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TPM and Industry 4.0: Integration of smart technologies in maintenance

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SUMMARY

This study addresses the integration between Total Productive Maintenance (TPM) and Industry 4.0, highlighting the impact of emerging technologies on the modernization of industrial maintenance practices. TPM, consolidated as an effective methodology for maximizing equipment efficiency, has been enhanced by the advancement of Industry 4.0, which introduces the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, and cyber-physical systems. The convergence of these approaches has enabled the transition from corrective and preventive maintenance models to more predictive and prescriptive strategies, allowing for the early identification of failures and the reduction of unscheduled downtime. The study discusses how smart sensors, machine learning algorithms, and cloud computing have revolutionized maintenance management, optimizing productivity and reducing operating costs. In addition, the research highlights the positive impact of these technologies on quality management, occupational safety, and employee training, promoting an organizational culture focused on continuous improvement and innovation. The analysis indicates that the adoption of these practices contributes to a more efficient, sustainable and competitive industrial environment, ensuring greater predictability and reliability of production assets. It is concluded that the modernization of maintenance, made possible by Industry 4.0, represents a strategic differentiator for companies seeking operational excellence and optimization of their production processes.

Keywords: Total Productive Maintenance (TPM). Operational Efficiency. Maintenance Management. Equipment Availability.

ABSTRACT

The present study addresses the integration between Total Productive Maintenance (TPM) and Industry 4.0, highlighting the impact of emerging technologies on the modernization of industrial maintenance practices. TPM, established as an effective methodology for maximizing equipment efficiency, has been enhanced by the advancements of Industry 4.0, which introduces the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, and cyber-physical systems. The convergence of these approaches has enabled the transition from corrective and preventive maintenance models to more predictive and prescriptive strategies, allowing for early failure detection and a reduction in unplanned downtime. The study discusses how smart sensors, machine learning algorithms, and cloud computing are revolutionizing maintenance management, optimizing productivity, and reducing operational costs.

Furthermore, the research highlights the positive impact of these technologies on quality management, workplace safety, and employee training, fostering an organizational culture focused on continuous improvement and innovation. The analysis indicates that adopting these practices contributes to a more efficient, sustainable, and competitive industrial environment, ensuring greater predictability and reliability of productive assets. It is concluded that the modernization of maintenance, enabled by Industry 4.0, represents a strategic advantage for companies seeking operational excellence and process optimization.

Keywords: Total Productive Maintenance (TPM); Operational Efficiency; Maintenance Management; Equipment Availability.

1 INTRODUCTION

Maintenance plays an essential role in the industrial environment, directly influencing productivity and operational efficiency. Unexpected machine failures during the production process can have significant impacts on the production schedule, resulting in delays, increased overtime costs, and the need for rework to minimize losses. In addition, the lack of effective maintenance strategies can compromise profitability and even the survival of the business, since inefficient equipment reduces production capacity and increases waste of resources (Marques; Brito, 2019).

In this context, companies that adopt lean production principles and*just-in-time*constantly seek to eliminate waste and optimize industrial processes. Equipment reliability becomes a strategic factor for reducing stocks, ensuring the delivery of products with higher quality standards and lower rates of scrap and rework. Thus, investing in more efficient maintenance practices not only improves operational performance, but also strengthens the competitiveness and sustainability of industries (Silva*et al.*, 2018).

One of the most effective methodologies for ensuring equipment reliability and optimizing production processes is Total Productive Maintenance (TPM). This approach aims to maximize the efficiency of industrial assets through the active participation of employees at different organizational levels, promoting a culture of continuous improvement and failure prevention. Its principles include autonomous maintenance, team training, and the adoption of systematic strategies to reduce failures and production losses (Ribeiro, 2014). The application of TPM has proven to be essential for minimizing waste, improving quality, and of products and increase the reliability of processes, ensuring operational stability and contributing directly to the competitiveness of companies (Ribeiro, 2014).

With the advances of Industry 4.0, new technologies have been incorporated into industrial processes, promoting a more automated, interconnected and intelligent production environment. The introduction of cyber-physical systems, the Internet of Things (IoT), Artificial Intelligence (AI), Big Data and cloud computing has revolutionized the way industries manage their assets and production processes. These technologies allow the collection and analysis of large volumes of data in real time, facilitating the implementation of predictive and prescriptive maintenance strategies that anticipate failures and optimize the useful life of equipment (Borlido, 2017).

The integration of TPM with Industry 4.0 concepts represents a significant advance in industrial maintenance management, enabling greater predictability of failures, reduction of unscheduled downtime, and increased operational efficiency. Smart sensors combined with machine learning systems allow equipment to be continuously monitored, identifying wear patterns and suggesting interventions before critical failures occur. In addition, predictive analysis based on historical and real-time data contributes to more efficient maintenance planning, reducing operating costs and increasing productivity (Viannini; Miranda Junior, 2020).

Given this scenario, this study aims to analyze the convergence between Total Productive Maintenance and emerging technologies of Industry 4.0, investigating how this integration can improve industrial maintenance practices and increase the competitiveness of organizations. The research aims to demonstrate that the application of technological solutions in maintenance management not only enhances the benefits of TPM, but also represents a strategic differentiator for companies seeking greater efficiency and sustainability in their production processes.

2 DEVELOPMENT

2.1 Total Productive Maintenance (TPM): concept, pillars and benefits

Total Productive Maintenance (TPM) is a management methodology that originated in Japan in the 1970s and aims to maximize the efficiency of industrial equipment by involving all employees in the maintenance and continuous improvement of production processes. The main objective of TPM is to eliminate losses, reduce unscheduled downtime and ensure product quality, promoting an organizational culture of shared responsibility (Ribeiro, 2014).

According to Nakajima (1989), the main objectives of TPM are to increase equipment reliability, eliminate failures and optimize machine availability in the industrial environment. To achieve these results, the methodology promotes integrated management between operators and equipment, encouraging structural improvements in the company. In this context, technical training of employees becomes essential, since it strengthens awareness of the importance of the performance of productive assets. However, training represents a long-term investment, providing benefits such as the formation of multifunctional operators, a greater sense of responsibility, reduced repair time and more efficient collaboration between operational and maintenance teams.

TPM is a management methodology developed in Japan, whose main objective is to maximize the efficiency of industrial equipment, reducing failures and promoting the continuous improvement of production processes. According to Nakajima (1989), TPM involves the active participation of all company employees, from operators to senior management, creating a work environment where maintenance is seen as a shared responsibility. This approach aims to eliminate waste and improve the overall performance of the organization.

The TPM structure is based on eight fundamental pillars, which serve as guidelines for the effective implementation of the methodology. The first pillar, Focused Improvement, seeks to eliminate losses that negatively impact production efficiency, using methodologies such as the PDCA cycle and the Ishikawa diagram to identify and solve problems at the root (Ribeiro, 2014). The application of this pillar allows significant gains in equipment reliability and in the reduction of recurring failures.

The second pillar, Autonomous Maintenance, encourages operators to take a more active role in maintaining equipment by performing daily inspections, cleaning and minor preventive maintenance. This practice helps to increase awareness of the condition of machines and prevent failures before they cause problems.

impacts on production (Tsuchiya, 1992). In this way, operators become more responsible for the equipment they use daily.

Planned Maintenance represents the third pillar of TPM and is focused on establishing systematic strategies for preventive and predictive maintenance. According to Wireman (2005), this approach is based on the analysis of historical equipment data, enabling more efficient planning and reducing the need for corrective maintenance. This practice contributes directly to machine reliability and the reduction of unscheduled downtime.

The fourth pillar, Education and Training, is essential to ensure that employees have the necessary knowledge to operate and maintain equipment efficiently. For Nakajima (1989), the continuous development of employees improves the technical capacity of the team, reducing operational errors and strengthening the culture of continuous improvement within the company. In this way, training becomes a long-term investment for the organization.

The fifth pillar, Anticipatory Management, aims to predict failures and continually improve equipment to meet future demands. According to Shirose (1996), this practice is based on the collection and analysis of maintenance data, allowing industries to anticipate problems and adopt solutions before they impact production. This approach reduces costs and improves asset availability.

The sixth pillar, Quality Maintenance, is directly related to ensuring that equipment operates in a way that prevents product defects. According to Jostes and Helms (1994), equipment failures can compromise the final quality of the product, increasing rework and waste. The application of this pillar ensures that machine conditions are always optimized for production with high quality standards.

Safety is also an essential aspect of TPM, represented by the seventh pillar, Safety, Health and Environment (SSMA). According to Ahuja and Khamba (2008), the integration of this pillar into the industrial routine reduces work accidents and improves the ergonomic conditions of operators. Furthermore, sustainable practices in productive maintenance minimize the environmental impact of industrial operations.

The eighth pillar, Office TPM, deals with the application of continuous improvement concepts in administrative management. According to Bhadury (2000), this initiative seeks to eliminate waste in administrative processes, ensuring greater efficiency in document management, inventory control and communication between sectors.

In this way, TPM expands beyond the factory floor, impacting the entire organizational structure.

The adoption of these eight pillars brings several benefits to organizations, including increased equipment reliability, reduced operating costs and improved product quality. According to Rodrigues and Hatakeyama (2006), TPM promotes integration between the maintenance and production sectors, resulting in more efficient processes and an organizational culture focused on excellence. Furthermore, by encouraging employee involvement, the methodology improves team motivation and engagement, strengthening industrial competitiveness.

2.2 Industry 4.0: concept, principle, main technologies and impact on manufacturing

Industry 4.0, also known as the Fourth Industrial Revolution, is a revolutionary model that encompasses various technological innovations, mainly in the fields of automation, control and technology. Schwab (2016) indicates that Industry 4.0, or the Fourth Industrial Revolution, goes beyond connected systems and machines. The difference between this revolution and previous ones is the fusion and interaction of technologies from various areas of knowledge, such as physical, digital and biological.

For Morais and Monteiro (2017), based on the concepts of innovation, the Industry Industry 4.0 emerges as a set of disruptive innovations that have major impacts on operational concepts, characterized by the increasing digitalization and interconnection of products, value chains and business models, centered on the intelligent production of products, methods and processes (Smart Production). The smart factory is an important element of Industry 4.0, as it dominates complexity, is less susceptible to human interference and increases production efficiency. In the smart factory, communicating with people, machines and resources will be as natural as in a social network context, and the paradigm shift required for Industry 4.0 is a long-term project and is only just beginning.

Industry 4.0 enables greater automation of tasks, which means that workers must be prepared to perform new tasks. The same applies to engineering education, which has great potential to train professionals of the future and make them aware of new technological trends and opportunities. Managers must also adapt their management strategy to new market requirements (Erol*et al*., 2016).

According to Rübmann*et al*. (2015), these advances are possible due to technological advances seen in the last decade, combined with advances in the areas of information technology and engineering. According to the authors, there are nine axes that support this development and that allow sensors, machines, tools and information technologies to be connected throughout the entire production chain: Big Data and data analysis, robotics, simulation, Internet of Things, cybersecurity, cloud computing, horizontal and vertical integration systems, augmented reality and additive processes.

Industry 4.0 has the potential to significantly impact management and the job market in the future, enabling the creation of new business models with broad influence on the industry and markets. These transformations affect the entire product life cycle, redefining production processes and business strategies. Furthermore, the adoption of these innovations promotes the optimization of industrial processes, improving operational efficiency and strengthening the competitiveness of companies in the global scenario (Pereira; Romero, 2017).

Industry 4.0 has had a profound impact on manufacturing, transforming production processes and driving gains in efficiency, quality and flexibility. According to Kagermann, Wahlster and Helbig (2013), automation and digitalization enable greater integration between production systems, enabling real-time decision-making and the adaptation of manufacturing processes to market demands in a more agile manner. This evolution reduces production times and minimizes waste, contributing to more sustainable industrial management.

In addition to optimizing production, Industry 4.0 has had a significant impact on industrial maintenance. According to Lee, Bagheri and Kao (2015), the implementation of cyber-physical systems enables the application of predictive maintenance, in which smart sensors continuously monitor equipment conditions and anticipate failures before they compromise production. This approach reduces operating costs and improves the reliability of industrial assets, avoiding unscheduled downtime and increasing equipment availability.

Another direct effect of Industry 4.0 on manufacturing is mass customization. According to Frank, Dalenogare and Ayala (2019), the digitalization of production processes allows companies to adapt production to the specific needs of customers, ensuring customized products without compromising the efficiency of the production line. This results in greater competitiveness and the ability to serve increasingly segmented markets, expanding business opportunities.

The adoption of Industry 4.0 also impacts logistics within industrial plants. For Ivanov, Dolgui and Sokolov (2019), the interconnectivity between machines and systems allows for more efficient management of the supply chain, reducing unnecessary stocks and improving the flow of materials. This improvement in internal logistics contributes to leaner and more integrated production, strengthening the competitiveness of companies in the global scenario.

Industry 4.0 has also brought about changes in the profile of the industrial workforce. According to Pfeiffer, Siemsen and Abele (2021), the digitalization and automation of production processes require professionals with new skills, focused on data analysis, programming and operation of intelligent systems. This has led industries to invest in training programs to prepare workers for the challenges of digital manufacturing, ensuring adaptation to the new technological scenario.

2.3 The relationship between TPM and Industry 4.0: modernizing maintenance

TPM and Industry 4.0 represent innovative approaches that, when integrated, promote a profound transformation in industrial maintenance. TPM, created in Japan, aims to maximize equipment efficiency, involving all employees in the search for continuous improvement of production processes. In parallel, Industry 4.0 brings with it a set of advanced technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI) and Big Data, which enable the creation of highly intelligent and interconnected production environments. The combination of these approaches not only improves maintenance management, but also increases the competitiveness and operational efficiency of companies (Souza, 2022).

The convergence between TPM and Industry 4.0 changes the traditional approach to industrial maintenance, making it increasingly predictive and less reactive.

The implementation of IoT sensors in equipment allows for the continuous collection of operational data in real time. This information is analyzed by AI systems, which identify behavior patterns and anticipate possible failures. This advancement enables preventive interventions and drastically reduces the number of unexpected shutdowns, in line with the TPM principles of eliminating losses and maximizing productivity (Silvestri et al., 2020).

In addition to predictive maintenance, autonomous maintenance, one of the fundamental pillars of TPM, is significantly enhanced by Industry 4.0. According to Carvalho (2022), operators equipped with mobile devices, augmented reality interfaces, and remote monitoring software can monitor machine performance in real time, perform periodic inspections, and perform basic interventions with greater precision and agility. This new paradigm reduces the dependence on specialized teams for simple activities, while increasing operator autonomy, improving equipment reliability, and reducing response times for fault correction.

Planned maintenance also benefits directly from the analysis of historical and real-time data provided by Big Data. Based on detailed information about equipment performance, it becomes possible to schedule interventions in an optimized way, ensuring that maintenance is carried out at the right time. This approach reduces operating costs, increases the useful life of assets and improves the reliability of industrial systems. The ability to predict failures before they impact production also promotes greater stability in processes, minimizing financial losses resulting from unscheduled shutdowns (Silvestri et al., 2020).

In addition to operational gains, employee training has become more effective with the use of digital technologies applied to corporate education. E-learning platforms, virtual simulators, and augmented reality enable interactive and personalized training, allowing employees to acquire practical knowledge in a dynamic and efficient way. These tools facilitate the learning of new methodologies and technologies, ensuring that workers are prepared to deal with the complexity of Industry 4.0 systems. The strengthening of the culture of continuous improvement driven by these resources consolidates a more innovative and productive work environment (Lima; Silva, 2018).

Quality management also benefits from the integration between TPM and Industry 4.0. The incorporation of real-time monitoring systems ensures that any deviation in production processes is detected immediately, enabling the implementation of corrective actions without compromising production efficiency. This constant monitoring helps reduce product defects, minimizes rework, and improves the standardization of industrial quality. As a result, companies are able to increase customer satisfaction and increase their competitiveness in the global market (Aguiar et al., 2019).

In terms of safety, health and environment (SSMA), the adoption of Industry 4.0 technologies redefines the way risks are managed in the manufacturing environment. Environmental sensors monitor temperature, noise levels, air quality and vibrations in equipment, ensuring safer conditions for workers. In addition, wearable devices and AI algorithms are capable of identifying behavior patterns that indicate fatigue or ergonomic risk, triggering preventive alerts to avoid accidents and promote a safer and more sustainable work environment (Silva et al., 2021).

Administrative maintenance management is also modernized with the integration of TPM and digital technologies. Enterprise Resource Planning (ERP) and Computerized Maintenance Management Systems (CMMS) provide a unified, real-time view of all maintenance processes, facilitating strategic decision-making. This digitalization of operations reduces waste, optimizes workflows, and improves communication between company sectors, making management more efficient and aligned with the demands of Industry 4.0 (Carvalho, 2022).

Another relevant innovation is in the initial management of products, which now considers maintenance and operational efficiency aspects at the design stage of industrial projects. The use of digital models, digital twins and computer simulations makes it possible to anticipate possible failures and optimize components even before they are manufactured. This alignment between product engineering and maintenance engineering favors the creation of more reliable and easy-to-maintain equipment, reducing costs throughout the life cycle of industrial assets (Silvestri et al., 2020).

In this way, the integration between TPM and Industry 4.0 promotes a significant advance in the modernization of industrial maintenance. In addition to increasing operational efficiency, this convergence strengthens the organizational culture around continuous improvement and drives innovation within companies. The use of advanced technologies not only optimizes production processes, but also provides a safer, more sustainable and competitive environment, ensuring that the industry is prepared for the challenges of the digital age.

3 FINAL CONSIDERATIONS

The evolution of industrial maintenance practices has been a determining factor for the efficiency and competitiveness of organizations. TPM emerged as a methodology capable of reducing failures, optimizing processes and involving employees in the search for continuous improvements. However, the increasing complexity of production systems and the need for greater predictability of failures required the adoption of new strategies to ensure operational reliability. In this scenario, Industry 4.0 brought a set of technological innovations that expand the possibilities of maintenance, making it more intelligent, efficient and predictive. The combination of these approaches has driven a structural transformation in the way companies manage their production assets.

The integration between TPM and Industry 4.0 allows traditional maintenance practices to evolve from a corrective and preventive approach to predictive and prescriptive maintenance, based on real-time data analysis and artificial intelligence. The use of smart sensors, IoT and Big Data enables the collection and processing of operational information with a high degree of precision, anticipating failures and significantly reducing machine downtime. In this way, maintenance becomes more strategic, reducing operational costs and improving production efficiency. In addition, the modernization of processes positively impacts product quality, environmental sustainability and worker safety, reinforcing the fundamental pillars of TPM.

Another relevant aspect of this convergence is employee training. With the digitalization of maintenance, professionals need to develop new skills to operate and interpret the integrated systems of Industry 4.0. Tools such as augmented reality, artificial intelligence and virtual simulators make learning more dynamic and interactive, ensuring that operators can act more efficiently and autonomously. Thus, Maintenance modernization not only improves the management of industrial assets, but also strengthens the organizational culture focused on innovation and continuous development of teams.

Given this scenario, it can be concluded that the integration between TPM and Industry 4.0 represents a significant advance for industrial maintenance, ensuring greater predictability, reliability and efficiency of production processes. This synergy not only optimizes the use of resources, but also promotes a safer, more sustainable work environment that is aligned with the demands of the global market. Companies that invest in this modernization not only reduce costs and operational losses, but also strengthen their competitiveness and capacity for innovation. Therefore, the adoption of these strategies should not be seen only as a technological trend, but as an imperative for organizations seeking operational excellence and differentiation in the industrial sector.

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