.: Project society: paths and challenges. Project Management Journal 47(4), 7–15 (2016).
25. Project Management Institute: The standard for Portfolio Management. 4th edn. Project Management Institute, Newton Square (2017).
26. Almeida, N. O.: Gerenciamento de Portfólio e PMO. 1st edn. Editora FGV, Rio de Janeiro (2017).
27. Barcaui, A.: PMO: escritórios de projetos, programas e portfólio na prática. Brasport, Rio de Janeiro (2012).
28. Jugend, D., Barbalho, S. C. M., Silva, S. L. (org.): Gestão de Projetos: Teoria, Prática e Tendências. 1st edn. Elsevier, Rio de Janeiro (2014).
29. Martins, A. P., Martins, M. R., Pereira, M. M. M., Martins, A. M.: Implantação e consolidação de escritório de gerenciamento de projetos: um estudo de caso. Production 15(3), 404–415 (2005).
30. Oliveira, R. R., Cruz, J. E., Oliveira, R. R.: Fatores críticos de sucesso na gestão de projetos: Análise dos indicadores que constituem os predecessores da estratégia, pessoas e operações. Revista de Gestão e Projetos (9)3, 49–66 (2018).
31. Ferreira, S. A., Neto, J. V., Batista, H. M. C. S.: Critical success factors on project and process management in competitive strategy implementation. Brazilian Journal of Operations & Production Management 16(4), 605–616 (2019).
32. Suarez, E., Calvo-Mora, A., Roldán, J. L.: The role of strategic planning in excellence management systems. European Journal of Operational Research 248, 532–542 (2016).
33. Aubry, M., Hobbs, B., Muller, R., Blomquist, T.: Identifying the Forces Driving Frequent Change in PMOs. Project Management Institute, Newton Square (2011).
34. Aubry, M.: Project Management Office Transformations: Direct and Moderating Effects That Enhance Performance and Maturity. Project Management Journal 46(5), 19–45 (2015).
35. Bredillet, C., Tywoniak, S., Tootoonchy, M.: Why and how do project management offices change? A structural analysis approach. International Journal of Project Management 36(5), 744–761 (2018).

36. Confido, J. V., Wibisono, D., Sunitiyoso, Y.: A proposed selection process in over-the-top Project Portfolio Management. Journal of Industrial Engineering and Management 11(3), 371–389 (2018).
37. Baptestone, R., Rabechini Jr, R.: Influence of Portfolio Management in decision-making. Journal of Industrial Engineering and Management 11(3), 406–428 (2018).
38. Sandhu, M. A., Al Ameri, T. Z., Wikström, K.: Benchmarking the strategic roles of the project management office (PMO) when developing business ecosystems. Benchmarking: An International Journal 26(2), 452–469 (2019).
39. Rother, E. T.: Revisão Sistemática x Revisão Narrativa. Acta Paulista de Enfermagem 20(2), (2007).
40. Prado, D.: Gerenciamento de projetos de capital: para expansão da capacidade produtiva. Editora Falconi, Nova Lima (2014).
41. Scoot-Young, C., Samson, D.: Project success and project team management: Evidence from capital projects in the process industries. Journal of Operations Management 26(6), 749–766 (2008).
42. Unger, B. N., Gemunden, H. G., Aubry, M.: The three soles of a project portfolio management office: their impact on portfolio management execution and success. International Journal of Project Management 30(5), 608–620 (2012).
43. Crawford, J. K.: The Strategic Project Office. CRC Press, Boca Raton (2010).
44. Englund, R. L., Graham, R. J., Dinsmore, P. C.: Creating the Project Office - a manager's guide to leading organizational change. Jossey-Bass, San Francisco (2003).
45. Verzuh, E.: The fast forward MBA in Project Management. John Wiley & Sons Inc, New York (2005).
46. Desouza, K., Evaristo, J.: Project Management Offices: a case of knowledge-based archetypes. International Journal of Information Management 25(6), 414–423 (2006).
47. Casey, W., Peck, W.: Choosing the right PMO setup. PM Network 15(2), 40–47 (2001).
48. Kendall, G., Rollins, S.: Advanced Project Portfolio Management and the PMO: Multiplying ROI at Warp Speed. J. Ross Publishing, Boca Raton (2003).
49. Kerzner, H.: Project Management - A systems approach to Planning, Scheduling and Controlling. John Wiley Inc, New Jersey (2009).
50. Dinsmore, P. C., Cabanis-Brewin, J.: The AMA Handbook of Project Management. AMACOM, New York (2011).
51. Verzuh, E.: The Portable MBA in Project Management. John Wiley & Sons Inc, New Jersey (2003).
52. Hobbs, B., Aubry, M.: An Empirically Grounded Search for a Typology of Project Management Offices. Project Management Journal 39(1), 569–582 (2008).

PMS-SMEs Network: A Framework to Measure the Performance of SMEs in a Collaborative Context

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Abstract The purpose of this paper is to develop a performance measurement system for small and medium-sized enterprises (SMEs) in a collaborative context (PMS – SME networks). This proposal uses the Balanced Scorecard (BSC) and fuzzy TOPSIS method to address the strategic alignment that frames a performance measurement and management process and; at the same time, the complexity of the group decision-making process, present in collaborative contexts. This proposal assesses how the integration of the multidimensional perspective of BSC together with the multi-criteria decision analysis can support the collaborative performance measurement process. Following a constructivist approach, a framework based on three phases is conceptualized. The methodologic procedure adopted provides promising results for decision-makers, as it helps to integrate a set of indicators from a group-structured strategic map. With this framework the collaborative networks of SMEs are able to structure their PMS with a strategic focus, integrating an expert group within the process.

Keywords Performance measurement system · Collaborative context · Fuzzy TOPSIS method

1 Introduction

The strategic importance of collaborations between companies is now broadly recognized under an operative, scientific and institutional perspective [1, 2]; in this sense, several research contributions have shown that small and medium-sized enterprises (SMEs) in their path towards development and competitiveness have

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incorporated new trends of configuration and organization using collaboration [1, 3]. Technological, social and consumer behavior changes, derived from globalization, increase complexity in the business environment [2, 4, 5], which demands more intense collaboration to improve strategic and operational performance.

In the management practice of SMEs, the need to establish links between planning, decision, action and results by organizations both in individual and collective action has generated a substantial interest in the measurement of organizational performance [6]. Researchers and practitioners in the areas of management and performance measurement have been working on a wide range of issues related to the design, use, implementation and evaluation of performance measurement systems [7–13]. However, the results obtained do not fully evidence a specific approach of the factors that interact in the different collaborative contexts in which SMEs participate, such as collaborative networks. In this sense, the present study seeks to answer the following interrelated question: How can the performance of SMEs acting in collaboration be measured?

In the current context, characterized by globalization and high competition, the performance measurement (PM) in collaborative SMEs must be formulated in such a way that it considers the set of particularities of their environment, trying to cover the reality that wraps it up. Therefore, this proposal seeks to contribute to the knowledge of networks' performance measurement of SMEs where collective efficiency is the driving force for a sustainable development. Based on a constructivist approach, the study emphasizes in the importance of developing a conceptual understanding of related literature; then, it investigates the facts and interprets them dynamically to reach a new learning paradigm [14, 15]. The conceptual framework integrates two tools: (1) the BSC as a method for the strategic direction and growth of the study network from a circular analysis [16], which guides its development with the recognition of the initial strategic management of the network; and (2) fuzzy TOPSIS, as a method to address the multicriteria analysis process in the network decision ambit. Then, an updated strategic map is obtained and with this, a set of measurement indicators is established.

The following section presents a literature review of the performance measurement in the collaborative context of SMEs; next, a review of the main methodological foundations used in the study is presented. Section 3 presents the conceptual framework developed. Section 4 presents the conclusions, contributions and next steps.

2 Literature Review

2.1 Performance Measurement (PM)

[6] defined performance as "a notion that permeates contemporary societies, as it is used to assess the quality of individual and collective efforts". [17] noted that "collaborative work at the organizational level is a key factor in maintaining or

creating a competitive advantage". In this sense, performance measurement systems (PMS) have been playing an important support to develop this type of organization (SME) [8] and, at the same time, these have been transformed according to the demands of the dynamic environment [18].

The strategic alignment of PM is essential for large and small companies. However, many of the available performance measurement methodologies do not take into account the differences generated by company size [7, 19]. For [7], the performance measurement in SMEs needs appropriate and specific systems that tackle the specific and organizational characteristics of these companies. Table 1 shows some studies carried out in the field of PM in SMEs, highlighting their respectful contributions: performance measures (M), PMS developed (D) and PMS proposals (P) and; the business context adopted: supply chain (SC) and networks or clusters (N/C).

Despite the progress made in this field, contributions towards the design and implementation of PMSs in SMEs are still limited [12, 20–22], even more so when collaborative contexts are addressed [5]. The literature highlights the challenge of designing and implementing PMSs for SMEs that work collaboratively and use them as a support for decision making [21, 23, 24]. Some studies (Table 1) highlight the importance of PM in SMEs in different business contexts and with different focuses: reference models [13, 25–28], performance measures [29–31] and treatment of the uncertainty present in the measurement process [32, 33].

These new developments and approaches emphasize the relevance of change, collaboration, shifting professional boundaries and knowledge sharing [10, 34]. Knowledge Translation allows a greater understanding of how and to what extent new ideas and advances (scientific and technological) are translated in different contexts, which encourages new thoughts and frameworks for management and improvement studies [34].

Another challenge identified is related to the uncertainty associated with the process of formulating a PMS. According to de Sousa et al. [24], most PMSs are affected by the inaccuracy and vagueness of a number that is not able to represent the uncertainty of the process design. Problems of decision making inherent in the design process frequently demonstrate this type of issue. Given these limitations, the present study integrates in a conceptual framework a proposal to measure the performance in SME networks (PMS-SME Networks), based on Balanced Scorecard (BSC) and the fuzzy TOPSIS method. All this with the objective of overcoming some of the gaps identified in previous studies regarding the formulation of a PMS for SMEs acting in collaborative spaces.

Although the methodologies for measuring performance in SMEs acting in collaboration are increasingly varied [20], it is clear that none of them brings together all the particularities and challenges highlighted. With the PMS-SME Network based on BSC, the study establishes the strategic alignment of indicators to performance measurement with strategic objectives of the network [19], incorporating the group of variables present at the collaborative level [35, 36]. In addition, with the incorporation of fuzzy TOPSIS as a method for multicriteria analysis (MCDA) [37–41], it contributes addressing the uncertainty present in the decision making process during the PMS definition phase.

Table 1 Proposals in the field of SMEs PM in collaborative contexts

Authors	Business context	Brief description of the study	Scope
[20]	N/C	Based on the financial statements, the performance of the virtual network of SMEs is evaluated	M
[21]	N/C	Identification of patterns for the analysis and evaluation of networks	D
[22]	N/C	Conceptual model for performance management based on innovation and PM of SMEs	M
[12]	SC	Model to evaluate the performance of a SC based on BSC	P
[23]	SC	Performance measurement in an enterprise as part of the SME's revitalization program	D
[24]	N/C	Conceptual model for a cluster performance measurement	P
[9]	N/C	Model for evaluation of network performance	P
[25]	SC	Model for the performance evaluation of a SC based on BSC-AHP	P
[26]	SC	Model for the performance evaluation in a SC based on BSC-SCOR model	P
[27]	N/C	Model for the evaluation of the performance of a local cooperative network	P
[28]	SC	Implementation of BSC for performance evaluation	D
[29]	N/C	Network and cluster configurations and the evaluation of their performance	D
[30]	SC	Performance evaluation model based on the dimensions of cost, time and reliability	P
[4]	N/C	Model to evaluate cooperative network performance based on key success factors	P
[31]	SC	PMS for the marine fisheries SC	P
[32]	SC	Proposal that quantified the operation of a lean supply chain with respect to stochastic and diffuse uncertainties of performance measures	D
[33]	N/C	Evaluation of the level of collaborative performance	M
[34]	N/C	Performance evaluation of a system for food safety of animal origin—European case	M
[35]	N/C	This study assessed the impact of collaborative practices on the performance of SMEs	D
[36]	SC	PM in SC: Literature review	D
[37]	SC	Comparative performance evaluation model for utilities, 47 performance indicators were identified.	M
[38]	SC	This study identifies critical supply chain measures which are interrelated and in contradiction with each other	M
[39]	SC	Relationship between green supply chain management, environmental performance and SC performance in South African SMEs	D
[40]	SC	Assessment of knowledge in lean supply chain management in SMEs and PMS in SC for the twenty-first century	D
[41]	N/C	The exchange of information and the integration of suppliers and their influence on the buyer-supplier relationship in the context of small businesses.	D
[13]	N/C	Comprehensive model to measure the performance dimensions of industrial clusters, using a hybrid approach of Q factor analysis and cluster analysis.	P

The combination of the mentioned methods can contribute with significant benefits to situations of performance measurement of SMEs acting in collaborative networks, where inevitably a set of variables takes part and, consequently, the methodologies used can be effective for their approach. The following section presents the conceptual framework development.

2.2 Balanced Scorecard (BSC)

The BSC is the most used PMS model [44]. It analyses the performance of an organization from four different perspectives: financial, customer, process, and innovation and learning. Following Kaplan & Norton [45], these perspectives are adapted according to an organization's needs and context. The BSC is one of the management practices most frequently used by large, medium and small companies and, during the last decade, there has been considerable progress to improve its implementation in SMEs [2, 36, 46, 47]. However, despite the broad benefits of BSC in SMEs [45], studies of the application of this practice in these types of companies are still scarce [2, 36].

The BSC is not only a strategic PMS, it is also a tool for knowledge transfer, as it allows the deployment of the strategy of the organizations to the bottom level in a structured manner through the establishment of achievable objectives [19]. Among the highlights of the BSC are: deploy the vision and strategy of the organization; communicate and link the strategic management processes; perform business planning based on available resources; and support the learning and communication processes (feedback and feedforward) [45]. When using the BSC, SMEs that are collaborating integrate this set of elements through different performance measures. The heterogeneity of the group's objectives is captured from financial objectives, allowing its consolidation in terms of reputation, visibility and growth [2, 9].

2.3 Multi-Criteria Decision Analysis (MCDA)

The challenge for an individual or group of individuals facing a complex decision is to try to solve it. Among the possible benefits of performing a decision-making process are: the creation of innovative alternatives; a better understanding of the key factors of the problem and the interrelationships of its components and variables; better communication between the stakeholders of the problem; and the evaluation of the solution alternatives [48].

MCDA methods have been diversifying and increasing to support decision-makers, these methods are widely used tools to deal with unstructured problems that contain multiple and potential conflicting objectives [49]. The group multi-criteria decision analysis adds: experience, knowledge and creative ideas of each individual as well as the synergy search that strengthens the quality of the decision process [50]. The creation of expert panels, dialogue tables or specialized juries are the most common schemes of group decision-making [51].

The Technique for order performance by similarity to ideal solution (TOPSIS) is part of the set of methods to solve MCDA problems [49]. TOPSIS is widely used to solve ranking problems [52, 53]. It is based on the concept that the chosen alternative must have the shortest distance to the positive ideal solution (that is, obtain minimum gaps in each criterion) and the longest distance to the negative ideal solution (that is, achieve the maximum level in each criterion) [39, 54].

The traditional TOPSIS method assumes ratings and weights of criteria in crisp numbers. However, in real-life scenarios, the crisp data is inadequate to model a real-life situation since human judgement is vague and cannot be estimated with exact numerical values [49]. In this situation, fuzzy set theory is introduced to model the uncertainty of human judgments. In fuzzy TOPSIS valuations and weights are defined by using linguistic variables [55].

In this study, the fuzzy TOPSIS method is considered as an approximation for the prioritization of alternatives. In the literature, there are several applications of TOPSIS in management. These include marketing studies [56], supply chain [49], manufacturing problems, evaluation and selection of personnel and suppliers [38, 40, 53] and identification of strategies in various fields [41]. Likewise, this method is integrated with other methods for increasing the potentiality of the solution provided.

2.4 Fuzzy Set Theory

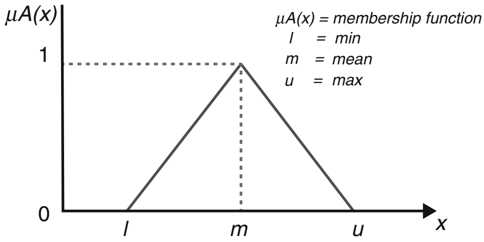
Fuzzy set theory [57] has been used to support decision-making processes based on inaccurate and uncertain information [40], aiding in modelling problems that involve qualitative information and that are not quantifiable by nature. A fuzzy set is a class of objects characterized by a membership function $\mu_A(x)$, belonging to the universe X, in relation to the fuzzy set A, whose possible values vary between 0 and 1 that represents a degree of membership of the $\mu_A(x)$ objects, as shown in (1) [57].

$$\mu_A(x) : X \rightarrow [0, 1]; x \epsilon X \tag{1}$$

If $\mu_A(x)$ is equal to 0, x does not belong to the fuzzy set A; and if $\mu_A(x)$ is equal to 1, x belongs completely to the fuzzy set A. In fuzzy set theory, the values of the variables are qualitatively expressed by linguistic terms, and quantitatively by diffuse sets in the universe of discourse and the respective membership function [40].

The morphology of a fuzzy number is defined by the behavior of $\mu(x)$. A fuzzy triangular number is described by its membership function that constructs linear segments in the shape of a triangle. Using a more concise notation (Eq. 2), a

Fig. 1 Triangular fuzzy number



triangular number A can be written in the form (l, m, u) where m denotes a formal value for the fuzzy set, l is the lower limit and u the upper limit, as shown in Fig. 1.

The degree of membership of $\mu_A(x)$ is defined by (2).

$$\mu_A(x) = \begin{Bmatrix} 0, \text{if} \leq l \\ \frac{x-l}{m-l}, \text{if } x \in [l, m] \\ \frac{u-x}{u-m}, \text{if } x \in [m, u] \\ 0, \text{if } x \geq u \end{Bmatrix} \quad (2)$$

3 Conceptual Framework

In this work, a conceptual framework, both theoretically and empirically, is used as a structure to synthesize the existing visions in the literature about a given situation [42, 43]. The conceptual framework represents an integrated way of looking at the problem, based on an inductive process, where a series of elements that allow a broad understanding of the phenomenon of interest and its complete approach is gathered [42].

The proposed framework is based on the performance measurement of collaborative networks of SMEs and allows the integration of a set of indicators with the vision and strategic planning of the SMEs network. With the dynamic participation of the main stakeholders, both the strategic direction of the network and the formalization of the pertinent indicators for the study network are established.

The framework inputs are the measurement requirements considered based on the criteria of the stakeholders and the influencing factors taken from the environment; the generated result is a PMS for SMEs networks acting in collaboration (Fig. 2).

Then, the framework proposes firstly the design of a PMS using the BSC for the recognition of the current measurement scheme in the network, and subsequently for the consolidation of a desired strategic planning and consequently an updated strategic map and, secondly, Fuzzy TOPSIS as a MCDA method for determining strategic objectives, which will support the development of a set of indicators linked to the objectives pursued by the network (Fig. 3).

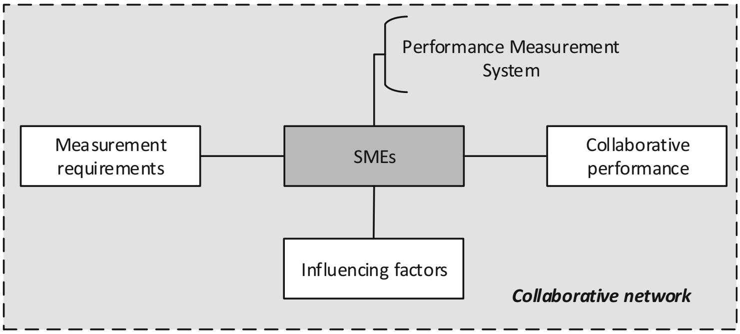


Fig. 2 Framework inputs for performance measurement in collaborative networks

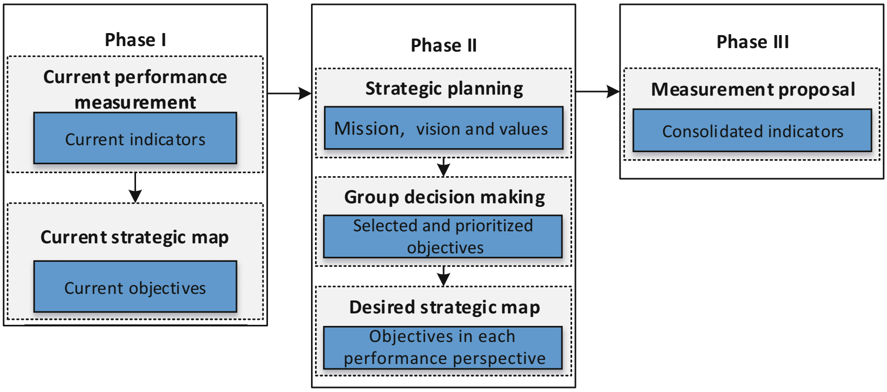


Fig. 3 Conceptual framework for performance measurement in collaborative networks

3.1 Phase I

The conceptual framework begins with the recognition of the current strategic actions, this is "to reveal what is currently controlled", so, in this phase, it is sought to identify performance indicators and therefore the strategic objectives (SOs) in force in the network. The purpose of this recognition is to identify a current situation regarding performance measurement.

3.2 Phase II

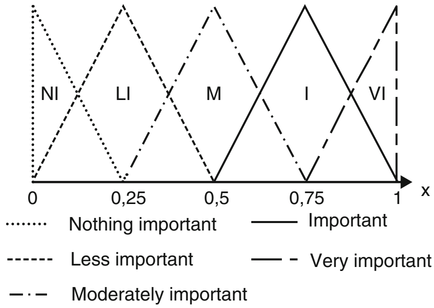
Next, Phase II develops a group decision-making process with the participation of a panel of experts to guide the identification and prioritization of SOs at a financial level, which later will be called alternative decisions. The SOs from the perspectives related to stakeholders, internal processes and learning, and growth are triggered below. A strategic map includes the set of objectives obtained.

Table 2 Group decision-making process for the selection of alternatives (SOs)

Stages	Definition
Structuring	Establish the purpose of the decision
	Set up the decision-maker committee
	Determine the decision alternatives
Evaluation	Determine the evaluation criteria
	Determine the weights of the criteria
	Evaluation of the alternatives with respect to the aggregate criteria
	Add the preferences of decision-makers
Ranking and selection	Prioritise and select the evaluated alternatives

Table 3 Scale used to assess the importance of the criteria

Criteria	
Linguistic value	**Fuzzy value**
Nothing important (NI)	(l_{NI}, m_{NI}, u_{NI})
Less important (LI)	(l_{LI}, m_{LI}, u_{LI})
Moderately important (MI)	(l_{M}, m_{M}, u_{M})
Important (I)	(l_{I}, m_{I}, u_{I})
Very important (VI)	(l_{VI}, m_{VI}, u_{VI})



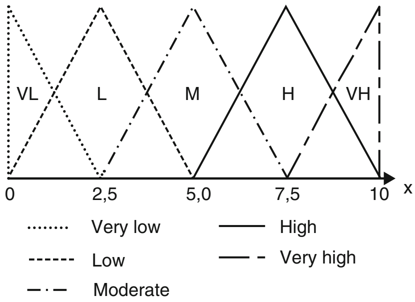
The process designed for this purpose consists of three stages: structuring, evaluation and ranking - selection [51]. Eight sequential steps are part of this process (Table 2).

Next, the definition of the weight of the criteria is carried out using Table 3, where the scale that allows decision makers (DMs) to evaluate the proposed criteria is stipulated. Similarly, the DMs use the information in Table 4 to evaluate the decision alternatives. Finally, the process of aggregation of preferences for the judgments of the DMs is carried out. In the ranking and selection stage, specialists established the most relevant alternatives in the financial perspective; for this, they considered the available resources and the commitment to use them.

With this, the strategic alignment of PMS is established. The strategic map desired by the network is structured based on the definition of the SOs in the three remaining perspectives from a top-down approach. The decision committee established the SOs that support the network strategy and planning. The information that came from this phase was consolidated in a Strategic Map (Fig. 4).

Table 4 Scale used to assess the relevance of decision alternatives

Alternatives	
Linguistic value	**Fuzzy value**
Very low (VL)	(l_{VL}, m_{VL}, u_{VL})
Low (L)	(l_L, m_L, u_L)
Moderate (M)	(l_M, m_M, u_M)
High (H)	(l_H, m_H, u_H)
Very high (VH)	(l_{VM}, m_{VM}, u_{VM})



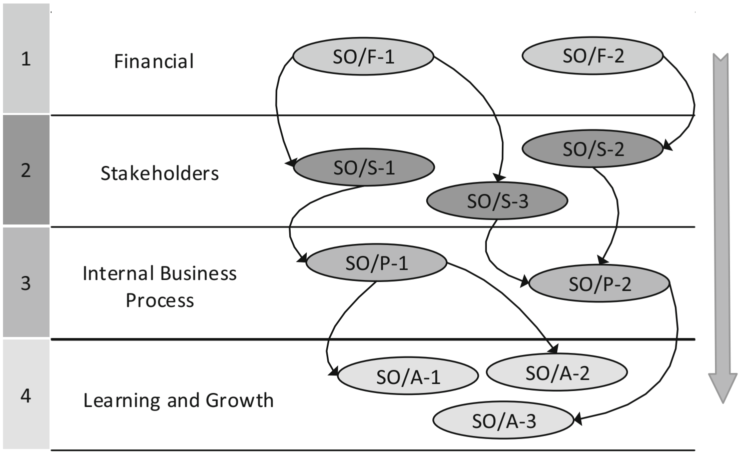


Fig. 4 Example of strategic network map

3.3 Phase III

In this phase, the definition of indicators is carried out within each perspective. The specialists summoned are in charge of establishing the indicators based on the SOs of each perspective.

4 Conclusions, Contributions and Next Steps

The proposed framework can be very useful for structuring a PMS in SMEs networks that take a current measurement situation as a reference, redefine strategic planning and trigger measurement indicators based on a group decision-making process. Additionally, the framework can be used as a reference for SMEs' managers acting in collaborative environments when they seek to achieve a sustainable development based on specific measurements of their operations.

In the development of the proposal it was evident that understanding the influencing factors and measurement requirements are crucial to designing a PMS; with this the participation of decision makers (an expert group), allows incorporating these elements from direct sources.

The research question was addressed through the combined use of two tools, the BSC (reference model for performance measurement) in which strategic alignment is framed, and fuzzy TOPSIS as a multi-criteria analysis method to address decision-making processes in groups.

This research is a work in progress that can lead to various research projects. Below, we can point out some of these possible directions: The implementation of this conceptual framework would provide information on the influence of external factors on the operation of the PMS in the study sector. Likewise, the implementation of the strategic map and the indicators derived for performance measurement in other networks of the same sector would determine the robustness and reliability of the proposal. In addition, complementary studies could include the use of other multicriteria methods, as well as addressing the uncertainty present in the group decision-making process.

References

1. Bititci, U., Turner, T., Mackay, D., Kearney, D., Parung, J., Walters, D.: Managing synergy in collaborative enterprises. Production Planning & Control. 18, 454–465 (2007). https://doi.org/10.1080/09537280701494990
2. Aureli, S., Cardoni, A., Baldo, M.D.: The balanced scorecard logic in the management control and reporting of small business company networks: A case study. 17, 24 (2018)
3. Rojas-Lema, X., Alfaro-Saiz, J.-J., Rodríguez-Rodríguez, R., Verdecho, M.-J.: Organizational Structures in Small and Medium-Sized Enterprises (SMEs) and Their Performance Measurement Systems. En: Ortiz, Á., Andrés Romano, C., Poler, R., y García-Sabater, J.-P. (eds.) Engineering Digital Transformation. pp. 121–131. Springer International Publishing (2019)
4. Ferreira, P.S., Shamsuzzoha, A.H.M., Toscano, C., Cunha, P.: Framework for performance measurement and management in a collaborative business environment. International Journal of Productivity and Performance Management. 61, 672–690 (2012). https://doi.org/10.1108/17410401211249210
5. Bititci, U., Garengo, P., Doerfler, V., Nudurupati, S.: Performance Measurement: Challenges for Tomorrow*. International Journal of Management Reviews. 14, 305–327 (2012). https://doi.org/10.1111/j.1468-2370.2011.00318.x
6. Micheli, P., Mari, L.: The theory and practice of performance measurement. Management Accounting Research. 25, 147–156 (2014). https://doi.org/10.1016/j.mar.2013.07.005
7. Hudson, M., Smart, A., Bourne, M.: Theory and practice in SME performance measurement systems. International Journal of Operations & Production Management. 21, 1096–1115 (2001). https://doi.org/10.1108/EUM0000000005587
8. Garengo, P., Biazzo, S., Bititci, U.S.: Performance measurement systems in SMEs: A review for a research agenda. International Journal of Management Reviews. 7, 25–47 (2005). https://doi.org/10.1111/j.1468-2370.2005.00105.x

9. Varamäki, E., Kohtamäki, M., Järvenpää, M., Vuorinen, T., Laitinen, E.K., Sorama, K., Wingren, T., Vesalainen, J., Helo, P., Tuominen, T., Pihkala, T., Tenhunen, J.: A framework for a network-level performance measurement system in SME networks. International Journal of Networking and Virtual Organisations. 5, 415–435 (2008). https://doi.org/10.1504/IJNVO.2008.018830
10. Cocca, P., Alberti, M.: A framework to assess performance measurement systems in SMEs. International Journal of Productivity and Performance Management. 59, 186–200 (2010). https://doi.org/10.1108/17410401011014258
11. Sousa, S., Aspinwall, E.: Development of a performance measurement framework for SMEs. Total Quality Management & Business Excellence. 21, 475–501 (2010). https://doi.org/10.1080/14783363.2010.481510
12. Pekkola, S., Saunila, M., Rantanen, H.: Performance measurement system implementation in a turbulent operating environment. International Journal of Productivity and Performance Management. 65, 947–958 (2016). https://doi.org/10.1108/IJPPM-01-2015-0018
13. Yadegari, R., Rahmani, K., Khiyabani, F.M.: Providing a Comprehensive Model to Measure the Performance Dimensions of Industrial Clusters Using the Hybrid Approach Of Q-Factor Analysis And Cluster Analysis. International Journal for Quality Research. 13, 235–248 (2019). https://doi.org/10.24874/IJQR13.01-14
14. Ensslin, L., Dutra, A., Ensslin, S.R.: MCDA: a constructivist approach to the management of human resources at a governmental agency. Int Trans Operational Res. 7, 79–100 (2000). https://doi.org/10.1111/j.1475-3995.2000.tb00186.x
15. Vogel-Walcutt, J.J., Gebrim, J.B., Bowers, C., Carper, T.M., Nicholson, D.: Cognitive load theory vs. constructivist approaches: which best leads to efficient, deep learning? Journal of Computer Assisted Learning. 27, 133–145 (2011). https://doi.org/10.1111/j.1365-2729.2010.00381.x
16. Biazzo, S., Garengo, P.: Performance Measurement with the Balanced Scorecard. Springer Berlin Heidelberg, Berlin, Heidelberg (2012)
17. Bititci, U.S., Mendibil, K., Martinez, V., Albores, P.: Measuring and managing performance in extended enterprises. International Journal of Operations & Production Management. 25, 333–353 (2005). https://doi.org/10.1108/01443570510585534
18. Yadav, N., Sagar, M.: Performance measurement and management frameworks: Research trends of the last two decades. Business Process Management Journal. 19, 947–971 (2013). https://doi.org/10.1108/BPMJ-01-2013-0003
19. Garengo, P., Biazzo, S.: Unveiling strategy in SMEs through balanced scorecard implementation: A circular methodology. Total Quality Management & Business Excellence. 23, 79–102 (2012). https://doi.org/10.1080/14783363.2011.637800
20. Taticchi, P., Asfalti, A., Sole, F.: Performance measurement and management in smes: Discussion of preliminar results from an Italian survey. En: Business Performance Measurement and Management: New Contexts, Themes and Challenges. pp. 3–11 (2010)
21. Chalmeta, R., Palomero, S., Matilla, M.: Methodology to develop a performance measurement system in small and medium-sized enterprises. International Journal of Computer Integrated Manufacturing. 25, 716–740 (2012). https://doi.org/10.1080/0951192X.2012.665178
22. Bertolli, M.P., Roark, G., Urrutia, S., Chiodi, F.: A Review of Performance Measurement's Maturity Models. INGE CUC. 13, 70–83 (2017). https://doi.org/10.17981/ingecuc.13.1.2017.07
23. Aramyan, L.H., Oude Lansink, A.G.J.M., van der Vorst, J.G.A.J., van Kooten, O.: Performance measurement in agri-food supply chains: a case study. Supply Chain Management: An International Journal. 12, 304–315 (2007). https://doi.org/10.1108/13598540710759826
24. de Sousa, S.D.T., Nunes, E.M.P., da Silva Lopes, I.: Uncertainty Components in Performance Measures. En: Yang, G.-C., Ao, S., y Gelman, L. (eds.) IAENG Transactions on Engineering Technologies: Special Volume of the World Congress on Engineering 2012. pp. 753–765. Springer Netherlands, Dordrecht (2013)
25. Bhagwat, R., Sharma, M.K.: Performance measurement of supply chain management: A balanced scorecard approach. Computers & Industrial Engineering. 53, 43–62 (2007). https://doi.org/10.1016/j.cie.2007.04.001

26. Thakkar, J., Kanda, A., Deshmukh, S.G.: Supply chain performance measurement framework for small and medium scale enterprises. Benchmarking. 16, 702–723 (2009). https://doi.org/10.1108/14635770910987878
27. Argyropoulou, M., Sharma, M.K., Bhagwat, R., Lazarides, T., Koufopoulos, D.N., Ioannou, G.: Measuring Supply Chain Performance in SMES. En: Handbook on Business Information Systems. pp. 699–715. WORLD SCIENTIFIC (2010)
28. Manville, G., Papadopoulos, T., Garengo, P.: Twenty-first century supply chain management: a multiple case study analysis within the UK aerospace industry. Total Quality Management & Business Excellence. 0, 1–17 (2019). https://doi.org/10.1080/14783363.2019.1642101
29. Kim, J., Kim, Y., Chang, H.: A study on performance evaluation of intelligent collaboration system. Multimedia Tools and Applications. 74, 3305–3316 (2015). https://doi.org/10.1007/s11042-013-1834-9
30. Haider, H., Sadiq, R., Tesfamariam, S.: Inter-Utility Performance Benchmarking Model for Small-to-Medium-Sized Water Utilities: Aggregated Performance Indices. Journal of Water Resources Planning and Management. 142, UNSP 04015039 (2016). https://doi.org/10.1061/(ASCE)WR.1943-5452.0000552
31. Boonsothonsatit, G.: Generic decision support system to leverage supply chain performance (GLE) for SMEs in Thailand. Journal of Manufacturing Technology Management. 28, 737–748 (2017). https://doi.org/10.1108/JMTM-02-2017-0029
32. Bhagwat, R., Chan, T.S.F., Milind, K.: Performance measurement model for supply chain management in SMEs. International Journal of Globalisation and Small Business. 2, 428–445 (2008). https://doi.org/10.1504/IJGSB.2008.018103
33. Behrouzi, F., Wong, K.Y.: An integrated stochastic-fuzzy modeling approach for supply chain leanness evaluation. International Journal of Advanced Manufacturing Technology. 68, 1677–1696 (2013). https://doi.org/10.1007/s00170-013-4966-1
34. Spyridonidis, D., Currie, G., Heusinkveld, S., Strauss, K., Sturdy, A.: The Translation of Management Knowledge: Challenges, Contributions and New Directions. International Journal of Management Reviews. 18, 231–235 (2016). https://doi.org/10.1111/ijmr.12110
35. Pekkola, S., Ukko, J.: Designing a performance measurement system for collaborative network. International Journal of Operations & Production Management. 36, 1410–1434 (2016). https://doi.org/10.1108/IJOPM-10-2013-0469
36. Malagueño, R., Lopez-Valeiras, E., Gomez-Conde, J.: Balanced scorecard in SMEs: effects on innovation and financial performance. Small Bus Econ. 51, 221–244 (2018). https://doi.org/10.1007/s11187-017-9921-3
37. Shih, H.-S., Shyur, H.-J., Lee, E.S.: An extension of TOPSIS for group decision making. Mathematical and Computer Modelling. 45, 801–813 (2007). https://doi.org/10.1016/j.mcm.2006.03.023
38. Kelemenis, A., Askounis, D.: A new TOPSIS-based multi-criteria approach to personnel selection. Expert Systems with Applications. 37, 4999–5008 (2010). https://doi.org/10.1016/j.eswa.2009.12.013
39. Sun, C.-C.: A performance evaluation model by integrating fuzzy AHP and fuzzy TOPSIS methods. Expert Systems with Applications. 37, 7745–7754 (2010). https://doi.org/10.1016/j.eswa.2010.04.066
40. Lima-Junior, F.R., Carpinetti, L.C.R.: Combining SCOR® model and fuzzy TOPSIS for supplier evaluation and management. International Journal of Production Economics. 174, 128–141 (2016). https://doi.org/10.1016/j.ijpe.2016.01.023
41. Maghsoodi, A.I., Khalilzadeh, M.: Identification and Evaluation of Construction Projects' Critical Success Factors Employing Fuzzy-TOPSIS Approach. KSCE J Civ Eng. 22, 1593–1605 (2018). https://doi.org/10.1007/s12205-017-1970-2
42. Imenda, S.: Is There a Conceptual Difference between Theoretical and Conceptual Frameworks? Journal of Social Sciences. 38, 185–195 (2014). https://doi.org/10.1080/09718923.2014.11893249

43. Adom, D., Hussein, E., Agyem, J.: Theoretical and Conceptual Framework: Mandatory ingredients of a Quality Research, (2018)
44. Kaplan, R.S., Norton, D.P.: The Balanced Scorecard—Measures that Drive Performance. 10 (1992)
45. Kaplan, R.S., Norton, D.P.: Using the Balanced Scorecard as a Strategic Management System. harvard business review. 14 (1996)
46. Machado, M.J.C.V.: Balanced Scorecard: an empirical study of small and medium size enterprises. Rbgn-Revista Brasileira De Gestao De Negocios. 15, 129–148 (2013). https://doi.org/10.7819/rbgn.v15i46.1175
47. Zhang, J.L., Zhou, S.Y.: The construction of informatization performance measurement indicator system for small-and-medium sized enterprises. (2013)
48. Keeney, R.L.: Identifying, prioritizing, and using multiple objectives. EURO J Decis Process. 1, 45–67 (2013). https://doi.org/10.1007/s40070-013-0002-9
49. Singh, R.K., Agrawal, S.: Analyzing disposition strategies in reverse supply chains: fuzzy TOPSIS approach. Management of Env Quality. 29, 427–443 (2018). https://doi.org/10.1108/MEQ-12-2017-0177
50. Goodwin, P., Wright, G.: Decision Analysis for Management Judgment. John Wiley & Sons Ltd, England (2004)
51. Kabak, Ö., Ervural, B.: Multiple attribute group decision making: A generic conceptual framework and a classification scheme. Knowledge-Based Systems. 123, 13–30 (2017). https://doi.org/10.1016/j.knosys.2017.02.011
52. Hwang, C.L., Yoon, K.: Multiple attribute decision making: methods and applications: a state-of-the-art survey. Springer-Verlag, Berlin; New York (1981)
53. Polat, G., Eray, E., Bingol, B.N.: An Integrated Fuzzy MCGDM Approach for Supplier Selection Problem. Journal of Civil Engineering and Management. 23, 926–942 (2017). https://doi.org/10.3846/13923730.2017.1343201
54. Ishizaka, A., Nemery, P.: Multi-criteria decision analysis: methods and software. Wiley, Chichester, West Sussex, United Kingdom (2013)
55. Chen, C.-T.: Extensions of the TOPSIS for group decision-making under fuzzy environment. Fuzzy Sets and Systems. 114, 1–9 (2000). https://doi.org/10.1016/S0165-0114(97)00377-1
56. Chen, Y., Wang, S.: Purchasing channel choice based on fuzzy TOPSIS method. IJSTM. 23, 237 (2017). https://doi.org/10.1504/IJSTM.2017.10006358
57. Zadeh, L.A.: Fuzzy sets. Information and Control. 8, 338–353 (1965). https://doi.org/10.1016/S0019-9958(65)90241-X

Asset Prioritization for Predictive Maintenance in the Context of Industry 4.0: A Group Multicriteria Approach

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Abstract In an industrial facility with hundreds of assets, the difficulty of choosing the equipment to belong to a predictive maintenance project requires a complex resolution strategy since it involves conflicting aspects. The digitalization brought by Industry 4.0 makes companies drastically reduce equipment downtime to offer higher production numbers at lower costs, reducing the working hours of their employees. Still, a lot of maintenance planning relies on the diffuse knowledge of the experts and technicians, lacking a structured and data-driven approach. This study aims to propose and apply a hybrid multicriteria decision-making approach to prioritize assets for predictive maintenance in the digital transformation era. The methodology involved a case study in a manufacturing company, with multiple data collection through scoping review to identify which models were used to prioritize assets for maintenance and digitalization, document analysis (ISO 55000 and ISO 45001 standards), and interviews with professional managers and technicians. The approach involved a hybrid multicriteria group technique to select the preferred asset for predictive maintenance from a set of large-scale printers in a security printing company. Therefore, this study contributes to proving the effectiveness of the approaches employed. From a practical perspective, a Python code was developed and used to implement the methods.

Keywords Hybrid MCDM · Smart maintenance · Printing industry

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1 Introduction

According to [1], Industry 4.0 directly contributes to the technological revolution. Both machines and managers are, daily, faced with decision-making. Considering this, companies must look beyond traditional methods to increase their efficiency [2, 3]. In practice, the current industrial maintenance scenario is still mainly reactive and preventive, with the predictive strategy only applied to critical situations. Implementing frameworks for maintenance management are still scarce, combining data processing, fault diagnosis, prognosis, and decision reasoning [4].

Considering that industries are looking for ways to save financial resources effectively, the possibility of performing predictive maintenance contributes to expanding machine costs, control, and production quality [1]. In this way, there is a stimulus to research for predictive maintenance, and by analogy, [5] assumes that industrial equipment is possible to repair at an appropriate time (before failure occurs) since this approach will restore the equipment to its original condition after the completion of each maintenance.

In this scenario, it is necessary to make an informed decision analysis to select the equipment to initiate the first predictive maintenance tests. Thus, decision-making involves criteria and alternatives for prioritization [6]. Therefore, decision-making involves criteria and alternatives for prioritization, and there is a gap in selecting a decision-making method in maintenance management based on the decision-makers preference [7]. In this sense, with the aid of multicriteria decision-making methods (MCDM), the evaluation process of this work was defined. Maintenance selection using MCDM is in line with [8]. This study aims to propose and apply a hybrid multicriteria decision-making approach to prioritize assets for predictive maintenance in the digital transformation era.

Given this, multiple MCDM techniques can be used for equipment selection, such as Analytic Hierarchy Process (AHP) [8], the Multi-Objective Optimization based on Ratio Analysis (MOORA) method [9], the MULTIMOORA method, which is the sequence of the MOORA method, also proposed by Kracka, Karel, Brauers, and Zavadskas [10] and the Borda method, proposed by Jean Charles de Borda [11].

Therefore, the originality of our work is integrating AHP, MOORA, MULTIMOORA, and Borda methods, to perform the priority ranking of which printer should be submitted first to predictive maintenance in a sequence of 8 large printers. The study will contribute to the improvement of Industry 4.0 as well as to the topic of Smart Maintenance (SM) planning. The contributions mentioned have a strong relationship with production lines since, in industries, equipment maintenance is a crucial aspect and affects equipment uptime and efficiency.

The work is structured as follows: Section 2 presents the background on asset maintenance and the application of multicriteria methods for this purpose. Section 3 presents the methods involved and the case study. In Sect. 4, the results are discussed, and in Sect. 5, the conclusions and research agenda are presented.

2 Background: MCDM in Asset Maintenance

As most manufacturers face limitations of time, money, and other resources, maintenance managers need to focus their attention on investing in the current bottleneck dimension (if any) to achieve the desired level of maintenance performance, and plants with strong and balanced Smart Maintenance standards have higher maintenance performance and productivity [12].

Regarding asset maintenance, in [13], the authors performed a comprehensive study of multicriteria approaches in maintenance applications. The authors found that in maintenance problems, the most common criterion among more the 100 different criteria was cost, which is present in 61.3% of all 259 publications reviewed. [14] used a Fuzzy Multicriteria Decision Making (MCDM) method to contribute to decision-makers in choosing between self-owned or contracted maintenance for the fleet of a cargo or passenger air transport company. [13] applied the AHP to select the best Predictive Maintenance alternative for five practical case studies, including a petrochemical plant, a pharmaceutical company, machine manufacturing, and two food factories [14].

The AHP method is a pairwise hierarchical approach that can be applied to numerous variations of problems [15]. It can be observed that 73% of the applications are handled using AHP, and 39% of the articles use multicriteria decision-making [13]. As a complement, [16, 17] point out that the method aims to explore a qualitative problem using quantitative methods. Furthermore, the Multi-Objective Optimization based on the Ratio Analysis (MOORA) method consists of a matrix of responses of different alternatives on different objectives. This method consists of two components: the ratio system and the reference point approach or the Tchebycheff matrix [9, 10]. [18] report that the MOORA method can be applied in selecting parameters for the operation of a tool.

The Multi-Objective Optimization based on a Ratio Analysis plus the full MULTIplicative form (MULTIMOORA), or the Full Multiplicative Form, is an additional sequence of the MOORA method, which becomes more robust with multiple optimizations with conditions supporting the improved nominal group technique and Delphi technique. The development of MULTIMOORA can also be based on the uncertainty of theories and the analyses of novel models' mathematical formulations [19].

3 Case Study

3.1 Definition of the Unit of Analysis

The manufacturing company, located in the city of Rio de Janeiro, is a public security printing company linked to the Ministry of Finance of Brazil. The case study goal consists of choosing equipment for the final ranking of large printers to apply predictive maintenance to mitigate maintenance costs. The research is based on offset, serigraphic, flexographic, and calcographic type printers.

A flexographic printer is suitable for high and very high print runs. A characteristic of this printing system is a small shadow or blur appearing on the graphics' side. On the other hand, offset equipment is indicated for low, medium, or high runs and has excellent precision. It can be printed on plastics, paper, and metal [20]. A calcographic printer, also known as intaglio, with its characteristic relief, is the main line of defense of the industry against counterfeiters, having the direct printing process by applying pressure and transferring the ink deposited on the lines engraved on the matrix to the paper [21].

3.2 Criteria, Alternatives, and the Hierarchical Structure

Initially, to understand all the stages of the AHP, the research began by discovering the criteria necessary to judge the eight possible alternatives and meet the institution's prerequisites. This way, a group of decision-makers was selected, formed by managers and supervisors of the Maintenance Department.

First, three steps were followed: problem definition, significant criteria identification and alternatives [6]. Five main criteria were obtained that impact the choice of printers (Failure, Safety, OEE, Cost, and Preventive) as per Table 1. The proposed work begins with establishing criteria and scales for evaluation. For this purpose, the ISO 55000 series was followed due to its importance for asset management. Next, the following criteria were developed (see Table 1):

Criteria C1, C3, and C4 are related to performance, criterion C2 regards safety, and criterion C5 regards failure monitoring.

C1 was chosen because the failure of a single machine result in downtime in the other machines. C2 concerns Safety Management because there is a significant and positive relationship between implementing the ISO 45001: 2018 Safety Management System and business performance [22]. C3 is necessary because production managers often use it to examine the performance of machines. This tool is calculated using performance, quality, and availability values [23]. C4 is used to develop advanced maintenance strategies, reducing maintenance costs while maintaining

Table 1 Initial data for data entry

Criteria	Description
C1 fault diagnostics	As a first criterion observing the abnormal state of the equipment
C2 safety information	Unplanned event or occurrence that results in damage or loss. ISO 45001: 2018 Safety Management
C3 OEE	Overall equipment effective
C4 cost	It concerns how much an idle printer impacts production
C5 preventive	Planned and systematic action of prevention tasks on an ongoing basis

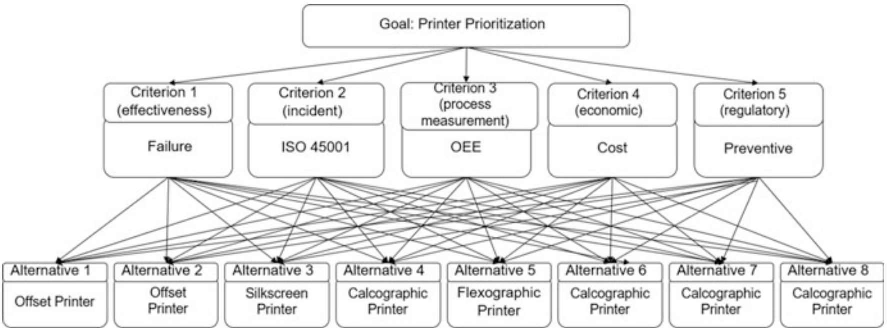

Fig. 1 Hierarchical structure of the decision problem

safety. Finally, C5, because of the dynamic nature of maintenance and the existence of unforeseen or unplanned equipment reliability factors, planning tasks become more complex [20]. Given this, criterion C1 is considered objective, while others are subjective.

To help in the decisions for C1, the decision-makers received the results from the printer failure history over 5 years and a graph developed in Excel with the trend curve tool available in the program. Thus, according to Table 1, five criteria were selected to judge the printers. It also covered the identification of possible alternatives to proceed with the implementation.

As alternatives, there are four types of printers, two offsets (A1 and A2), one silkscreen (A3), one flexographic (A4), and four calcographic (A5 to A8). As Offset is based on the incompatibility between water and grease [24], there are two types of offset printers: flatbed and web offset. Screen printing is the printing process in which ink is pressed through one of a set of perforated screens, of which some holes are closed and others open, allowing a selective passage of the ink onto the paper [19]. A characteristic of these flexographic and calcographic printings is a slight shading or blur appearing on the graphic's side [1]. Figure 1 shows the hierarchical structuring of the decision problem.

3.3 MCDM Methods

The steps envisaged for this work involve multiple MCDM methods, such as AHP with aggregation of individual priorities (AIP). The AHP-AIP approach determines the weights and ranks the alternatives with geometric mean. Then, the Multiple Objective Optimization by Proportion Analysis (MOORA), combined with a more advanced optimization method, and MULTIMOORA were used. Finally, the Borda method ranks the printers that must be submitted in descending order in the predictive maintenance project. The weights used for the criteria in these methods are obtained via the AHP method.

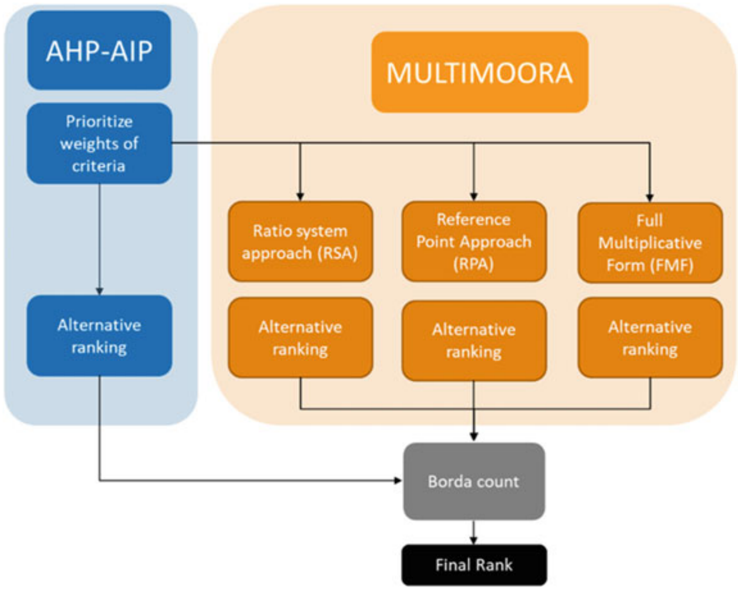

Fig. 2 Hybrid group MCDM approach: AHP-MULTIMOORA-Borda

The four rankings generated by AHP, AHP-MOORA, AHP-MOORA with reference point, and AHP-MULTIMOORA, were presented, and, in the end, the Borda method was used to give the final ranking based on the results of the hybrid MCDM approach applied in the study.

The methods were implemented using Python programming language and Microsoft Excel to collect and process the data. Figure 2 describes the macro steps of the methods.

The steps for the AHP, MOORA and MULTIMOORA methods were performed according to the steps in [8–10], and AHP and MULTIMOORA rankings were aggregated using the Borda method [11].

AHP results can be validated by the consistency rate (CR) formula calculated using the formula CR = CI/RI, where consistency index (CI) is, in turn, measured using the following equation [25]:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

Where λ_{max} is the maximum eigenvalue of the decision matrix, and n is the number of alternatives being compared. RI is the Random Consistency Index [25]. CI must be lower than 0.01 so that pairwise comparisons are considered consistent.

MOORA considers beneficial and non-beneficial objectives (criteria) to rank or select one or more alternatives from a set of available options [26]. Some characteristics of this method are: it belongs to the compensatory methods, attributes are independent, qualitative attributes are converted into quantitative attributes, and it is a simple execution method. The method starts with a matrix of responses to different alternatives to different objectives: (x_{ij}) where x_{ij} is the response of the alternative already to objective i, i = 1, 2, ..., are not the objectives, j = 1, 2, ..., m are the alternatives. MOORA refers to a system in which each response of an alternative on an objective is compared to a denominator, ratio system approach (RSA), which is representative of all alternatives relative to that objective. For this denominator, the square root is chosen as the sum of the squares of each alternative per objective [27].

$$N^{x_{ij}} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}} \tag{2}$$

X_{ij} = response of alternative j to objective i, j = 1, 2, ..., m; m the number of alternatives, i = 1, 2, ..., n; n the number of objectives, NX_{ij} = a dimensionless number representing the normalized response of alternative j to objective i; these normalized responses of alternatives to objectives belong to the interval [0; 1].

For method optimization, these responses are added in case of maximization and subtracted in case of minimization.

$$N^{y_{ij}} = \sum_{i=1}^{i=g} N^{xij} - \sum_{i=g+1}^{i=n} N^{xij} \tag{3}$$

i = 1, 2, ..., g for the objectives to be maximized, i = g + 1, g + 2, ..., n for the objectives to be minimized, $N^{y_{ij}}$ = the normalized valuation of the alternative already with respect to all objectives. In this formula, linearity concerns dimensionless measures in the interval [0; 1]. An ordinal rating of $N^{y_{ij}}$ shows the final preference.

The reference point approach (RPA) is already normalized as defined in the MOORA method, namely Eq. (2). Then, the reference point theory chooses for maximization a reference point, which has as coordinates the highest coordination per objective of all candidate alternatives. For minimization, the lowest coordination is chosen. To measure the distance between the alternatives and the reference point, the Tchebycheff Min-Max metric is chosen [28]:

$$\min_{(j)} \left\{ \max_{(i)} \left| r_i - N^{x_{ij}} \right| \right\} \tag{4}$$

i = 1, 2, ..., n are the objectives, j = 1, 2, ..., m are the alternatives, r_i = i^{th} coordination of the reference point of the maximum objective; each reference point coordinate is selected as the highest corresponding coordinate of the alternatives, $N^{x_{ij}}$ = the normalized objective i of alternative j.

According to [9], MULTIMOORA is an additional sequence of the MOORA method and the full multiplicative form (FMF) of multiple objectives. Finally, the

Borda counting method was used to find the best classification to help technicians and managers understand which printer needs the most urgent preventive maintenance. This method is based on the steps of [29], briefly described in Fig. 2.

3.4 Ranking with AHP-AIP

To implement the case study, it was started with the pairwise comparison scale for the AHP-AIP method, which is suitable when the group of decision-makers is heterogeneous. Saaty's [6] fundamental scale was used to compare the criteria used by the degree of importance [7]. To calculate the consistency ratio, the Random Index (RI) was proposed by Saaty [6].

Then, four decision makers (DM) were chosen from the industry studied. In this way, the reason for the choice was defined since all the decision makers work directly in the maintenance of the printers. With this, a manager, a supervisor, and two technicians from the maintenance area were chosen, and each has a different hierarchy and knowledge level. Table 2 shows the judgments given by one of the DMs, in the position of Manager, through a pairwise comparison matrix and using the Saaty scale [6], to define the relative importance of the criteria.

The matrix in Table 3 shows the alternatives' final ranking according to each DM's judgments and the geometric mean with the final result derived from the AHP.

Table 2 Comparison of criteria according to Saaty's scale (e.g., evaluator Manager)

	C1	C2	C3	C4	C5
C1	**1**	3	3	3	1
C2	0.33	**1**	1	3	1
C3	0.33	1	**1**	1	1
C4	0.33	0.33	1	**1**	1
C5	1	1	1	1	**1**

Table 3 Composite priority of alternatives

	Ranking DM 1	Ranking DM 2	Ranking DM 3	Ranking DM 4	Geometric average
A1	0.25	0.24	0.23	0.20	0.23
A2	0.19	0.19	0.21	0.13	0.18
A3	0.15	0.16	0.16	0.11	0.15
A4	0.14	0.15	0.15	0.11	0.14
A5	0.13	0.13	0.14	0.11	0.13
A6	0.06	0.05	0.05	0.04	0.05
A7	0.05	0.04	0.04	0.03	0.04
A8	0.02	0.02	0.02	0.02	0.02

3.5 Ranking with MULTIMOORA and Borda Count

First, the calculations were performed according to the weights derived from AHP for the criteria. Then the MULTIMOORA method was applied. The rankings obtained from MULTIMOORA and AHP-AIP were then aggregated using the Borda method. Results are shown in Table 4.

4 Discussion

The hybrid MCDM approach was chosen due to the complex nature of the problem [22, 23] and the MULTIMOORA method already provides a meta-ranking of the three MOORA approaches. It is worth mentioning that all matrices generated during the AHP process phases passed the consistency test, thus all pairwise comparisons are considered consistent.

AHP with geometric mean was used to rank the alternatives. Table 4 shows the geometric mean and ranking of the alternatives. Alternative 1 (A1 – Offset printer 01) was selected as the first to undergo predictive maintenance in this classification. Regarding the MOORA approaches (RSA, RPA, and FMF) and the aggregated meta ranking generated by MULTIMOORA, using the weights established from AHP pairwise comparison of criteria importance, A1 also ranked first.

Although all the rankings were the same in the studied case, this can be due to the small set of printers chosen for the proof of concept. To the end of implementing the methods described, Python codes were developed to be used for other problems, select from a larger pool of equipment in the future, or be integrated into digital systems to assist the managers. The hybrid, multimethod approach used provides robustness to the decision-making process, given that different methods can lead to different rankings. From a practical point of view, the MCDM methods used complement each other and help for better management. From a methodological point of view, the MCDM methods used complement each other and enable better management. Another important point for maintenance theory was using an open-source language, thus allowing freedom of use of all methods without the need for expensive commercial-off-the-shelf (COTS) software. These can be considered strengths of the proposed approach.

Gaining knowledge about the equipment that needs to be prioritized for predictive maintenance can drastically mitigate maintenance costs, in addition to increasing the organization's profit and saving operating time, which can bring numerous benefits to operation management in the context of Industry 4.0. Also, the use of digital tools that can provide an assertive decision process, implemented via MCDM methods, to the maintenance teams as well as to managers can enable the use of methods mentioned above even for practitioners in the industry that are not familiar with them.

Table 4 Results

Alternative (Printer)	MOORA ratio system approach		MOORA reference point approach		MOORA full multiplicative form		MULTIMOORA	AHP		Borda
		Rank		Rank		Rank	Rank		Rank	Rank
A1	1.2	1	0.00	1	0.0158	1	1	0.23	1	1
A2	0.94	2	0.13	2	0.00611	2	2	0.18	2	2
A3	0.78	3	0.13	3	0.00389	3	3	0.15	3	3
A4	0.71	4	0.15	4	0.00282	4	4	0.14	4	4
A5	0.66	5	0.17	5	0.00226	5	5	0.13	5	5
A6	0.25	6	0.23	6	0.000136	6	6	0.05	6	6
A7	0.22	7	0.25	7	0.000085	7	7	0.04	7	7
A8	0.10	8	0.27	8	0.000010	8	8	0.02	8	8

5 Conclusion

The research was carried out in a public manufacturing company in a developing country and aimed to prioritize assets to compose predictive maintenance from the digital transformation perspective. A new approach was proposed and applied, combining the rankings of multiple MCDM methods, such as AHP and MULTIMOORA, with Borda counting. The methodology proposed in the case study can help in the selection of assets, regarding the prioritization of equipment, due to the high cost of implementing maintenance. Considering digitalization, the hybrid group decision-making approach can generate a unique ranking to evaluate eight large printers to implement a predictive maintenance project. The whole approach was developed in Python, aiming to automate and make it available for new analyses with the input of new equipment, thus guaranteeing autonomy to improve the model. From a practical perspective, the developed methodology can empower managers and maintenance teams to adopt a more pragmatic and data-driven approach to maintenance planning, leveraging data availability in the context of digital transformation and Industry 4.0 to save costs [30]. Also, it allows practitioners to efficiently plan resource acquisition and allocation, such as spare parts and personnel. Thus, correctly identifying, applying, monitoring, and executing appropriate MCDM methods for maintenance or digitization is an extremely relevant task, as it increases overall maintenance efficacy, ruling out the high costs of implementing new machines. Future works could improve upon the approach adopted by integrating more criteria into the decision problem, which could be composed of data obtained from Machine Learning models that could predict the information of each equipment.

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References

1. Zonta, T., da Costa, C.A., da Rosa Righi, R., de Lima, M.J., da Trindade, E.S., Li, G.P.: Predictive maintenance in the Industry 4.0: A systematic literature review. Comput. Ind. Eng. 150, 106889 (2020). https://doi.org/10.1016/j.cie.2020.106889
2. Machado, E., Scavarda, L.F., Caiado, R.G.G., Thomé, A.M.T.: Barriers and Enablers for the Integration of Industry 4.0 and Sustainability in Supply Chains of MSMEs. Sustain. 13, 11664 (2021)
3. Lima, B.F., Neto, J.V., Santos, R.S., Caiado, R.G.G.: A Socio-Technical Framework for Lean Project Management Implementation towards Sustainable Value in the Digital Transformation Context. Sustain. 15, (2023). https://doi.org/10.3390/su15031756
4. Cachada, A., Barbosa, J., Leitño, P., Gcraldcs, C.A.S., Deusdado, L., Costa, J., Teixeira, C., Teixeira, J.: Maintenance 4.0: Intelligent and Predictive Maintenance System Architecture. In:

IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA) (2018)
5. Zhang, W., Yang, D., Wang, H.: Data-Driven Methods for Predictive Maintenance of Industrial Equipment: A Survey. IEEE Syst. J. 13, 2213–2227
6. Saaty, T.L.: Decision making — the Analytic Hierarchy and Network Processes (AHP/ANP). J. Syst. Sci. Syst. Eng. 13, 1–35 (2004). https://doi.org/10.1007/s11518-006-0151-5
7. Sabaei, D., Erkoyuncu, J., Roy, R.: A Review of Multi-criteria Decision Making Methods for Enhanced Maintenance Delivery. Procedia CIRP. 37, 30–35 (2015). https://doi.org/10.1016/j.procir.2015.08.086
8. Bokrantz, J., Skoogh, A.: Adoption patterns and performance implications of Smart Maintenance. Int. J. Prod. Econ. 256, 108746 (2023). https://doi.org/10.1016/j.ijpe.2022.108746
9. Karel, W., Brauers, W., Zavadskas, E.: The MOORA method and its application to privatization in a transition economy. Control Cybern. 35, (2006)
10. Kracka, M., Karel, W., Brauers, W., Zavadskas, E.: Ranking heating losses in a building by applying the MULTIMOORA. Eng. Econ. 21, (2010)
11. Costa, H.G.: AHP-De Borda: a hybrid multicriteria ranking method. Brazilian J. Oper. Prod. Manag. 14, 281–287 (2017). https://doi.org/10.14488/BJOPM.2017.v14.n3.a1
12. Bokrantz, J., Skoogh, A., Berlin, C., Wuest, T., Stahre, J.: Smart Maintenance: a research agenda for industrial maintenance management. Int. J. Prod. Econ. 224, 107547 (2020). https://doi.org/10.1016/j.ijpe.2019.107547
13. Syan, C.S., Ramsoobag, G.: Maintenance applications of multi-criteria optimization: A review. Reliab. Eng. Syst. Saf. 190, 106520 (2019). https://doi.org/10.1016/j.ress.2019.106520
14. Filho, E.A.C.: Uma contribuição ao estudo do problema da escolha entre manutenção própria ou contratada numa empresa de transporte aéreo, tomando-se por base o método fuzzy multicriteria decision-making (MCDM), (2011)
15. de Paula Vidal, G.H., Caiado, R.G.G., Scavarda, L.F., Ivson, P., Garza-Reyes, J.A.: Decision support framework for inventory management combining fuzzy multicriteria methods, genetic algorithm, and artificial neural network. Comput. Ind. Eng. 174, (2022). https://doi.org/10.1016/j.cie.2022.108777
16. Paz, T. da S.R., Rocha Junior, V.G. da, Campos, P.C. de O., Paz, I., Caiado, R.G.G., Rocha, A. de A., Lima, G.B.A.: Hybrid method to guide sustainable initiatives in higher education: a critical analysis of Brazilian municipalities. Int. J. Sustain. High. Educ. (2022). https://doi.org/10.1108/ijshe-07-2021-0281
17. Cunha, V.H.C., Caiado, R.G.G., Corseuil, E.T., Neves, H.F., Bacoccoli, L.: Automated compliance checking in the context of Industry 4.0: from a systematic review to an empirical fuzzy multi-criteria approach. Soft Comput. 25, 6055–6074 (2021). https://doi.org/10.1007/s00500-021-05599-3
18. Villa Silva, A.J., Pérez Dominguez, L.A., Martínez Gómez, E., Alvarado-Iniesta, A., Pérez Olguín, I.J.C.: Dimensional analysis under pythagorean fuzzy approach for supplier selection. Symmetry (Basel). 11, (2019)
19. Wu, X., Liao, H., Xu, Z., Hafezalkotob, A., Herrera, F.: Probabilistic Linguistic MULTIMOORA: A Multicriteria Decision Making Method Based on the Probabilistic Linguistic Expectation Function and the Improved Borda Rule. IEEE Trans. Fuzzy Syst. 26, 3688–3702 (2018). https://doi.org/10.1109/TFUZZ.2018.2843330
20. Aires, R.F. de F., Ferreira, L.: The rank reversal problem in multi-criteria decision making: a literature review. Pesqui. Operacional. 38, 331–362 (2018). https://doi.org/10.1590/0101-7438.2018.038.02.0331
21. Costa, G.R.T.: O design das cédulas brasileiras do cruzeiro ao real (1970–2010), (2011)
22. Purwanto, A., Putri, R., Haji Ahmad, A., Asbari, M., Santoso, P., Sihite, O.: The Effect of Implementation Integrated Management System ISO 9001, ISO 14001, ISO 22000 and ISO 45001 on Indonesian Food Industries Performance. TEST Eng. Manag. 82, 14054–14069 (2020)

23. Bilgin Sari, E.: Measuring The Performances of the Machines Via Preference Selection Index (PSI) Method and Comparing Them with Values of Overall Equipment Efficiency (OEE). Dokuz Eylul Univ. Iktis. ve Idari Bilim. Derg. 34, 573–581 (2019). https://doi.org/10.24988/ije.2019344859
24. Silva, A.J.V., Domínguez, L.P., Gómez, E.M., Olguín, I.J.C.P., Durán, S.N.A.: Una revisión de literatura de 1980 a 2018 de los métodos Multi-criterio. Mundo Fesc. 9, 89–102 (2019)
25. Taherdoost, H.: Decision Making Using the Analytic Hierarchy Process (AHP); A Step by Step Approach. Int. J. Econ. Manag. Syst. (2017)
26. Karande, P., Chakraborty, S.: Application of multi-objective optimization on the basis of ratio analysis (MOORA) method for materials selection. Mater. Des. 37, 317–324 (2012). https://doi.org/10.1016/j.matdes.2012.01.013
27. Nijkamp, P., van Delft, A.: Multi-Criteria Analysis and Regional Decision-Making. Springer New York, NY, New York (1977)
28. Karlin, S., Studden, W.J.: Tchebycheff Systems: With Applications in Analysis and Statistics. Wiley (1966)
29. Seker, S., Kahraman, C.: Socio-economic evaluation model for sustainable solar PV panels using a novel integrated MCDM methodology: A case in Turkey. Socioecon. Plann. Sci. 77, 100998 (2021). https://doi.org/10.1016/j.seps.2020.100998
30. Lins, M.G., Zotes, L.P., Caiado, R.: Critical factors for lean and innovation in services: from a systematic review to an empirical investigation. Total Qual. Manag. Bus. Excell. (2019). https://doi.org/10.1080/14783363.2019.1624518

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