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IMPLEMENTATION OF PRESCRIPTIVE MAINTENANCE ON THE FACTORY FLOOR: STRATEGIC DECISION STRUCTURED IN SWOT ANALYSIS

IMPLEMENTAÇÃO DE MANUTENÇÃO PRESCRITIVA NO CHÃO DE FÁBRICA: DECISÃO ESTRATÉGICA ESTRUTURADA EM ANÁLISE SWOT

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ABSTRACT

Purpose: The objective of this research is to identify the important factors for implementing the prescriptive maintenance paradigm on the factory floor, considering three main factories as research objects (Company A: Steel; Company B: Mining; Company C: Pulp and Paper), located in the State of Espírito Santo, Southeast Region of Brazil.
Theoretical framework: The implementation of proactive strategies in factories, such as prescriptive maintenance policies, has become increasingly important due to the effects on factory floor productivity and the competitive development of its resources.
Methodology/Approach: The methodological procedures used were the combination of three data collection mechanisms, narrative bibliographic review, document analysis and participant observation. To achieve the general objective, the perceptions of experts and researchers were considered. The contributions arising from the application of SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis for the internal and external environments of the factories made it possible to understand the implications for the implementation of Prescriptive Maintenance in the factory floor.
Findings: Two important results emerged from the research, one model of general use that shows the importance of the implications of the SWOT Matrix in the positioning of decision making and another model specific to the context, to assist in the implementation of the proactive process of Prescriptive Maintenance, providing recommendations for managers and professionals who work on the factory floor.
Research, practical & social implications: The results of this study provide valuable information for formulating proactive maintenance policies aimed at increasing the efficiency of physical assets on the factory floor. They also have important practical implications for strategic maintenance management, for example, the SWOT analysis also suggests that implementing the prescriptive maintenance paradigm is not an easy task for any professional and that it is necessary to weigh all opportunities and threats before making any decision strategic.

Originality/ Value: Based on the data obtained, it is presented an academic contribution to the literature on the importance of implementing proactive maintenance policies on the factory floor, expanding and strengthening the theoretical foundation of intelligent maintenance, and also provided management information for decision-making in the process of implementing the Prescriptive Maintenance paradigm.
Keywords: Efficiency, Maintenance 4.0, Prescriptive maintenance, Factory floor.

RESUMO

Objetivo: O objetivo desta pesquisa é identificar os fatores importantes para a implementação do paradigma de manutenção prescritiva no chão de fábrica, considerando três fábricas principais como objetos de pesquisa (Empresa A: Siderurgia; Empresa B: Mineração; Empresa C: Celulose e Papel), localizadas no Estado do Espírito Santo, Região Sudeste do Brasil.
Referencial Teórico: A implementação de estratégias proativas nas fábricas, como políticas de manutenção prescritiva, tem sido cada vez mais importante devido aos efeitos na produtividade do chão de fábrica e no desenvolvimento competitivo dos seus recursos.
Metodologia/Abordagem: Os procedimentos metodológicos utilizados foram a combinação de três mecanismos de coleta de dados, revisão bibliográfica narrativa, análise documental e observação participante. Para atingir o objetivo geral foram consideradas as percepções de especialistas e pesquisadores. As contribuições advindas da aplicação da análise SWOT (Strengths, Weaknesses, Opportunities, Threats) para os ambientes interno e externo das fábricas permitiram compreender as implicações para a implementação da Manutenção Prescritiva no chão de fábrica.
Resultados: Dois resultados importantes emergiram da pesquisa, um modelo de uso geral que mostra a importância das implicações da Matriz SWOT no posicionamento da tomada de decisão e outro modelo específico para o contexto, que auxilia na implementação do processo proativo de Manutenção Prescritiva, além de fornecer recomendações aos gestores e profissionais que atuam no chão de fábrica, mostrando as necessidades de melhoria nas tarefas de manutenção.
Contribuições, implicações práticas e sociais: Os resultados deste estudo fornecem informações valiosas para a formulação de políticas de manutenção proativas destinadas a aumentar a eficiência dos ativos físicos no chão de fábrica. Têm também implicações práticas importantes para a gestão estratégica da manutenção, por exemplo, a análise SWOT também sugere que implementar o paradigma da manutenção prescritiva não é uma tarefa fácil para qualquer profissional e que é necessário pesar todas as oportunidades e ameaças antes de tomar qualquer decisão estratégica.
Originalidade/Valor: Com base nos dados obtidos, apresenta-se uma contribuição acadêmica para a literatura sobre a importância da implementação de políticas proativas de manutenção no chão de fábrica, ampliando e fortalecendo a fundamentação teórica da manutenção inteligente, e se fornece informações gerenciais para a tomada de decisão no processo de implementando o paradigma da Manutenção Prescritiva.
Palavras-chave: Eficiência; Manutenção 4.0; Manutenção prescritiva; Chão de fábrica.

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1. INTRODUCTION

Studies show that every industrial revolution causes changes in technological, socioeconomic and cultural characteristics. For example, a study by Poór et al. (2019) shows that maintenance management is also among technological resources. The approach to equipment maintenance has changed throughout the evolution, from reactive to predictive maintenance – advanced prescriptive. Establishing a retrospective of the first industrial revolution with corrective maintenance (reactive policy), to the fourth industrial revolution with advanced predictive maintenance and prescriptive maintenance, it is possible to observe a technological leap, extremely proactive.

Roda & Macchi (2021) show that the evolution of maintenance together with the development of information and communication technologies has been studied in the literature since the early 2000s, including concepts such as e-maintenance and smart maintenance. The implementation of Industry 4.0 solutions for the maintenance of production assets is a relevant topic in the mainstream for researchers and industries around the world.

Syverson (2011) emphasizes that with the digitalization of production systems, a growing awareness of persistent differences in productivity and competitiveness across a large number of samples of companies and industries around the world has encouraged research in various fields of economic and industrial thought. Even research in the area of Industrial Organization has connected the productivity and competitiveness of the company with different elements of the value process and competitive market forces. In the article by Stachowiak (2015), it is stated that the performance and competitiveness of companies depend on the availability, reliability and productivity of their production facilities on the factory floor.

Traditional reliability assessment encompasses various statistical and probabilistic methods used to understand and quantify the reliability, availability, and maintainability of a system. According to Friederich & Lazarova-Molnar (2024), to maximize profit and at the same time reduce operational costs, system reliability assessment is typically carried out during the project development phase and applied until end-of-life phase of the system. Ideally, there should be a new assessment whenever changes occur to the system installed on the factory floor.

In this context, a factory floor with availability, reliability and economic levels, operations and processes synchronized with intelligent maintenance or prescriptive maintenance, also known as knowledge-based or cognitive maintenance and optimized based on conditional predictions by Artificial Intelligence, has become an increasingly important issue in the recent competitive world of business. According to the literature (Maleki & Yang, 2017; Manzini et al., 2015; Tsang, 2002; Yun et al., 2012), although trivial maintenance (corrective and preventive policies) frequent in production systems carried out to improve reliability, however resulting in high operational costs.

In recent decades, maintenance has changed radically according not only to technology requirements, but also due to new market requirements, that is, we are in the era of the smart factory (Industry 4.0). We are entering the prescriptive philosophy of maintenance (Smart Maintenance) (Errandonea et al., 2022). Prescriptive maintenance is primarily about shared value with customers through more services, and also with internal ecosystem stakeholders through service capabilities. But it is also coopetition (a set of cooperation and competition strategies) in the business environment, where companies simultaneously compete to capture value and cooperate to co-create value (Grijalvo Martín et al., 2021).

Prescriptive maintenance goes beyond productive, preventive, and predictive maintenance (Errandonea et al., 2022). Errandonea et al. (2022) report that descriptive focuses on what happened in the past. Predictive analytics uncovers potential options for the future. Prescriptive maintenance leverages all of these approaches and capabilities. The realm of what should happen and the execution of optimized maintenance strategies is precisely the realm of prescriptive maintenance. They include that with prescriptive maintenance, devices, in collaboration with operators, are proactive participants in their own maintenance. Several trends are emerging to disrupt manufacturing, especially with regard to maintenance. These include the major forces of digitalization (social, mobile, and cloud), and technologies such as Internet of Things, Big Data analytics, among others.

The focus of the article is to monitor the contributions of SWOT analysis in decision-making to implement Prescriptive Maintenance on the factory floor, with the expectation of generating value in physical assets in order to increase productivity and competitiveness in sync with performance indicators maintenance.

The findings present useful technological reflections and consolidate the implementation of the prescriptive maintenance philosophy in automated projects. Prescriptive maintenance is an important strategy for increasing the reliability, availability and useful life of a system. At the same time, prescriptive maintenance also aims to improve the level of competitiveness on the factory floor, however, in the implementation processes it faces challenges, such as the shortage of specialized labor, the implications for decision-making in the alignment between production management and maintenance, the complexity of production, operational costs with the use of classic preventive maintenance, the difficulties faced in the processes of implementing proactive strategies for sustainable business models, where an ecosystem of agents cooperating in long-term involvement through different workflows.

Thus, in other studies on factory floor maintenance models, researchers (Riis et al., 1997; Errandonea et al., 2020) have emphasized that the implementation of prescriptive analytics is not immediate, and its implementation is usually done gradually. First, addressing operations focused on Condition-Based Maintenance and advancing until prescriptive strategies are achieved. It should also be taken into account that if the asset of interest is not critical to production or does not affect safety, a prescriptive strategy may not be the most cost-effective option.

Therefore, as shown by Sikorska et al. (2011), prescriptive maintenance is an emerging concept addressed by several areas of research in recent years. There are few studies available in scientific literature, as it is a relatively recent term. Considering that the requirements of internal stakeholders change continuously, it is necessary to develop and improve maintenance policies for production systems, strategies to eliminate negative consequences on the factory floor and support the good development of the production system, taking advantage of the digitalization of the industry and the advancement of computing technologies, fundamentally the evolution of maintenance policies through the advent of Prescriptive Maintenance.

To fill this gap, this article aims to identify the important factors for implementing the prescriptive maintenance paradigm on the factory floor, considering three main factories as research objects (Company A: Steel; Company B: Mining; Company C: Pulp and Paper), located in the State of Espírito Santo, Southeast Region of Brazil. Two important models are proposed that emerged from this research, namely, a general purpose one that shows the importance of the implications of the SWOT Matrix in the positioning of decision making and another specific to the context, to assist in the implementation of Prescriptive Maintenance, in addition to providing recommendations to managers and professionals working on the factory floor, showing the needs for improvement in maintenance tasks, that is, considering the importance of digitizing the factory floor.

In this sense, this article follows the following structure. Section 2, we present a comprehensive literature review. In Section 3 we present the methodological development. Section 4 includes results and discussions. Section 5 contains general conclusions and important highlights for future work.

2. LITERATURE REVIEW

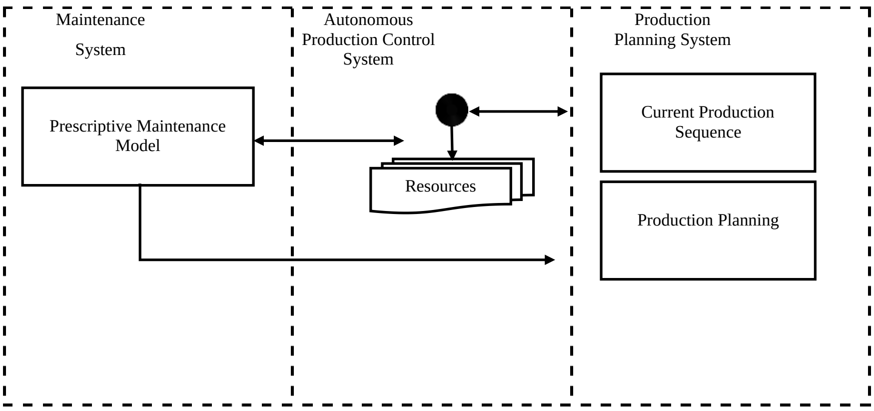
Maintenance is an important activity that occurs on the factory floor. The authors Hooi & Leong (2017) and Habidin et al. (2018) categorically show that machine failures during production can lead to adverse effects on the production schedule, delaying delivery or culminating in the need for overtime and rework of employees to compensate for production losses. Corroborating this, Rodrigues & Hatakeyama (2006), and Poduval et al. (2015) state that in essence, the effects of inadequate or inefficient maintenance activities can determine the profitability and survival of the business.

Manufacturers undergoing lean implementation are constantly seeking the elimination of wastes towards a just-in-time production system (Shah & Ward, 2003; Pinto et al., 2018). In this context, more reliable processes and equipment are fundamental to ensure lower inventory levels (Cua et al., 2001; Jiang et al., 2015). That can be observed either within one company or throughout the whole supply chain (Marodin et al., 2017). Additionally, the delivery of high-quality products with tighter product tolerances and lower levels of scrap and rework also relies on well-maintained equipment (Kaur et al., 2015), providing another reason for developing more effective maintenance activities and processes.

Maintenance has evolved from a reactive function to primarily a preventative (time or condition-based) approach. Robert et al. (2019) show an implementation of an integrated maintenance planning approach linked to the Prescriptive Maintenance Model in an autonomous production system (Figure 1).

Figure 1

Overview of the integrated autonomous production control model.



Source: Adapted from Robert et al. (2019).

Prescriptive maintenance is a proactive model that aims to answer the question "How should an event happen?". Monostori et al. (2016) and Ansari et al. (2017) argue that a direct link is established with maintenance planning and indirectly with production. This makes it possible to diagnose and predict potential issues more effectively. This new model is being adopted by many companies due to its ability to identify and address failure modes.

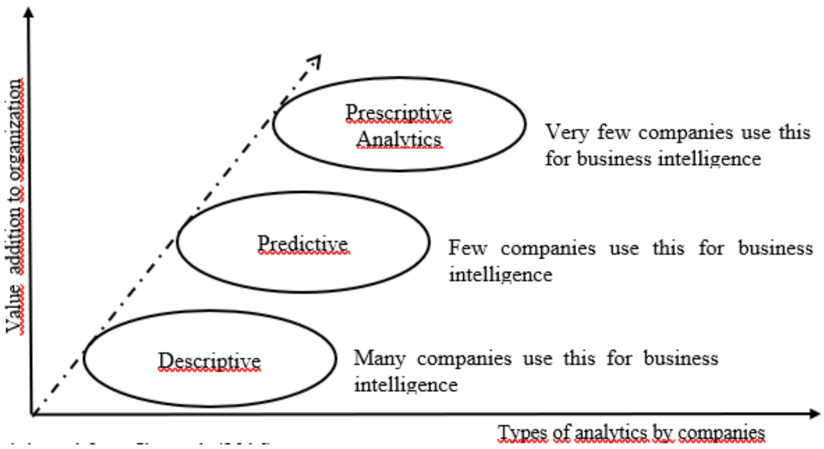
This "smart maintenance object" allows the incorporation of new technologies in the planning, implementation, monitoring and analysis of maintenance processes. These technologies define the next generation in the equipment maintenance approach referred to in the literature as Maintenance 4.0 (Smart Maintenance) or Prescriptive Maintenance.

The main strategy behind the Prescriptive Maintenance paradigm is not only to diagnose the problem, but also to prescribe a solution (Simões et al., 2011). Prescriptive analytics is used to predict multiple future predictions and makes the company use the possible outcome for its future (Sikorska et al., 2011). Prescriptive analytics combines tools and techniques and includes algorithms, business rules, computational modeling, and machine learning procedures. Such techniques are applied to different data sets: transactional and historical, big data, and real-time data.

Although it may have many advantages, it is very complex to manage, and companies avoid it in their daily routine. However, incorporating it into business leads to better decision-making regarding the company's financial results. Jin et al. (2016) emphasize that to successfully optimize production, inventory, and scheduling in large companies, prescriptive analytics is used and it provides better products to optimize customer experience. The use of such analytics in different companies as a value-added service is shown in Figure 2.

Figure 2

Usage of different analytics by companies.



Source: Adapted from Jin et al. (2016).

The reviewed literature is comprised of two parts. Initially, we present the process of evolution of the Prescriptive Maintenance paradigm, followed by a brief discussion on the main Industry 4.0 technologies and their role in transforming the manufacturing ecosystem. In the second part, we will address the concept and impacts of strategic alignment between Prescriptive Maintenance and the factory floor.

2.1 The prescriptive maintenance paradigm

The postmodern century and current society depend on technological and mechanized industries and services to produce and distribute products, meeting market demands. Industrial assets inevitably age and degrade their components, which has a strong impact on production availability and product quality. Due to the widespread use of machine learning techniques in this area of research, several intelligent maintenance paradigms (i.e., Condition-Based Maintenance and Prescriptive Maintenance) have been raised (Sikorska et al., 2011; Bojana et al., 2017).

To counter this situation, managers strategically plan and execute all operation and maintenance activities, for a significant fraction of the total business cost, complying with maintenance strategies classified as reactive, preventive, condition-based, predictive and prescriptive (Errandonea et al., 2020). Kim et al. (2016) showed that the condition-based maintenance strategy is a method of continuous investigation to maintain a constant level of condition. Industry 4.0 technologies, such as the Internet of Things (IoT) and artificial intelligence, have the advantage of detecting anomalies in real time, thus allowing an immediate response; however, the use of these technologies can be much more expensive than preventive maintenance strategies due to the high cost of implementing sensors in facilities.

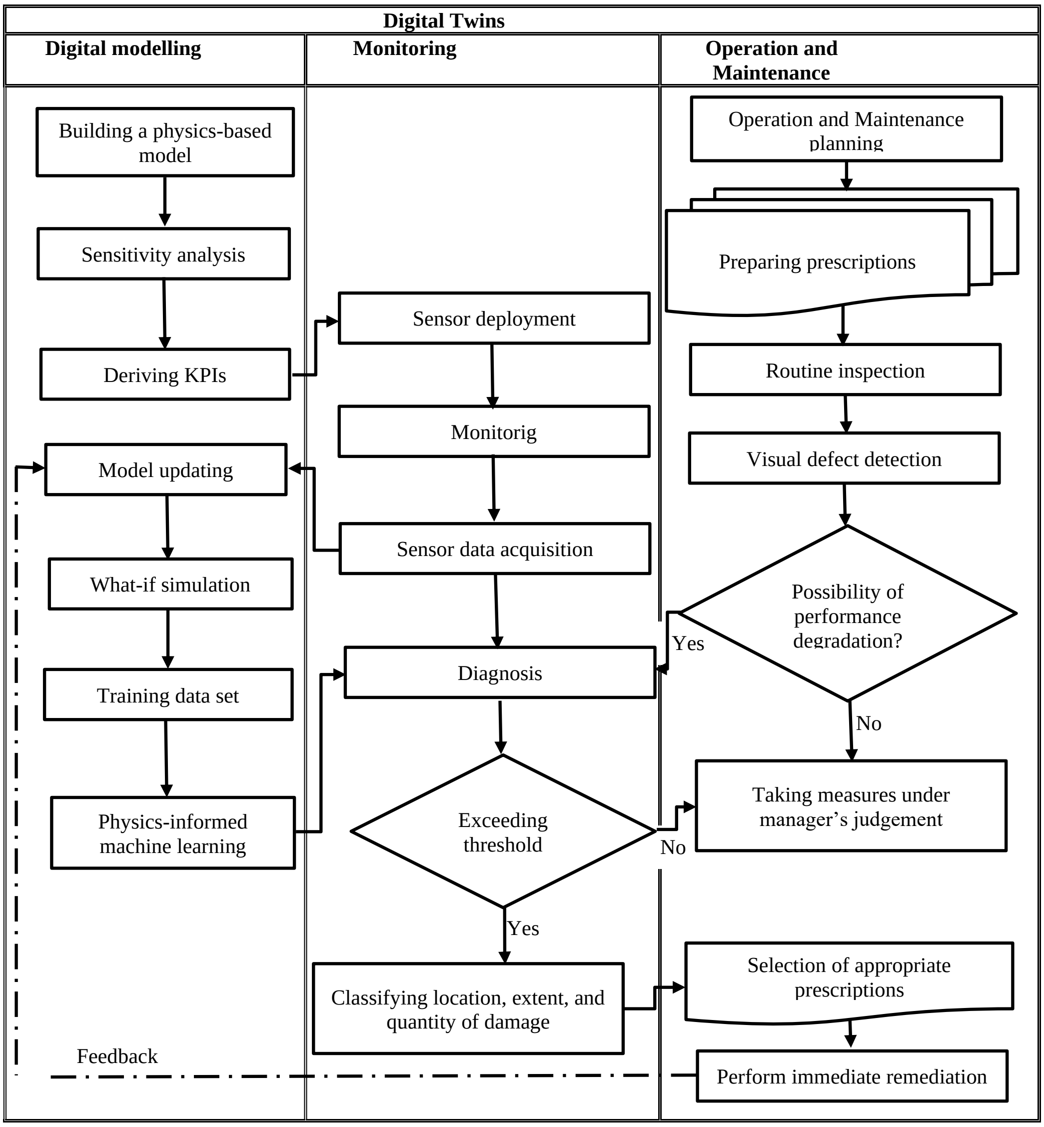
The introduction of digital twins is a strategy to change existing maintenance policies to an advanced method; therefore, achieve predictive or prescriptive maintenance (Errandonea et al., 2020). Figure 3 shows the prescriptive maintenance workflow considering the architecture and digital information system twins. The application of smart technologies on the factory floor is referred to as “Industry 4.0”, “smart manufacturing” and “digital factory” (Huh et al., 2018).

Considered the highest level of digitalization in the intelligent maintenance paradigm, Prescriptive Maintenance assisted by intelligent tools predict the timing and nature of possible system failures. Even so, it can also suggest the best possible action to achieve global efficiency, that is, in real time Prescriptive Maintenance performs the diagnosis and prognosis of the failure (Bokrantz et al., 2015).

A digital twin is a cost-effective virtual replica of a physical system, typically used to generate scenarios that are expensive or sometimes impossible to simulate in physical space. The service-oriented approach of the digital twin model exploits digital twin data to offer different composite services (design, production planning, diagnostics, model calibration, etc.) to perform various functions of the manufacturing cycle (Naqvi et al., 2022).

Figure 3

Prescriptive maintenance workflow using digital twins.



Source: Adapted from Jeon et al. (2024).

In recent years, human-centered approaches have become increasingly crucial in maintenance (Nguyen Ngoc et al., 2022). With digitalization and information systems, maintenance workers through the exploitation of digital tools collect more and more data (Li et al., 2019). This data contains crucial knowledge for a company's development and decision-making. In this modern era, the frequency and prioritization of maintenance tasks on the factory floor are now determined with the possibility of using modern information technologies in the planning, implementation, monitoring and analysis of maintenance processes carried out in manufacturing in companies (Daniewski et al., 2018; Fang et al., 2019; Gola, 2019).

The implementation of a policy based on Prescriptive Maintenance not only allows sustaining the integrity of assets, but also makes production plans immune to unplanned downtime, implementing the digital twin paradigm (Padovano et al., 2021). The manufacturing industry faces immense challenges to maintain and increase its productivity and flexibility. In this context, it is important that factories ensure that their employees have the relevant data, information and knowledge necessary to make assertive and well-informed decisions (Li et al., 2019).

Decision-making for production and maintenance operations benefits from Industry 4.0's advanced sensor infrastructure, enabling the use of algorithms that analyze data, predict emerging situations and recommend mitigation actions (Bousdekis et al., 2021). However, considering the complexity in implementing a digital twin with combined applications of alignment between Production Planning and Control and the Prescriptive Maintenance paradigm requires an effective integration of industrial data, requiring the use of machine learning techniques (Jeon et al., 2024).

2.2 Alignment between prescriptive maintenance and the factory floor

When implementing Prescriptive Maintenance aligned with operations and processes, one of the significant challenges is the lack of a vivid guideline that drives your development practice from a machine learning perspective (Elbasheer et al., 2022). The communication process between PPC (Production Planning and Control) and Prescriptive Maintenance in Cyber-Physical Production Systems (CPPS) is highly necessary for effective shop floor coordination, thus achieving overall flexibility and resilience of the production strategy (Hadidi et al., 2012).

In the work of Zhong et al. (2017), these researchers demonstrate that the increasing digitalization and connectivity of industrial systems brought about by the fourth industrial revolution offer an excellent opportunity to address the trade-off between Production Planning and Control and Maintenance strategies. Production Planning and Control activities (including line balancing, capacity planning, and work scheduling) are expected to become more autonomous and intelligent due to the vertical integration of the physical and cyber layers in the digital twin of the factory. However, companies still encounter difficulties in implementing the integration between Production Planning and Control and the Prescriptive Maintenance strategy, on a smart factory floor, as this integration still faces, firstly, uncertainties arising from the specificities of the product and variability of demand (mix of volumes) (Padovano et al., 2021).

Dealing with integrated planning models that combine production, maintenance and quality aspects is extremely challenging and often results in: a) longer planning times, b) shorter planning horizons, c) periodic manual adjustments by planner's specialists, d) frequent deviations of operations from plans and, ultimately, e) reduced plant availability and process stability. Furthermore, the use of isolated functional teams employing independent methodologies and autonomous software, which plan for a singular objective (often in conflict with other objectives), is a common practice in planning (Hadidi et al., 2012).

Another challenge on the factory floor that necessitates comprehensive research within the maintenance literature is the existence of numerous planners and software programs that demand an understanding of semantic and syntactic data interoperability, as this is an emerging trend (Karim et al., 2016). In addition, two significant factors have been identified in the recent discourse surrounding the transition from Industry 4.0 (technocentric) to Industry 5.0 (homocentric). Firstly, factories are improving their performance capabilities with the increasing automation of the factory floor. Secondly, there is a growing recognition of the role of human beings in managing industrial processes.

In addition to the difficulties already mentioned, the design choices for an integrated decision support system (and its successful implementation in a real production environment) are considerably determined by the complexity of a factory's planning and its level of technological readiness. This can be assessed in a number of ways, for example, by considering the available information and communication technology infrastructure, data accessibility, availability, and quality, as well as staff qualifications. Therefore, there is a need for applied studies to evaluate and discuss the challenges and technical issues arising from real use cases.

2.3 Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis

The SWOT methodology has its origins in the field of business management literature, with the researchers at the Stanford Research Institute playing a pivotal role in its development. The impetus for SWOT analysis arose from the necessity to ascertain the underlying causes of failed corporate planning initiatives (Panagiotou, 2003; Helms & Nixon, 2010; Rostirolla & Rostirolla, 2011). Thus, the process of studying organizations and their environments is called

SWOT analysis (Figure 4).

Figure 4

Elements of the SWOT analysis.

Source: Authors own work.

The acronym SWOT is used to identify and analyze the strengths, weaknesses, opportunities, and threats associated with a company. According to proponents of SWOT, such as Panagiotou (2003), Helms & Nixon (2010), and Rostirolla & Rostirolla (2011), strengths refer to the inherent abilities to compete and grow strong. Weaknesses are the inherent deficiencies that hinder growth and survival. Strengths and weaknesses are primarily internal. Opportunities are the good chances and openings available for growth. Threats are externally exerted challenges that can suppress inherent strengths, accelerate weakness, and stifle opportunities from being exploited (see Figure 5).

Figure 5

SWOT Analysis (Strengths-Weaknesses-Opportunities-Threats).

Aspects	Descriptions
S Strengths	These are the internal strengths of the factory, such as the characteristics and resources (human and operational) that the factory has and that place it in an advantageous position in relation to the competition (market requirements).
W Weakness	These are the internal limitations of the factory, the areas in which the factory is at a disadvantage relative to its competitors (market requirements).
O Opportunities	These are positive external factors that the factory can take advantage of to achieve its objectives and goals.
T Threats	These are negative external factors that can represent challenges or risks for the factory.

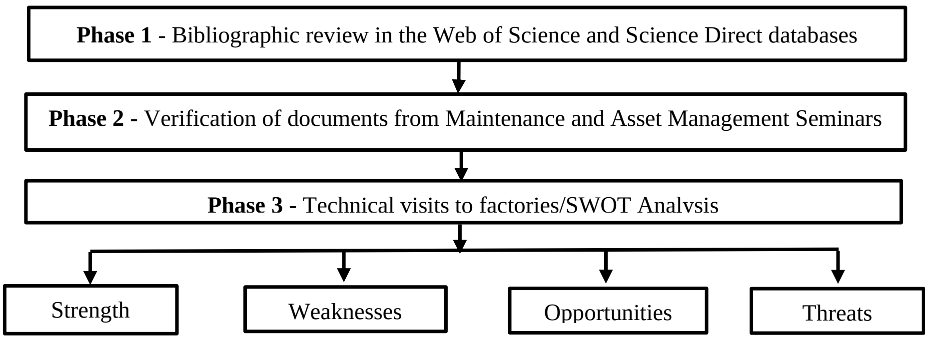
Source: Authors own work.

3. METHODOLOGY

To achieve the general objective, this article was conducted according to the phases presented in Figure 6. The methodology used consists of three phases. The first was to carry out a bibliographic review to select relevant articles in the Science Direct and Web of Science databases. The second was the documentary analysis resulting from participation in seminars and workshops to synthesize and extract the terms associated with the implementation of Prescriptive Maintenance. Finally, the third phase consisted of carrying out technical visits to the studied factories to conduct interviews with researchers and experts in the maintenance area. The three factories were Company A (Steel industry), Company B (Mining), and Company C (Paper and Cellulose). All of the companies are situated within the state of Espírito Santo, which is located in the southeastern region of Brazil. In this phase, we verified the recommendations defined in the SWOT analysis for decision-making by managers regarding the process of implementing the Prescriptive Maintenance strategy on the factory floor.

Figure 6

Methodological diagram.



Source: Adapted from Khan (2018).

The perceptions of experts and researchers were considered, based on the questions contained in Table 1. The results of the literature review and participation in seminars and workshops were used to develop the research questions contained in the interview script, which was applied to experts and researchers from the three factories studied. The respondents (researchers and specialists) present profiles with the following professional characteristics: researchers are engineers and project development managers, while specialists are engineers and managers in the maintenance area at the factories studied.

Table 1

Script for interviews with researchers and experts.

Aspects	Questions
S Strengths	When thinking about a Prescriptive Maintenance strategy implementation process on the factory floor, what strengths come to mind that favour increased productivity and competitiveness in Production? What attributes allow the Prescriptive Maintenance strategy to satisfactorily meet the demands for innovation on the factory floor?
W Weakness	What are the weaknesses of the Prescriptive Maintenance paradigm in the implementation process that can lead to a reduction in competitiveness on the factory floor?
O Opportunities	What opportunities do you see in consolidating the implementation of the Prescriptive Maintenance strategy on the factory floor?
T Threats	What threats do you see for the factory floor if managers do not prioritize the process of implementing the Prescriptive Maintenance strategy?

Source: Adapted from: literature review, technical visits and participation in seminars and workshops (2023).

The data collected made it possible to evaluate the contributions of the SWOT Matrix to the internal and external environments of the factories. SWOT analysis is a proven technique to help formulate strategy and is often used as a tool to analyze the organization's internal and external environment (Nikolaou & Evangelinos, 2010; Terrados et al., 2007). The factors of strengths and weaknesses evaluate the system's internal environment, while the factors associated with opportunities and threats evaluate the system's external environment (Dyson, 2004).

With SWOT analysis, it was possible to summarize the most significant and effective factors associated with the internal and external environment that can affect the future of the organization. These factors are strategic (Kangas et al., 2003) and the information collected helped to understand the implications of Prescriptive Maintenance on the factory floor, based on methodological approaches such as narrative bibliographic review, document analysis and participant observation.

After obtaining the information from the SWOT analysis, the research went through a phase of theoretical discussion and fieldwork. It is worth mentioning that researchers and experts as participants evaluated the results of the data collection phase in specific meetings.

Through the methodology of grounded theory, the data analysis was carried out and results presented in the next section were extracted.

4. RESULTS AND DISCUSSION

In order to survive the competitive demands of the market, modern production companies implement the assumptions of Industry 4.0, in which the optimization of maintenance processes is important due to the financial situation. It is highlighted that an intelligent production system normally allows the improvement of common maintenance strategies, as well as developing new ones, such as Prescriptive Maintenance. In fact, digital data represents additional insight into factory floor management. Based on Al-Najjar (2000), Riis et al. (1997), and Mckone & Elliott (1998), the importance of maintenance function has increased due to its role in maintaining and improving availability, performance efficiency, quality products, on-time deliveries, environmental and safety requirements and the overall cost-benefit ratio of the plant at high levels.

Table 2 shows the main aspects and disadvantages for implementing Prescriptive Maintenance, which mainly consist of addressing the complexity of the technology and the need for advanced decision-making algorithms. In fact, such algorithms are often necessary to implement advanced maintenance strategies.

Even with the disadvantages that normally arise when implementing prescriptive maintenance as a recent technology, it is very clear that the factory floor with intelligent functionalities will require a new role for the maintenance operator, who must adapt to this technological environment, with the use of intelligent tools from Industry 4.0, that is, mastery of IoT – Internet of Things, Artificial Intelligence, Cloud Computing, Smart Sensors, Digital Twins, Collaborative Robots, among others. To improve their intellectual and technological capacity, maintenance operators need to overcome their difficulties to be able to supervise automated production, as well as drive advanced monitoring systems on the factory floor.

At the same time, technologies can also help the operator to have easier, more effective and real-time information, contributing to the development of efficient and safe maintenance. Thus, factories will need labor with a new professional profile.

Table 2

Key aspects and disadvantages for the implementation of Prescriptive Maintenance.

	Maintenance policies
Policies based on Industry 4.0 technologies	Predictive maintenance Proactive and prescriptive maintenance Remote maintenance Self-maintenance
Disadvantages	Complexity of technology Need of advanced decision-making algorithms New roles for the maintenance operator

Source: Adapted from Gianpaolo Di Bona et al. (2021).

The empirical study of the three factories (Companies A, B and C) demonstrated substantial benefits from developing strategic policies based on the Prescriptive Maintenance paradigm. The benefits of implementing the Prescriptive Maintenance strategy in factories can be summarized in the following points:

- Elimination of human errors (greater human reliability).
- Safer operations and processes (greater operational reliability on the factory floor).
- Greater focus on the customer (factory and market interaction, favoring the customer's perception of the quality added to the product).
- Increased Overall Equipment Effectiveness (OEE) - higher performance, higher quality and greater operational availability on the factory floor.
- Best Mean Time Between Failures (MTBF)- this metric indicates that the equipment can operate for a long time without developing defects, keeping factory productivity high.
- Reduction of maintenance costs - on the factory floor the main objective is to prevent failures before they occur, keeping equipment in ideal operating condition and thus providing cost reductions.

Table 3 presents a summary of the main insights and responses obtained in the interviews with the researchers and experts. In discussions with experts from the three factories under study, a consensus emerged regarding the implementation of intelligent technologies on the factory floor. It was agreed that all employees and factory managers, from the corporate sector to operational personnel, must be involved in this transformation process. Still based on the experts' opinion, they emphasize that it is very important that the implementation planning is systemically coordinated, emphasizing the changes in the transformations that will occur in the life of the factory in terms of results. A critical success factor of the Prescriptive

Maintenance paradigm is the notion of a closed loop.

Table 3

Key insights and answers established by researchers and experts.

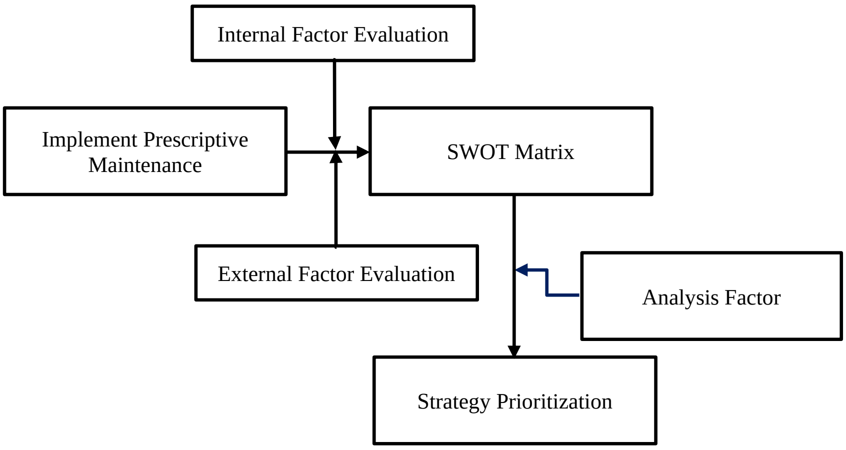
Number	Question/Answers
01	*When thinking about a process of implementing a Prescriptive Maintenance strategy on the factory floor, what strengths come to mind that favour increased competitiveness?* **Answers** The systemic view of the factory by managers and employees, bearing in mind the importance of the factory's mission, vision and values to its customers. The sharing of tacit knowledge between managers (corporate level) and employees (operational level), allowing the flow of information and communications. An important perception for the factory floor is the technological advantages of analysing the condition of the asset with the help of intelligent Industry 4.0 tools, that is, it is a contribution to reliable data collection and more assertive decision-making in real time.
02	*What attributes allow the Prescriptive Maintenance strategy to satisfactorily meet the demands of productive innovation?* **Answers** The vision of innovation as a strategic value that needs to be constantly fed from adoption, by senior management. A strong interaction between production resources and competitive market demands. Technological mastery of operations and processes carried out on the factory floor, with the priority of making it easier for the market to perceive the quality added to the product.
03	*What are the weaknesses of the Prescriptive Maintenance paradigm in the implementation process that can lead to a reduction in competitiveness on the factory floor?* **Answers** An important perception that can generate weaknesses, the implementation of the Prescriptive Maintenance paradigm, when the factory neglects the perfect alignment between resources, maintenance strategy and Production.
04	*What opportunities do you see in consolidating the implementation of the Prescriptive Maintenance strategy on the factory floor?* **Answers** Most researchers and experts realize that Brazilian companies are on the path to innovation, especially if the company establishes innovation policies for its products and services in its Strategic Planning, taking advantage of the opportunities generated by Industry 4.0 and now in the transition to Industry 5.0.
05	*What threats do you see for the factory floor if managers do not prioritize the process of implementing the Prescriptive Maintenance strategy?* **Answers** The factory floor's vision is to develop strategic policies, considering the proactive aspects of Prescriptive Maintenance, however, if the factory neglects to prioritize this evolution, a sharp loss of competitiveness will supposedly occur in the future, generating an increase in loss of profit due to the loss to competitors with characteristics of innovation.

Source: Prepared by the authors, based on the responses and perceptions of researchers and experts interviewed during the meetings (2024).

The empirical work conducted in the selected factories, in conjunction with the bibliographic review, yielded two significant findings. The first pertains to the general implications of the SWOT matrix (see Figure 7), which plays a pivotal role in decision-making processes.

Figure 7

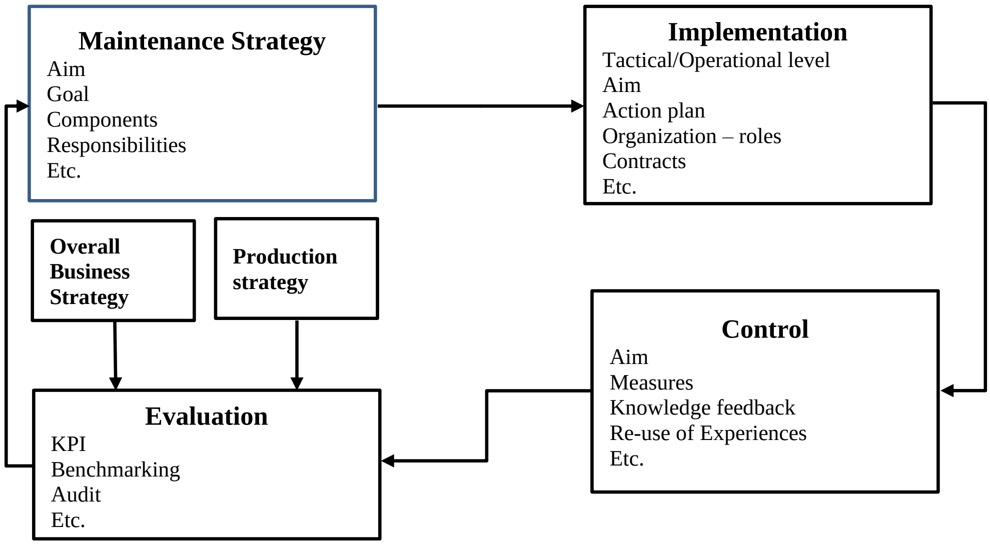
Implications of the SWOT matrix in implementing prescriptive maintenance.



Source: Adapted from: literature review, technical visits and participation in seminars and workshops (2023).

The second is a specific outcome tailored to the context, namely, a model that facilitates the implementation of proactive prescriptive maintenance (Figure 8). This model also offers guidance to managers and professionals engaged in on-site operations, highlighting areas requiring improvement in maintenance tasks. This underscores the necessity for digitizing the factory floor.

Figure 8
The development cycle in implementing prescriptive maintenance.



Source: Adapted from literature review, technical visits and participation in seminars and workshops (2023).

5. CONCLUSION

In this article, we investigated the implementation of the Prescriptive Maintenance paradigm on the factory floor in three large companies. The information collected from interviews with experts and researchers in the maintenance area originated two important results. The first one (Figure 7) is for general use and shows the importance of the implications of the SWOT Matrix in positioning decision-making. The second, it is specific to the context (Figure 8), consisting of a model to assist in the implementation of the proactive Prescriptive Maintenance process on the factory floor, in addition to providing recommendations to managers and professionals working on the factory floor.

Considering the contributions of the SWOT analysis, the main conclusions include: (i) the current technological capabilities of maintenance staff present weaknesses in terms of academic training; (ii) gaps in team knowledge and spare parts support (warehouse sector) hinder the process of implementing prescriptive maintenance strategies on the factory floor. However, measures are recommended that include improving training, increasing staffing, developing new facilities and ensuring adequate material support, given that with consolidated implementation, operations and processes carried out on the factory floor tend to generate cost reduction for the factory.

Regarding theoretical implications, our study provides empirical evidence on the integration of Industry 4.0 into maintenance activities managed through the Prescriptive

Maintenance framework. From the technical visits to the factories studied, our investigation provides a deeper understanding of the benefits and barriers to the success of this integration. The analysis enabled us to ascertain how the innovation associated with the digitalization of the prescriptive maintenance paradigm, despite its status as a nascent technology in the maintenance domain, can serve as an alluring factory floor strategy for prospective adopters, thereby enhancing their likelihood of success.

It is therefore notable that strategic maintenance policies have undergone significant changes over time, evolving from traditional reactive approaches to proactive strategies such as predictive and prescriptive. This evolution has led to fundamental changes in the approaches to the operation and maintenance of industrial facilities, promoting greater competitiveness and productivity on the factory floor.

This research also contributed by identifying a series of driving forces and obstacles that influence the implementation of proactive maintenance strategies. In addition, an important benefit of SWOT analysis in the implementation processes of new technologies is to prepare the factory floor for problems that may arise, allowing the development of contingency plans. Thus, SWOT analysis, as a strategic tool, helps managers to better understand the integration between Prescriptive Maintenance and Intelligent Production Planning, and Control.

A limitation of this research is the lack of investigation into the potential correlation between the results of a change process and the implementation of the Prescriptive Maintenance paradigm on the factory floor. However, it is important to note that this limitation does not reduce the overall importance of the research; rather, it paves the way for future investigations into the effectiveness and efficiency of the Prescriptive Maintenance strategic policy.

Future studies could address the following recommendations: (a) the present study may result in the prevalence of short-term perceptions in the information collected. To counter this situation, longitudinal studies are recommended that examine how Industry 4.0 has allowed the Prescriptive Maintenance paradigm to progress in the long term; (b) to understand how processes and functions are changing on the factory floor with the technologies brought by the transition from Industry 4.0 to Industry 5.0 in maintenance; (c) to explore what skills are needed in the future, especially for small and medium-sized companies, to mitigate the difficulties of implementing and/or deploying digital technologies on the factory floor.

Finally, it should be noted that the ideas contained in this research are not interpreted as conclusive results, but rather as contributions to support new theoretical or empirical works.

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