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INDUSTRY 4.0: A PROPOSAL FOR IMPLEMENTATION IN A METAL-MECHANIC COMPANY IN THE INDUSTRIAL POLE OF MANAUS

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ABSTRACT

INTRODUCTION: Industry 4.0, considered the Fourth Industrial Revolution, introduces a comprehensive transformation in the productive sector, marked by the integration of advanced technologies that connect the physical and digital environment. With the use of cyber-physical systems, the Internet of Things (IoT), big data, and artificial intelligence (AI), Industry 4.0 enables automated and intelligent operations, enabling real-time production, flexibility, and resource optimization. This revolution especially impacts highly complex production sectors, such as the metal-mechanic sector, essential for strategic industries, including automotive, aeronautics, and electronics (STAUFFER et al., 2020).

Keywords: Industry 4.0. Technological Implementation. Metal-Mechanic Company. Manaus Industrial Pole.

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INTRODUCTION

Industry 4.0, considered the Fourth Industrial Revolution, introduces a comprehensive transformation in the productive sector, marked by the integration of advanced technologies that connect the physical and digital environment. With the use of cyber-physical systems, the Internet of Things (IoT), big data, and artificial intelligence (AI), Industry 4.0 enables automated and intelligent operations, enabling real-time production, flexibility, and resource optimization. This revolution especially impacts highly complex production sectors, such as the metal-mechanic sector, essential for strategic industries, including automotive, aeronautics, and electronics (STAUFFER et al., 2020).

In Brazil, the implementation of Industry 4.0 still faces significant challenges, mainly related to infrastructure, high startup costs, and lack of skilled labor. According to the National Confederation of Industry (CNI, 2018), the main barriers to adoption in the country include the need for substantial investments in technology and the lack of training policies that prepare the workforce to deal with new technological demands. These barriers become even more evident in regions such as the Manaus Industrial Pole (PIM), where infrastructure and incentives are aimed at traditional manufacturing sectors (TORTORELLA et al., 2021).

The Manaus Industrial Pole, one of the main industrial centers in the country, concentrates a wide range of companies in the metal-mechanic sector, responsible for products such as motorcycles, electronic components and household appliances. Founded in 1967, PIM offers tax incentives with the aim of promoting economic and industrial development in the Amazon region (SUFRAMA, 2020). However, the industry faces the challenge of modernizing its operations to remain competitive in the global market, adopting Industry 4.0 technologies to increase its efficiency and production quality.

The transition to Industry 4.0 represents a strategic opportunity for companies in the metal-mechanic sector of the PIM. The integration of advanced technologies can bring substantial gains in terms of cost reduction, increased productivity, and flexibility of production processes (HERMANN et al., 2016). In addition, by adopting these technologies, the sector can contribute to the sustainable development of the Amazon region, mitigating the environmental impact of industrial operations through the optimization of resources and the reduction of waste (GAO et al., 2015).

The research problem addressed in this study is: *How can a company in the metal-mechanic sector located in the Manaus Industrial Pole implement Industry 4.0 technologies*

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to improve its operational efficiency, product quality and competitiveness in the market? To answer this question, the research proposes to carry out a detailed analysis of the current conditions of a representative company in this sector and to develop a strategic plan for the implementation of Industry 4.0. This plan includes a diagnosis of the company's needs and limitations, followed by the definition of an implementation roadmap that addresses the main challenges and steps for the technological transition (LEE et al., 2015).

The general objective of this study is to propose a methodology for the adoption of Industry 4.0 in a company in the metal-mechanic sector of the PIM, aiming to optimize production processes and increase competitiveness. To this end, the following specific objectives were defined: (1) to diagnose the current situation of the company in relation to the technological infrastructure and production processes; (2) identify the Industry 4.0 technologies that are most appropriate to the company's context; (3) develop an implementation plan for these technologies, detailing steps, required resources, and timeline; and (4) propose a continuous monitoring model to evaluate the results and promote continuous improvements.

The structure of the article is organized into five sections, in addition to this introduction. In the second section, a literature review is presented that addresses the fundamental concepts of Industry 4.0, the main technologies involved, and the maturity models used to assess the readiness of companies. The third section details the methodology adopted in the study, including the application of the Impuls questionnaire and data collection through technical visits and interviews with managers of the company studied. In the fourth section, the results obtained are presented and discussed, including the roadmap for the implementation of Industry 4.0 technologies. Finally, the fifth section presents the conclusions of the study, highlighting the main contributions of the research and suggesting directions for future studies in the context of PIM and Industry 4.0 in Brazil.

THEORETICAL FRAMEWORK

Industry 4.0, also known as the Fourth Industrial Revolution, represents a new phase in the organization and control of the value chain, with an emphasis on the digitalization and interconnectivity of production processes. This concept arises from the integration of emerging technologies such as cyber-physical systems, Internet of Things (IoT), artificial intelligence (AI), big data, and cloud computing, which transform factories into intelligent and adaptable environments (HERMANN et al., 2016).

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FUNDAMENTAL CONCEPTS OF INDUSTRY 4.0

Industry 4.0 is characterized by the convergence of digital and physical technologies, which enable real-time control and advanced automation of industrial processes. According to Lee, Bagheri and Kao (2015), cyber-physical systems are central to this paradigm, as they connect the physical environment with digital systems through sensors, actuators and communication networks. These systems enable continuous data collection and immediate adaptation of production processes to changing operating conditions.

Another fundamental concept is the Internet of Things (IoT), which allows devices and machines to share data automatically, promoting integrated communication between different areas of production (XU et al., 2018). This interconnectivity makes it possible to create digital twins — virtual replicas of physical assets that can be monitored and optimized in real time (TAO et al., 2019).

EMERGING TECHNOLOGIES IN INDUSTRY 4.0

The technologies that drive Industry 4.0 not only improve efficiency and productivity, but also open up new opportunities for personalization and innovation. Artificial intelligence and machine learning, for example, allow the analysis of large volumes of data, helping in the detection of failures and quality control (RUSSELL; NORVIG, 2016). In addition, advanced robotics makes it possible to automate complex and repetitive tasks, such as inspections and assemblies, increasing accuracy and safety in the workplace (BOGUE, 2016).

Cloud computing is another essential technology, offering a scalable infrastructure for data storage and processing (ARMBRUST et al., 2010). In the context of Industry 4.0, the cloud allows remote access to information and analysis systems, facilitating collaboration between different sectors of the company and the integration of operations in real time (BUYYA et al., 2009).

BENEFITS OF INDUSTRY 4.0 FOR METAL-MECHANICAL PRODUCTION

The implementation of Industry 4.0 in the metal-mechanic sector brings a series of benefits, profoundly transforming production processes. One of the main gains is the increase in efficiency and productivity. Technologies such as IoT and AI allow for the

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continuous optimization of processes, reducing waste and increasing production flexibility (LEE et al., 2015).

Another benefit is the possibility of mass customization, allowing companies to meet specific customer demands efficiently. Big data analytics offers insights into consumer preferences and needs, allowing for quick adjustments to the production line to meet these expectations (RÜßMANN et al., 2015). In addition, predictive maintenance reduces machine downtime and optimizes equipment life, which is essential for the continuity and productivity of operations (LEE et al., 2013).

MATURITY MODELS FOR INDUSTRY 4.0 ASSESSMENT

The transition to Industry 4.0 requires companies to understand their level of readiness and ability to integrate new technologies. Several maturity models have been developed to assess this readiness, providing a detailed diagnosis and strategic guidance. Kagermann's maturity model, for example, evaluates six main dimensions, such as strategy, customers, and technology, identifying the company's level of alignment with Industry 4.0 principles (KAGERMANN et al., 2013).

Another relevant model is the Impuls questionnaire, developed by the Fraunhofer Institute, which examines six key areas, including organization, operations, and data-driven services. This questionnaire allows for a practical and structured analysis, facilitating the creation of an action plan for the gradual implementation of Industry 4.0 technologies (SCHUMACHER et al., 2016).

CHALLENGES AND BARRIERS TO THE IMPLEMENTATION OF INDUSTRY 4.0

Despite the benefits, the adoption of Industry 4.0 faces significant barriers, both technological and organizational. The lack of interoperability between legacy systems and new devices is one of the main technical challenges, making it difficult to integrate advanced technologies with existing structures (HERMANN et al., 2016). In addition, the lack of skilled professionals represents a barrier to the successful implementation of Industry 4.0, especially in regions such as PIM, where workforce training in advanced technologies is still limited (CNI, 2018).

Cultural resistance and the need for organizational change are also critical challenges. According to Müller, Kiel and Voigt (2018), cultural adaptation is essential for innovation to be accepted by employees and integrated into the organizational culture.

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Cybersecurity is another crucial factor, as increased connectivity exposes companies to additional risks, requiring robust data protection measures (KOLBERG and ZÜHLKE, 2015).

STRATEGIES FOR THE IMPLEMENTATION OF INDUSTRY 4.0

To face the challenges and maximize the benefits, several strategies are suggested for the implementation of Industry 4.0. Strategic planning, including an initial maturity assessment, is essential to establish a clear roadmap and identify priority technologies. Continuous workforce empowerment and fostering a culture of innovation are recommended strategies to facilitate adaptation and reduce internal resistance (FRANK et al., 2019).

Investments in technological infrastructure, such as 5G networks and security systems, are equally important to ensure the stability and security of processes. Strategic partnerships with research institutions and technology companies are also indicated to share knowledge and resources, reducing costs and accelerating innovation (KAGERMANN et al., 2013).

METHODOLOGY

The methodology adopted in this study is based on a qualitative and quantitative approach, structured as a case study. This method was selected due to its effectiveness in providing an in-depth analysis of a specific scenario, allowing the identification of the challenges and opportunities of the implementation of Industry 4.0 in a metal-mechanic company located in the Manaus Industrial Pole (PIM). The research follows the recommendations of Gil (2010) and Marconi and Lakatos (2010), who emphasize the importance of the case study as a tool to examine complex phenomena in real environments.

RESEARCH CATEGORIZATION

The research is characterized as applied, as it seeks practical solutions and strategies for the implementation of Industry 4.0 to improve the competitiveness of the company studied. Regarding the objectives, the study is descriptive and exploratory, as it details the current scenario of the company in relation to digital technologies and investigates the possibilities of improvement and adoption of Industry 4.0 technologies. The

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approach to the problem combines qualitative and quantitative aspects, allowing a comprehensive analysis of the organizational context and the data collected (GIL, 2010).

UNIVERSE, POPULATION AND SAMPLE

The study was conducted in a company representative of the metal-mechanic sector of the PIM, with a history of large-scale production of components for the automotive and electronics industry. The company was selected for its relevance in the sector and the need to adapt to new technological demands to increase its competitiveness. The universe of the survey includes companies in the metal-mechanic sector in the PIM, while the sample is composed of managers and technicians responsible for the production, maintenance and technological innovation of the company.

DATA COLLECTION INSTRUMENTS

Data collection was carried out through semi-structured interviews with managers and technicians of the company, in addition to technical visits for direct observation of the production processes. The semi-structured interviews allowed us to explore the perceptions and expectations of managers in relation to Industry 4.0, addressing topics such as challenges, necessary investments and expected impact on productivity. In addition, the Impuls questionnaire was applied, a tool developed by the Fraunhofer Institute to assess the company's maturity in relation to Industry 4.0. The Impuls questionnaire is widely recognized for its ability to provide a structured, practical analysis of an organization's technological capabilities (TORTORELLA et al., 2021).

DATA COLLECTION PROCEDURES

Data collection followed a structured schedule, with stages of planning, application and analysis of the instruments. Initially, meetings were held with the management team to present the objectives of the research and align expectations. Then, interviews and the Impuls questionnaire were applied, using a maturity scale ranging from 0 (not implemented) to 5 (fully implemented) to assess areas such as technology, infrastructure, organizational culture and operations. Each response was documented and categorized to facilitate analysis and development of a roadmap for implementation (SCHUMACHER et al., 2016).

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DATA ANALYSIS

Data analysis was carried out using descriptive statistics and content analysis methods, with the objective of interpreting the results of the interviews and the Impuls questionnaire. The responses were coded and grouped into categories, allowing the identification of the company's strengths and weaknesses in relation to Industry 4.0 readiness. The quantitative data from the Impuls questionnaire were tabulated and analyzed to identify the company's level of maturity in each of the six dimensions evaluated (strategy, operations, smart products, among others) (LEE et al., 2015).

DEVELOPMENT OF THE ROADMAP FOR THE IMPLEMENTATION OF INDUSTRY 4.0

Based on the results obtained, a detailed roadmap was developed to guide the company in the transition to Industry 4.0. The roadmap was structured in short, medium and long-term phases, with specific steps for the implementation of priority technologies. The first phase of the roadmap includes upgrading the IT infrastructure and training employees in digital technologies. The second phase focuses on automation and system integration, while the third phase covers the adoption of AI and big data analytics for continuous optimization of production processes. This plan was developed based on the best practices found in the literature, considering the financial and structural limitations of the company (KAGERMANN et al., 2013).

ADVANTAGES, DISADVANTAGES AND LIMITATIONS OF THE METHODOLOGY

The methodology adopted has several advantages, such as the depth of the analysis provided by the case study and the ability to adapt the Impuls questionnaire to the particularities of the company. However, there are also limitations, such as the possibility of bias in managers' responses and the restriction of data to a single company, which can limit the generalization of results. In addition, the implementation of the roadmap will depend on external factors, such as the availability of investments and the support of public policies aimed at technological innovation in the industrial sector (HERMANN et al., 2016).

RESULTS AND DISCUSSION

The results obtained with the application of the Impuls questionnaire and the interviews with managers and technicians of the company revealed critical points and significant opportunities for the implementation of Industry 4.0 in the metal-mechanic sector

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of the Manaus Industrial Pole (PIM). The analysis highlights the dimensions in which the company is most mature and identifies areas that require improvement to facilitate the technological transition. The main findings and their implications for the company's competitiveness and operational efficiency are discussed below.

PRESENTATION OF THE GENERAL RESULTS

The results of the Impuls questionnaire indicate that the company has varying levels of maturity in the six dimensions evaluated. In terms of strategy and leadership, the company is partially prepared, having an initial vision of the importance of Industry 4.0, but lacking a structured strategic plan for the adoption of technologies. The area of intelligent operations has a lower level of maturity, reflecting the need for improvements in automation and connectivity between production processes.

On the other hand, the smart products dimension showed greater readiness, as the company already uses sensors in some equipment to monitor the quality of the products. However, the absence of a robust IT infrastructure limits the ability to scale and integrate real-time data. These results suggest that, although the company has some foundations for the transition, there are significant challenges to be faced, especially in terms of infrastructure and organizational culture (LEE et al., 2015).

ANALYSIS OF THE EVALUATED DIMENSIONS

The detailed analysis of the six dimensions of the Impuls questionnaire revealed the following main points:

- Strategy and Organization: While leadership is aware of the opportunities provided by Industry 4.0, there is a lack of clear policies and goals to guide the transition. The absence of a well-defined strategic plan implies that the company depends, to a large extent, on the individual motivation of managers and technicians to innovate, without a unified direction.
- Smart Factory and Operations: The company does not have complete integration of production systems, with little connectivity between machines. In addition, the use of IoT and real-time monitoring systems is limited, making it difficult to efficiently automate processes. The lack of interconnectivity directly affects the ability to make quick adjustments in operations, an essential characteristic for the productive flexibility required by Industry 4.0 (RÜßMANN et al., 2015).

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- IT Technology and Infrastructure: The current technological infrastructure is a limiting factor for the adoption of advanced technologies, such as artificial intelligence and big data. The company uses legacy systems that are not designed to integrate with IoT technologies or to process large volumes of data. This represents a substantial barrier, as it prevents the implementation of predictive analytics and process optimization solutions (TORTORELLA et al., 2021).
- Culture and Skills: The lack of specific training for Industry 4.0 is an obvious obstacle. Employees, while experienced, lack the necessary skills to handle emerging technologies such as big data analytics and advanced automation. This aspect highlights the need for continuous training and development programs, aligned with the technological demands of Industry 4.0 (FRANK et al., 2019).

ROADMAP FOR IMPLEMENTING INDUSTRY 4.0

Based on the results obtained, a strategic roadmap was prepared to guide the company in the implementation of Industry 4.0 technologies. The roadmap is divided into three phases:

1. Phase 1: Preparation and Training (Short Term)

The first phase involves strengthening the IT infrastructure and training the team in digital technologies. At this stage, the company must perform software and hardware updates and invest in training courses focused on data analysis and basic automation. It is also recommended to create a formal strategic plan that guides the development of Industry 4.0 within the organization (KAGERMANN et al., 2013).

2. Phase 2: Integration and Automation (Medium Term)

The second phase focuses on the implementation of IoT systems and the interconnection of production processes. The company must install sensors and real-time monitoring devices on the machines and integrate this data into a centralized platform, enabling the analysis and automated control of processes. This phase aims to increase flexibility and operational efficiency by allowing for quick adjustments based on market demands (LEE et al., 2015).

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3. Phase 3: Artificial Intelligence and Continuous Optimization (Long-Term)

The last phase of the roadmap involves the adoption of artificial intelligence and big data analysis for the continuous optimization of processes. In this stage, the data collected is analyzed to identify patterns and predict possible failures, allowing predictive maintenance and improving the quality of products. The application of AI in areas such as demand forecasting and quality control increases the company's competitiveness and efficiency in the long term (HERMANN et al., 2016).

DISCUSSION OF THE RESULTS

The results obtained demonstrate that, although the company has some bases for the adoption of Industry 4.0, the complete transition will require a substantial investment in infrastructure and training. The literature confirms that organizational resistance and lack of digital skills are common challenges in the Brazilian context, especially in regions where Industry 4.0 is still in the early stages of implementation (CNI, 2018). In line with previous studies, the data suggest that the success of implementation will depend on a strategic approach that considers both the technical aspects and the necessary cultural changes (MÜLLER; KIEL; VOIGT, 2018).

The developed roadmap offers a viable path for the company to gradually adopt Industry 4.0 technologies, starting from basic training to the implementation of advanced analysis and automation systems. This plan can also serve as a model for other companies in the industry in the PIM, providing practical guidelines for overcoming region-specific barriers and achieving a more competitive level in the global marketplace.

CONCLUSION

The transition to Industry 4.0 in the Brazilian metal-mechanic sector, especially in the context of the Manaus Industrial Pole (PIM), represents a strategic opportunity to increase the competitiveness, efficiency and sustainability of industrial operations. This study investigated the current conditions of a metal-mechanic company in PIM and developed a detailed roadmap for the gradual implementation of Industry 4.0 technologies, addressing specific infrastructure, organizational culture, and capacity building challenges.

The results indicate that the company has an initial level of readiness for Industry 4.0, with some technological bases established, such as the use of sensors for quality monitoring. However, there is an urgent need for investments in IT infrastructure and

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workforce training for the transition to take place effectively. Cultural resistance and a lack of specific skills to deal with advanced technologies such as big data and artificial intelligence are significant barriers, which require a long-term strategic plan to overcome.

The roadmap proposed in this study provides a practical and structured path for the company to implement Industry 4.0 in three phases: preparation and training, integration and automation, and continuous optimization with artificial intelligence. The first phase emphasizes the importance of strengthening the technological infrastructure and empowering employees, while the subsequent phases progressively introduce automation and artificial intelligence to achieve an intelligent and flexible production model. This implementation model can be adapted by other companies in the sector in the PIM, serving as a guide to overcome the limitations common in the region and maximize the benefits of Industry 4.0.

In addition to contributing to practice, this study provides theoretical insights into the factors that drive and inhibit the adoption of Industry 4.0 in the Brazilian context. The literature points out that the lack of interoperability, cybersecurity, and resistance to change are universal challenges of Industry 4.0, but they take on specific characteristics in Brazil, where infrastructure and innovation policies are still limited. This context requires companies not only to invest in technologies, but also to promote organizational change that values innovation and continuous learning (CNI, 2018; HERMANN et al., 2016).

The main contributions of this study are in the elaboration of a practical implementation model and the identification of strategies to overcome the barriers associated with the transition to Industry 4.0. By adopting a structured roadmap, companies can prepare more efficiently for the future of digital production, fostering a culture of innovation and improving their competitiveness in a globalized market. Limitations of the study include focusing on a single company, which may restrict the generalizability of the results. Therefore, future research could explore the application of this roadmap in different sectors of the PIM, as well as assess the economic and social impact of Industry 4.0 in the Amazon region.

Industry 4.0 offers the potential to profoundly transform industrial production, bringing gains in productivity, sustainability, and quality. However, for this transformation to be sustainable and comprehensive, it is essential that public policies and government incentives support companies in the modernization journey, especially in regions where structural challenges are more significant. The implementation of Industry 4.0 in PIM will

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not only benefit the competitiveness of local companies, but will also contribute to the sustainable development of the Amazon region, aligning economic progress with environmental preservation.

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