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PRESCRIPTIVE MAINTENANCE SYNCHRONIZED TO THE CHARACTERISTICS OF INDUSTRY 5.0: A THEORETICAL DISCUSSION

José Barrozo de Souza and Sandra Mara Santana Rocha

Department of Industrial Technology, Technological Center, Federal University of Espírito Santo, Av. Fernando Ferrari, 514, Goiabeiras Campus; 29075-910 - Vitória - ES - Brazil

Corresponding author: jose.ba.souza@ufes.br

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ABSTRACT

This article aims to examine and understand the current scope of Prescriptive Maintenance integrated with the human-centric characteristics of Industry 5.0. Therefore, the main research question is the following: "In the view of the managers of the companies visited, located in the Southeast Region of Brazil, what are the main technical and administrative difficulties that companies encounter in successfully implementing proactive combinations on the factory floor, such as Prescriptive Maintenance integrated with the characteristics of Industry 5.0?". The evolution of industrial processes in recent decades and the advent of Industry 4.0 integrated with human-centered characteristics have placed maintenance as one of the protagonists of industrial processes. In a scenario where automation and humans are gaining more and more space, the future of industries lies in Prescriptive Maintenance. To achieve the objective of the article, professional experiences from participation in congresses, seminars and technical visits to several factories located in the Southeast Region of Brazil are used. In data collection, we explored documentary observation and bibliographic research in the Science Direct and Web of Science databases. The study focuses on research areas related to maintenance integration, Industry 4.0 (Techno centric) and human-centric characteristics (Industry 5.0). The article brought important conclusions, as it addresses the impact and trends on the factory floor so that managers can develop competitiveness and productivity. The article highlights the role of maintenance methods in improving factory floor performance, emphasizing human knowledge and Prescriptive Maintenance practices to ensure operations within World Class standards.

Keywords: Prescriptive maintenance, factory floor, maintenance 5.0, performance, industry 5.0

INTRODUCTION

This section presents the theoretical basis around the term Industry 4.0 and highlights the importance of the Prescriptive Maintenance paradigm, as a model to guarantee the performance of a production system. Modern manufacturing, arising from the transition between the Industry 4.0 (Techno centric) and Industry 5.0 (Homocentric) paradigms, includes modular and efficient production systems and presents scenarios in which products follow their own production process.

In 2011, the German government introduced the term “Industry 4.0” (or Industry 4.0) and thus established the future industrial orientation, not only in Europe, but also in the rest of the world. The concept of Industry 4.0 is known mainly in Europe, but 'Industrial Internet' Jian-Qiang Li et al. (2017), "Smart Industry" or 'Smart Manufacturing' Bauernhansl, T., et al. (2014) and Wiesmüller, M. (2014) are just a few examples of comparable industrial concepts.

The modern focus is to increase awareness of the production of individual products in a single batch size, while maintaining the economic conditions for the mass production system. A factory that provides these conditions becomes a user and part of the system – “Industry 4.0” (Dóra H. et al., 2019).

Industry 4.0 has technologically revolutionized the factory floor, increasing flexibility, mass customization, quality and productivity. In the current competitive production scenario, maintenance is one of the most critical issues and companies are approaching their digital transformation from technological and management perspectives (L. Silvestri, A. et al., 2020).

Furthermore, Industry 4.0 is revolutionizing decision-making processes in the manufacturing industry. Maintenance strategies play a crucial role in progressively improving the technical performance of the factory floor. The introduction of Industry 4.0 technology results in relevant innovations capable of influencing strategic maintenance policies. Furthermore, it allowed the introduction of innovative solutions, such as the “prescriptive maintenance” paradigm.

This perspective is gaining momentum because of the adoption of the Industry 4.0 paradigm, with the development of the Internet of Things (IoT) and smart sensing technology (Sun, S., 2020).

Traditional maintenance policies respond reactively to equipment or device failures. We understand this reactive policy of describing failures after they have occurred as the worst-case scenario for maintenance: reacting to failures in equipment or devices after the fact. The preventive maintenance policy enables operators to carry out continuous maintenance, following a periodicity, seeking to avoid critical situations, increasing their marginal cost. The next evolution in maintenance strategy interacts with prescriptive capabilities, simply trying to minimize equipment downtime and seeking to improve Overall Equipment Effectiveness (OEE), thus increasing Reliability and Availability levels on the factory floor. This strategy was strongly popularized because of incorporating intelligent software into the connected devices (Things) the machines incorporate Fusko, M., et al. (2018), thus providing machines with a sort of intelligence. Japanese management popularized this approach with the concept of JIDOKA or automation with a human touch (Hirano, H., 2019).

Industry 5.0 (Homocentric) has been deeply crafted by Society 5.0, sharing common ground by focusing on a human-centered approach, technology integration, cross-sector collaboration, and a shared vision of utilizing technology for a better future Carayannis and Morawska-Jancelewicz, (2022); (Ghobakhloo et al., 2023a, 2023b).

The growth from Society 5.0 to Industry 5.0 demonstrates the influence of the broader social context on the transformation of the industrial sector (Huang et al., 2022). Society 5.0 brings an expectation of more comprehensive transformation, leveraging technology for social challenges and improving quality of life (Mourtzis et al. (2023), while Industry 5.0 adopts a more industrial transformation approach (Xu et al., 2021a, 2021b).

Although Industry 4.0 has enormous potential for industrial growth, it has many challenges such as technical integration, human resource issues, and supply chain issues and data security. Industry 5.0 will face these challenges in the future. Industry 5.0 has introduced several new technologies such as predictive (advanced) maintenance, hyper-personalization in industry, cyber-physical cognitive systems and the introduction of collaborative robots. Industry 5.0, with its human-centric approach, has helped overcome the various challenges of Industry 4.0 (Khan et al., 2023).

The technological integration between Industry 4.0 and Industry 5.0 allows for better maintenance practices, as it allows the tracking and diagnosis of system and product integrity. The use of modern monitoring technologies, together with the vast amount of data generated by Industry 4.0 innovations, has also led to the development of sophisticated Artificial Intelligence algorithms for big data analysis (Ding & Li, 2017) and (Lu et al., 2022). Prescriptive maintenance supports efficient decision-making and optimizes maintenance processes by considering different types of information and predicting performance degradation (Meissner R. et al., 2021).

This method provides self-diagnostic results and recommendations for action plans in response to specific events. Recent studies on prescriptive maintenance have been conducted in many manufacturing industries Chi-Ho Jeon et al. (2024) and can be found in other fields such as the aviation industry (Meissner et al. (2021), railway infrastructure Consilvio et al. (2019) process optimization Gordon CAK. et al. (2020) and scheduling Antao et al. (2018). However, their applications in bridges appear to be in their infancy.

Prescriptive maintenance uses information about degradation projections, facilitating the scope of the decision-making process beyond the asset itself, for example, in an aircraft. Therefore, taking into account the surrounding ecosystem, a prescriptive maintenance strategy will allow a holistic analysis and optimization of maintenance measures. (Ansari et al., 2019).

Table 1 illustrates the evolution of maintenance strategies with each industrial paradigm, evolving in the order of (a) reactive-based maintenance that is, inspecting during the downtime of each machine (b) planned maintenance of production machines and tools, (c) addition of machine sensors and (d) prescriptive analysis, as the highest evolution of Predictive Maintenance.

Therefore, Prescriptive Maintenance allows for greater system reliability at a lower cost (Ran Y. et al., 2019) and can provide industrial benefits such as greater return on investment, reduced maintenance costs and fewer breakdowns and less downtime. Prescriptive Maintenance can also minimize inventory, spare parts, and overtime costs, leading to increased production and efficiency (Silvestri et al., 2020); (Compare et al., 2020).

Table 1

History of evolution of industry and maintenance

| Industry X | Maintenance X |
|--|---|
| 2021 – Industry 5.0 Human centricity – resilient manufacturing | Maintenance 5.0 advanced Predictive maintenance |
| 2011 – Industry 4.0 Smart/intelligent manufacturing | Maintenance 4.0 predictive maintenance |
| 1969 – Industry 3.0 Electronics/automation/IT systems | Maintenance 3.0 productive maintenance |
| 1870 – Industry 2.0 Division of labor/electrical energy | Maintenance 2.0 planned maintenance |
| 1784 – Industry 1.0 Mechanical production/steam power | Maintenance 1.0 reactive maintenance |

Source: Adapted by the authors from: (Psarommatis et al., 2023).

Condition-based maintenance is a method of continuous investigation to maintain a constant level of condition (Kim et al. 2016), Industry 4.0 technologies such as the Internet of Things (IoT) and artificial intelligence (AI) have the advantage of detecting anomalies in real-time, thereby enabling an immediate response; however, employing these technologies can be much costlier than preventive maintenance strategies owing to the high cost of sensor deployment per bridge.

Maintenance strategies have undergone a significant change over time, evolving from traditional reactive approaches to predictive and prescriptive strategies (Goby et al., 2023).

The maintenance process, included in operational activities, is a set of sequential technical actions that ensure that business assets remain functional throughout their economic life. In this context, the purpose of maintenance processes includes the creation and operation of plans that contribute to productivity and, therefore, production efficiency.

The Prescriptive Maintenance paradigm as a strategy brings benefits. However, these benefits come at the cost of an increasing level of complexity, seen in four main stages of development (although some papers may argue that there are additional stages of development, for example in (Menezes B.C et al., 2019) as shown in Table 2.

According to Baum et al. (2018), descriptive analysis aims to understand events based on historical data, while diagnostic analysis investigates why an event occurred. In predictive and prescriptive analytics, mathematical models used to predict future outcomes and prescribe optimal interventions, respectively.

The term “predictive maintenance” has gained traction in the literature, with many studies highlighting its business opportunities, especially the Prescriptive Maintenance policy (e.g., Bouskedis et al., 2020); (March & Scudder, 2017).

Table 2

Stages and complexity levels of prescriptive maintenance

| Stages | Levels of complexity |
|-------------------------|--|
| Descriptive Maintenance | The most fundamental form of proactive maintenance that is based on records of historical maintenance data and observed failure events to identify what observed equipment failure has resulted in which specific maintenance measure. (Ansari F. et al., 2019) and (Frazetto D. et al., 2019). |
| Diagnostic Maintenance | This approach additionally considers information about operating and system conditions to develop cause–effect-relationships and to allow the clear identification of root causes leading to the ultimate system failure. (Nemeth T. et al., 2018). |
| Predictive Maintenance | As arguably the most discussed maintenance strategy in recent years, the focus here is on extending the knowledge about degradation mechanisms and extending the degradation propagation into the future to project system failures. Subsequently, this approach utilizes the knowledge discovery process and combines insights into the experienced degradation in the past with anticipated operating loads in the future in order to support a maintenance decision-making process. (Soltanpoor R. & Sellis T. 2016). |

Prescriptive Maintenance

This approach will utilize the information about degradation projections and extend the scope of the maintenance decision-making process beyond the asset itself, e.g. the aircraft. Thus, by consideration of the surrounding ecosystem, a prescriptive maintenance strategy will allow a holistic analysis and optimization of maintenance measures (Ansari F. et al., 2019).

Source: Adapted by the authors from: (Menezes et al., 2019).

Concluding this section, with the aim of clarifying the development of the research, we compile and present research in related areas. We divide this section into two subsections:

- a) The current scope of industry 4.0 to understand its academic description, scope and adoption opportunities; and
- b) Understand Industry 5.0 for successful implementation on the factory floor.

The Current Scope of Industry 4.0

Industry 4.0 is associated with the digital transformation of industrial processes (manufacturing, production, value creation, etc.) driven by German industry. The transformation has focused on smart factories that benefit from cyber-physical systems, the Internet of Things, cloud computing, Artificial Intelligence, machine learning and cognitive computing. The concept of “Industry 4.0” (Thoben et al. (2017) introduced to promote the idea of machine (and therefore process) autonomy. In Lasi et al. (2014), Industry 4.0 is a new vision for a human-free production environment comprised of product, intelligence, machine-to-machine communication and networking.

However, what reveals the true potential of Industry 4.0 is the established connection and communication between computers and machines that allow making decisions without any human intervention Da Costa et al. (2019). Hence, the network formed by these interconnected machines and the generated big amount of data marks the true value of Industry 4.0 (Nagy et al., 2018). According to researchers Nagy et al. (2018), the main evolution of traditional production towards Industry 4.0 appears in four main characteristics:

- (1) Vertical networking of smart production systems;
- (2) Horizontal integration via a new generation of global value chain networks;
- (3) Through-life engineering across the entire value chain;
- (4) The impact of exponential technologies (Nagy et al., 2018).

A literature review (state of the art) on Industry 4.0 provided in (Oztemel & Gursev, 2020). It argues that the Industry 4.0 paradigm assumes that: robots will be more dominant in production; autonomous systems will make more self-decisions; processes will be coordinated and problems will be resolved without human involvement; and most communication will occur between machines rather than humans.

This intelligent production should improve the effectiveness of data collection and analysis, make systems and processes more consistent, robust and agile and, therefore, bring more efficient business models to the factory floor.

For (Oztemel & Gursev 2020), it is obvious that future production (according to the Industry 4.0 philosophy) will be more intelligent, flexible, adaptive, autonomous, unmanned and based on sensors (techno centric characteristics). Of the advances attributed to Industry 4.0, the continuous real-time interconnectivity between processes, products, services and people stands out as one of its singularities compared to previous industrial revolutions (Jabbour et al., 2019; Chiarini et al., 2020).

Various researchers have dealt with different frameworks and roadmaps to guide successful adoption of Industry 4.0. Fatorachian and Kazemi (2018) proposed a theoretical framework for the operationalization of Industry 4.0 in production processes, while Ghobakhloo (2018) conceptually designed an Industry 4.0 roadmap based on a systematic literature review.

The role of Industry 4.0 in manufacturing is fundamental. The industrial revolution will transform the production ecosystem, giving rise to new capabilities and boosting productivity (Jian Qina et al., 2016). Industry 4.0 characterized by the integration of production assets, facilitating connectivity, improving data communication and analytics-based decision-making capabilities, thereby significantly improving overall performance.

The enhanced data-driven and decision-making capabilities of Industry 4.0 make the system more autonomous, cognitive, and intelligent (Kusiak, 2018). The development of these capabilities within the production system, normally known as “smart”; therefore, the systems are commonly called intelligent manufacturing systems. The terms Industry 4.0 and smart manufacturing are interchangeable in most literature (Mittal et al., 2019).

Understanding Industry 5.0

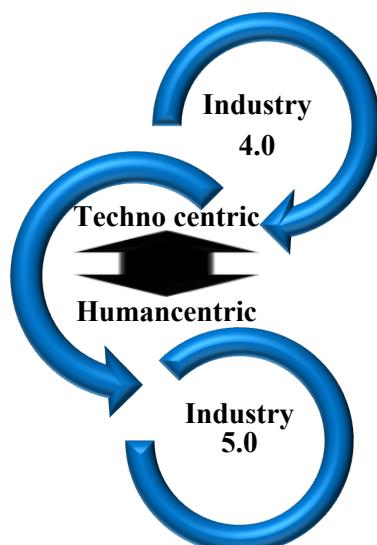
The industrial transformation is sociotechnical. Industry 5.0 is one of the recent terms to describe this phenomenon, defined as a humanized vision of technological transformations in industry, balancing the current and future needs of the workers and society with the sustainable optimization of energy consumption, materials processing, and product lifecycles (João Barata & Ina Kayser, 2023).

The current state of Industry 5.0 regarding related research trends was analyzed in Akundi, A. et al. (2022) it was observed that trends related to Artificial Intelligence, Big Data, Supply Chain, Digital Transformation, Machine Learning, Internet of Things, are still among the main drivers of Industry 5.0, as they were for Industry 4.0. Thus, we see the incorporation of the personal human touch into the pillars of Industry 4.0, such as efficiency and automation. Two paradigms shape smart production: Industry 4.0 (technology-centered) heralds the transition to digitalization and process automation, while the emerging Industry 5.0 (human-centered) emphasizes human centrality, as schematically shown in Figure 1.

Figure 1

Schematic representation of the integration between industry 4.0 and industry 5.0.

Source: Prepared by the authors, based on perceptions from participation in congresses and seminars (2023)



After about thirteen years since the introduction of Industry 4.0, the European Commission announced Industry 5.0 as a response to emerging societal challenges (Breque, M. et al., 2021). Industry 5.0 emerged as a vision of industry that aims beyond efficiency and productivity, towards respect for human values and contribution to the vital needs of society.

As a main characteristic, Industry 5.0 places the well-being of workers together with other human values (in relation to workers, customers and society in general) at the center of manufacturing/production processes (Longo, F. et al., 2020).

It is considered as a transition to a human-centric Nahavandi, (2019), sustainable Saw, et al. (2021) and resilient (Sindhwan, et al., 2022) industry. Javaid & Haleem Javaid and Haleem, 2020) believe that modern industry needs the transition from the efficient use of industrial automation (Industry 4.0) towards creating a new value from critical rethinking of human resources (Industry 5.0).

Although Industry 5.0 is still an evolving topic, that is, it has not yet evolved to its peak, there are several definitions provided by researchers and industry professionals, such as:

- (a) Industry 5.0 aims to harness the synergistic benefits of machines with the capabilities cognitive and decision-making processes of human beings (Pillai et al., 2021);
- (b) Industry 5.0 is about to become the first industrial revolution with human intervention and is based on the principle of 6 R's, which is Recognize, Reconsider, Realize, Reduce, Reuse and Recycle. Thus, Industry 5.0 is the systematic elimination of waste, ensuring high quality and highly customized products (Breque, M. et al., 2021);
- (c) Industry 5.0 considers human factors integrated into processes, systems and technological aspects (Friedman & Hendry, 2019).

For Industry 5.0 focuses on the principles of sustainability, resilience and human-robot collaboration, it constitutes a multitude of emerging technologies that have their roots in Industry 4.0. Notable technologies include Additive Manufacturing, Cyber-Physical Systems, Big Data, Augmented, Extended, Virtual and Mixed Reality, Digital Twins, 6G technology and beyond, IoT, Blockchain and Cloud Computing, to name a few.

The remainder of the article follows the following structure. Section 2 describes the methodological procedure. Section 3 presents the results of studies related to maintenance integration, Industry 4.0 (techno centric) and human-centered characteristics (Industry 5.0), including possible improvements that can be obtained on the factory floor. Finally, Session 4 presents our conclusions.

METHODOLOGY

As evidence in the literature on the integration of Prescriptive Maintenance with the characteristics of the Industry 5.0 paradigm is scarce and companies still struggle to envision its practical implications, we adopted a qualitative approach aligned with the exploratory and descriptive nature of this research. This article aims to examine and understand the current scope of Prescriptive Maintenance integrated with the human-centric characteristics of Industry 5.0. Therefore, the main research question is the following:

“In the view of the managers of the companies visited, located in the Southeast Region of Brazil, what are the main technical and administrative difficulties that companies encounter in successfully implementing proactive combinations on the factory floor, such as Prescriptive Maintenance integrated with the characteristics of Industry 5.0”?

Therefore, we first study the steps, the academic literature described for the current scope of Prescriptive Maintenance and the characteristics associated with Industry 5.0, resulting in the overview of several elements necessary for decision making for integration.

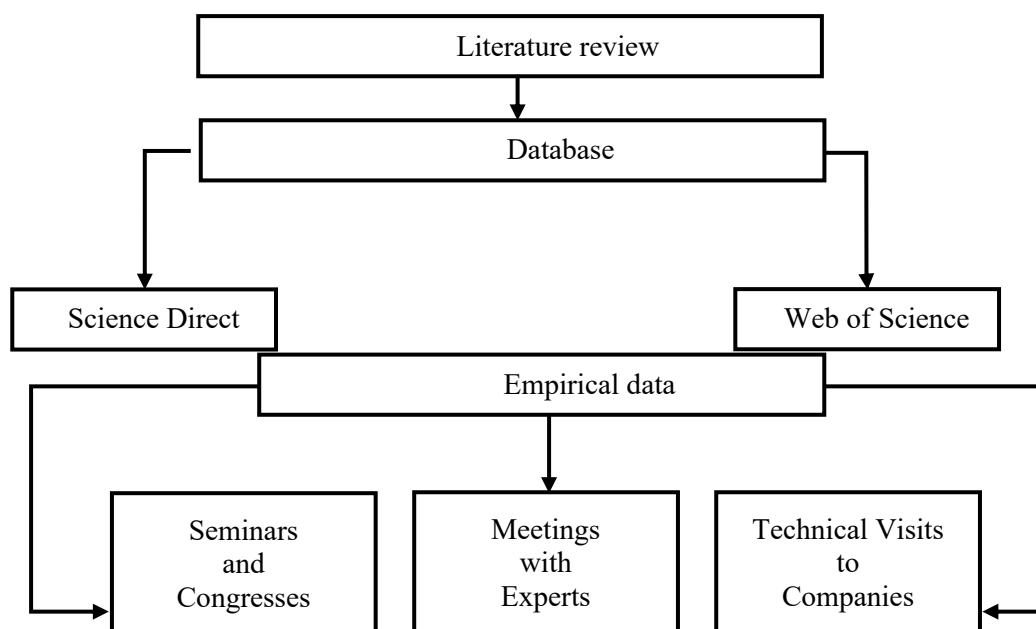
Based on the general objective of the article and our research problem, we used the following research workflow (see Figure 2). Through these research steps, we can obtain the desired results. This study will reveal motivators, benefits and difficulties in implementing Prescriptive Maintenance integrated with the characteristics of Industry 5.0 based on information collected in literature reviews, participation in congresses, seminars, opinions of industrial experts and technical visits to companies.

Next, the technical and administrative difficulties attributes were aligned with the requirements of the Innovation Diffusion Theory, producing the conceptual model illustrated in Figures 3 and 4, from which we extracted propositions for empirical research.

Figure 2

Research Workflow.

Source: Prepared by the authors, based on perceptions from participation in congresses, seminars and reference consultations (2023)



Our study will reveal motivators, technical and administrative difficulties and benefits of disseminating the characteristics of Industry 5.0 in Prescriptive Maintenance practices based on the information listed from the bibliographic review, participation in seminars, congresses, meetings with experts and technical visits to companies.

The proposed method comprises four main steps: (a) selection of interviewed experts; (b) Interviews with the experts; and (c) triangulation of information and development of propositions. Below we detail these steps.

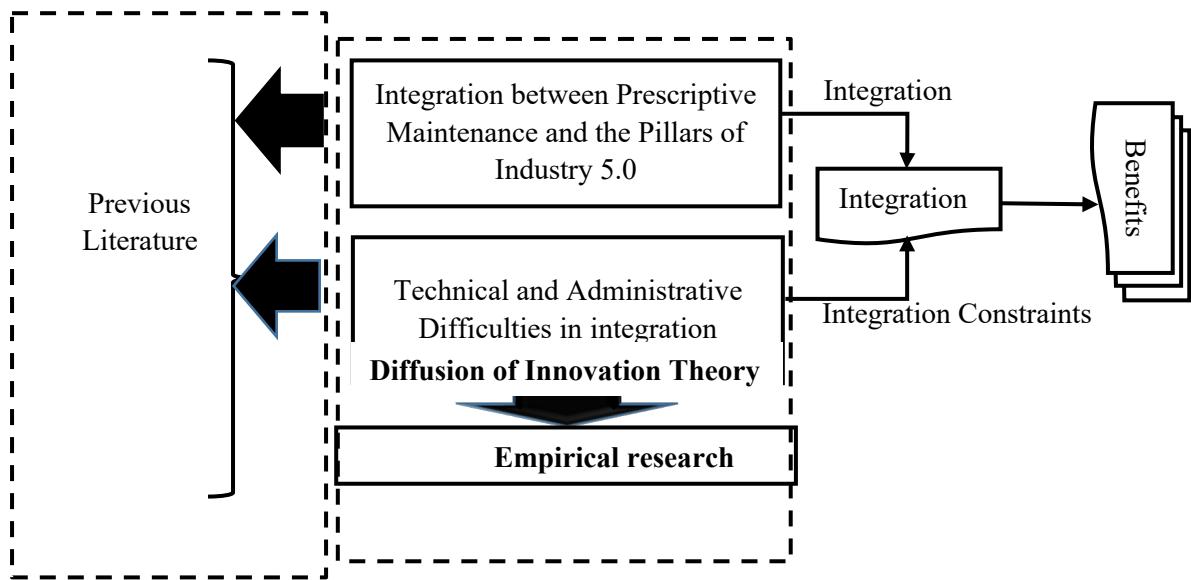
(a) Selection of interviewed experts:

As the integration of Prescriptive Maintenance and Industry 5.0 requires collaborative efforts from maintenance and production teams, we sought to interview at least two leaders (e.g., engineer, supervisor, coordinator or manager) from each company, one from the maintenance department and one responsible by production. The involvement of key leaders from the maintenance and production departments would allow us to confront and complement perceptions about integration, resulting in a more holistic understanding of our research problem.

Figure 3

Investigated conceptual model.

Source: Prepared by the authors, based on (Guilherme Luz Tortorella et al., 2021)



(b) Interviews with the experts:

This study carried out the interviews online during the first half of December 2023. We completed interview coding, cross-interview analysis, and fact checking during the second half of the month. We guarantee the anonymity of interviewees and their respective companies to encourage honest responses. Additionally, we modified any confidential information or data mentioned during interviews to support an argument to ensure confidentiality. Respondents work in government companies. In this study, an ordinal measurement scale from 1 to 5 was used to determine the level of importance. We asked interviewees to classify the levels of importance regarding the implementation of integration between Prescriptive Maintenance and the characteristics of Industry 5.0 that affect factory floor performance according to the degree of importance, assigning the following classifications:

- a) High (extremely important),
- b) Average (reasonably important)
- c) Low (between the levels not at all important and not very important); according to the relative importance level assessment scale (see Figure 4).

Figure 4

Relative importance level rating scale.

Source: Prepared by the authors, based on (A. Soekiman et al., 2011)

| Nothing important | Not very important | Reasonably important | Very important | Extremely important |
|-------------------|--------------------|----------------------|----------------|---------------------|
| 1, 80 | 2, 60 | 3, 40 | 4, 20 | |

(c) Triangulation of information and development of propositions

Triangulation is like using multiple methods to investigate the same phenomenon to increase the credibility of the study (Hussein, 2015). We triangulated the data listed in the interviews to develop a chain of evidence about the motivations and restrictions to the integration between Prescriptive

Maintenance and the characteristics of Industry 5.0. We then select the benefits of this integration on the factory floor (see Figure 3).

We used a relative importance index (RII) to analyze the data using an ordinal scale using the following equation (1):

$$RII = \frac{\sum_{i=1}^5 W_i X_i}{\sum_{i=1}^5 X_i} \quad (1)$$

Where:

Wi = the rating given to each level of importance by respondents ranging from 1 to 5

Xi = the percentage of respondents scoring

i = the order number of respondents

RESULTS

In this section, to achieve the objective of the article as well as answer the research question, we present the results of our assessment based on the literature review on prescriptive maintenance in the manufacturing sector. Our analysis covers research articles, providing a broad overview of the current state of prescriptive maintenance in the era of Industry 4.0, integrated with the human-centric characteristics of Industry 5.0. This allows us to identify trends in maintenance research in the industrial sector over the last five years.

Only Corés-Leal et al. (2022) provided the guidelines for Maintenance 5.0. Their analysis focused on wearable devices and their use in maintenance. This study differs from previous literature reviews because it focuses on how Industry 4.0 technologies along with maintenance policies used to achieve human-centricity.

Based on our studies, human factors such as safety, stress and skill development share the development of maintenance plans and decision-making procedures, according to our comprehensive analysis. This may involve creating human-centered models and tools that consider employee health and job satisfaction, as well as the effects of human factors on the effectiveness of maintenance operations and the reliability and availability of systems.

However, the top ten technical and administrative difficulties that companies surveyed encounter when successfully implementing proactive combinations on the factory floor, such as the integration between Prescriptive Maintenance and the characteristics of Industry 5.0 (see Tables 3 and 4).

Table 3

Classification of the six main technical difficulties that affect the process of implementing the integration between prescriptive maintenance and the characteristics of industry 5.0

| Technical difficulties | RII | Effect | Rank |
|--|------|--------|------|
| Complexity, seen in the four main development phases of Prescriptive Maintenance on the factory floor | 5.00 | High | 1 |
| Companies still struggle with the process of effectively implementing Prescriptive Maintenance in practice. | 4.00 | High | 2 |
| The use of modern monitoring technologies, together with the vast amount of data generated by Industry 4.0 innovations, has also led to the development of sophisticated Artificial Intelligence algorithms for big data analysis. | 4.00 | High | 2 |

| | | | |
|--|------|---------|---|
| Incorporating intelligent software into the connected devices (Things) the machines incorporate. | 4.00 | High | 2 |
| They propose intelligent support for maintenance decisions centered on human knowledge. | 3.00 | Average | 3 |
| Need for more practice-oriented research in this field. | 3.00 | Average | 3 |
| Prepared by the authors, based on responses from interviewees (Managers, Supervisors and Engineers) (2023) | | | |

Thus, formally, we perceive prescriptive analytics as comprising two fundamental components: a decision problem and noisy observations of an environment that provide an incomplete indication of the true state of the system. Prescriptive analytics seeks to leverage data to prescribe the optimal decision given noisy observations. Real-time prescriptive maintenance has been a pipe-dream that brings together sensor data, event-streaming, in-memory databases and real-time analytics, and combines them with decision and workflow orchestration.

Table 4

Classification of the six main administrative difficulties that affect the process of implementing the integration between prescriptive maintenance and the characteristics of industry 5.0

| Administrative difficulties | RII | Effect | Rank |
|--|------|---------|------|
| Conflicting objectives in the organization | 5.00 | High | |
| One of the main challenges when changing company culture from reactive to proactive maintenance strategies is the lack of management support. | 5.00 | High | 1 |
| The growth from Society 5.0 to Industry 5.0 demonstrates the influence of the broader social context on the transformation of the industrial sector. | 5.00 | High | 1 |
| Methods and tools to develop and analyze complex work with academic or professional support Operator 4.0 (new scarce professional profile). | 4.00 | High | |
| There are challenges to the widespread implementation of Prescriptive Maintenance at all technical levels, from data collection, through data analysis, to decision support. | 4.00 | High | 2 |
| Previous literature highlights a gap between the current focus of academic research and the real-world challenges companies face when implementing Prescriptive Maintenance | 3.00 | Average | 3 |

Prepared by the authors, based on responses from interviewees (Managers, Supervisors and Engineers) (2023)

Finally, we can consider that the need of the hour is to embrace the future and recognize that heavy investment in technology and human capital is a basic prerequisite of Industry 5.0.

Industry 5.0 is one of the recent terms to describe the sociotechnical phenomenon, defined as a humanized vision of the factory floor in industry. This phenomenon favors organizational synchronization between Prescriptive Maintenance and the main characteristics of Industry 5.0, balancing the current and future needs of workers and society with the sustainable optimization of energy consumption, material processing and product life cycles.

CONCLUSION

In this work, we list some technical and administrative difficulties based on research on support technologies and potential applications of Industry 5.0 synchronized with proactive Prescriptive Maintenance policies from the perspective of industrial and academic communities.

This article aims to examine and understand the current scope of Prescriptive Maintenance integrated with the human-centric characteristics of Industry 5.0. Therefore, the main research question is the following: "In the view of the managers of the companies visited, located in the Southeast Region of Brazil, what are the main technical and administrative difficulties that companies encounter in successfully implementing proactive combinations on the factory floor, such as Prescriptive Maintenance integrated with the characteristics of Industry 5.0"? Specifically, by integrating the Industry 4.0 reference architecture with the Industry 5.0, Society 5.0 framework, and digital transformation with data-driven technologies such as Machine Learning, 5G and Industrial Internet of Things (IIoT).

It is observed that intelligent activities in CPS, CPS collaboration with humans and at all levels where Industry 5.0 and Operator 4.0 paradigms improve and elucidate the human-machine structure, i.e. humans and machines are paired to optimize process efficiency (Montini, 2022); (Romero & Stahre, 2021). These integrations improve problem-solving literacy and provide intensive and imperative support for all activities in the smart factory (Umeda et al., 2022).

To this end, we researched the existing literature on the main topics, namely, the current scope of Prescriptive Maintenance integrated with the human-centered characteristics of Industry 5.0 and validated it with ten experts to come to understand the most relevant level of this integration in the factory floor.

Moreover, consequently, raise the main technical and administrative difficulties regarding the implementation of Prescriptive Maintenance integrated with the characteristics of Industry 5.0. In the strategic field of maintenance, smart tools such as IoT and data analysis allow factories to implement condition-based maintenance at its most advanced level, i.e. Prescriptive Maintenance in monitoring the real condition of equipment installed on the floor factory. The proactive factors of the Prescriptive Maintenance strategic policy can lead to more timely and efficient maintenance, better performance of equipment in use, reduced downtime in operations and a longer useful life, resulting in productivity and competitiveness of the factory floor.

Using information from bibliographic review, meetings with experts, participation in seminars, congresses and technical visits to various industries located in the Southeast Region of Brazil, we list the main challenges and possible solutions and translate them into a set of viable technical and administrative solutions for implementing the Prescriptive Maintenance synchronized with the characteristics of Industry 5.0.

Therefore, the study contributes with a comprehensive systemic view of the technical and administrative difficulties that occur in industrial practice, as shown in Table 5 (A and B). As such, we note that there is a gap between the challenges faced by companies that wish to implement such a maintenance policy and the advanced solutions presented in the literature, mainly those arising from Industry 5.0.

Olde Keiser et al. (2017), researchers report that the implementation of the Prescriptive Maintenance policy in practice registers a delay, explained by the complexity of real-life systems compared to the simplified systems often studied in academia. Stecki et al. (2014) conclude that there are challenges to the widespread implementation of Prescriptive Maintenance at all technical levels, from data collection, through data analysis, to decision support.

In several seminars on Asset Management and Maintenance, several companies emphasize the importance of looking beyond technology and focusing more on the processes and organizational changes (administrative difficulties) necessary for a successful implementation of the Prescriptive Maintenance policy on the factory floor.

Table 5

(A) Technical difficulties in implementing prescriptive maintenance synchronized with the characteristics of industry 5.0

| Technical difficulties | References |
|--|---|
| Incorporating intelligent software into the connected devices (Things) the machines incorporate. | Fusko, M., et al. (2018) |
| The use of modern monitoring technologies, together with the vast amount of data generated by Industry 4.0 innovations, has also led to the development of sophisticated Artificial Intelligence algorithms for big data analysis. | Ding, H. and Li, C. (2017) Lu Y. et al. (2022). |
| Complexity, seen in the four main development phases of Prescriptive Maintenance on the shop floor (although some articles may argue that there are additional development phases). | Menezes B.C et al. (2019) |
| Companies still struggle with the process of effectively implementing Prescriptive Maintenance in practice. | Ansari F. et al. (2019) Olde Keiser et al. (2017) (van de Kerkhof et al., 2016; Tiddens, 2018) |
| They propose intelligent support for maintenance decisions centered on human knowledge. | Veldman et al. (2011) |
| Need for more practice-oriented research in this field. | S.M.R. Naqvi et al. (2022) (Fraser et al., 2015). |

Prepared by the authors, based on responses from interviewees (Managers, Supervisors and Engineers) and bibliographic review (2023)

The implementation of Prescriptive Maintenance typically requires the selection of monitored components, identification of monitoring techniques and technologies, installation of the necessary technological means and definition of appropriate data analysis methods (Rastegari & Bengtsson., 2014).

Many studies such as those by researchers (Van De Kerkhof et al., 2016; Tiddens, 2018; Veldman et al. 2011) and Emilia Ingemarsdotter et al. (2021), bring conclusions that corroborate our study, as despite the abundance of technical literature, companies still face difficulties with the process of effectively implementing Prescriptive Maintenance in practice. Based on our review, the researchers observed that, among the companies that created Prescriptive Maintenance implementation projects, many do not follow systematic processes, including during our technical visits to companies located in the Southeast Region of Brazil, we came across such a situation.

Table 5

(B) Administrative difficulties in implementing prescriptive maintenance synchronized with the characteristics of industry 5.0

| Administrative difficulties | References |
|--|-----------------------------|
| The growth from Society 5.0 to Industry 5.0 demonstrates the influence of the broader social context on the transformation of the industrial sector. | Huang et al., (2022) |
| Methods and tools to develop and analyze complex work with academic or professional support Operator 4.0 (new scarce professional profile). | David Romero et al., (2020) |

| | |
|--|--------------------------------------|
| There are challenges to the widespread implementation of Prescriptive Maintenance at all technical levels, from data collection, through data analysis, to decision support. | Stecki et al., (2014) |
| One of the main challenges when changing company culture from reactive to proactive maintenance strategies is the lack of management support. | Emilia Ingemarsdotter et al., (2021) |
| Previous literature highlights a gap between the current focus of academic research and the real-world challenges companies face when implementing Prescriptive Maintenance | Golightly et al., (2018) |
| Conflicting objectives in the organization. | Emilia Ingemarsdotter et al., (2021) |

Prepared by the authors, based on perceptions from participation in technical visits and reference consultations (2023)

The fifth industrial revolution confined the merits of the fourth industrial revolution and brought human labor back into production. The fifth revolution makes it easier for robots and skilled labor to work together to produce personalized products and services in Industry 5.0. In our conclusions we used the article by researchers Naqvi et al. (2022) in the article proposed intelligent maintenance decision support centered on human knowledge. In the researchers' article, F. Psarommatis et al. (2023), which greatly corroborated our conclusions, present a Maintenance 5.0 structure, which emphasizes the integration of human-centered and Artificial Intelligence-driven strategies to achieve efficient and sustainable maintenance in Zero Defect Manufacturing systems ("Living Factory").

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