Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/SA6.20250048
Published: May 12, 2025

Maturity of Industry 4.0: Case Study of a Maturity Model Applied to a Two-Wheel Sector Company in the Manaus Free Trade Zone

André Luiz Viana da Silva
Graduate Student
Federal University of Amazonas (UFAM)
Manaus, Amazonas, Brazil
andre.viana@ufam.edu.br

Daniel Reis Armond de Melo
Associate Professor
Federal University of Amazonas (UFAM)
Manaus, Amazonas, Brasil
armond@ufam.edu.br

Sandro Breval Santiago
Associate Professor
Federal University of Amazonas (UFAM)
Manaus, Amazonas, Brasil
sbreval@gmail.com

Abstract

We are living in a time of profound transformations driven by the Fourth Industrial Revolution, which challenges companies to rethink their operational models. In this scenario, agility, flexibility, and responsiveness have become fundamental to maintaining competitiveness. The integration of digital technologies into production processes is no longer a distant trend but a current reality that demands immediate adaptation. With this concern in mind, this study applies the PIMM 4.0 (Integrated Manufacturing Measurement Platform) model to assess the digital maturity and Industry 4.0 readiness of a motorcycle engine manufacturer located in the Manaus Industrial Pole (PIM), Brazil. The evaluation combines qualitative and quantitative approaches, based on six dimensions that represent different aspects of digital transformation. Data were collected through self-assessment and the participation of five professionals from different functional areas of the company. The results reveal that the organization is positioned at the "Technological" level of maturity, outperforming the industry average in dimensions such as Interoperability, Sustainability, and Products and Services. Pearson correlation analysis highlighted significant relationships between key dimensions, particularly between Products and Services and Manufacturing and Operations, demonstrating that digital product features often require production line modernization. The study also indicates that integrated data flows are essential for operational efficiency. Conversely, dimensions related to Business Model, People and Culture demonstrated opportunities for improvement. Overall, the model proved suitable for diagnosing the digital maturity of the company and offers practical insights for guiding strategic actions toward a successful and sustainable Industry 4.0 transformation.

Keywords
Industry 4.0, PIMM 4.0, Maturity Model, Manaus Free Trade Zone.

1. Introduction
This article discusses the impacts of digitalization and the adoption of Industry 4.0 technologies on the operational efficiency of industries in the Manaus Industrial Pole (PIM). The incorporation of these technologies has significantly contributed to the optimization of production processes, the reduction of operational costs, increased productivity, promotion of sustainability by minimizing waste and improving resource management. Additionally, these solutions have enabled greater agility in adapting to market dynamics, ensuring the competitiveness of companies.

Technological transformations are also changing consumer behaviour, leading to a demand for increasingly personalized products and more agile solutions. In this scenario, organizations need to be prepared to respond quickly and efficiently to new demands, which requires greater dynamism and flexibility in production models. The modernization of processes, anchored in the concepts of Industry 4.0, thus becomes an essential strategic pillar to face the challenges of new digital business models.

The Manaus Industrial Pole, located in the capital of Amazonas, is one of the most important industrial complexes in Brazil, housing hundreds of national and multinational companies, especially in the sectors of electronics, two-wheel vehicles, chemicals, and thermoplastics. Created to boost the economic development of the Northern region and reduce regional inequalities, the PIM combines tax incentives with a strategic location to serve both the domestic market and exports.

In this context, the implementation of Industry 4.0 technologies within the PIM has been gradual, with significant advances in automation, process digitalization, and integration of production systems. However, the degree of digital maturity varies considerably among companies on the pole, which requires specific tools for diagnosing and strategically planning digital transformation.

To meet this need, the PIMM 4.0 (Integrated Manufacturing Measurement Platform) model was developed by Sandro Breval. This methodological model aims to assess the level of digital maturity of companies based on five strategic dimensions: technology, processes, people, sustainability, and management. Through the application of a structured questionnaire, the data are statistically processed, allowing the identification of the current stage of the organization, existing gaps, and consequently, formulating an action plan that guides investments and decisions towards a structured and effective digital transformation.

The PIMM 4.0 has been an essential tool for mapping the Industry 4.0 scenario in the Manaus Free Trade Zone, helping to prioritize critical areas, align strategy and operations, and strengthen regional competitiveness in the face of the global industry.

The structure of the article includes Abstract, Introduction, Objectives, Literature Review, Methodology, Data Collection, Results and Discussions, Conclusion, and References.

1.1 Objectives
In the context of the motorcycle industry, the versatility of these vehicles in urban mobility and their significantly lower acquisition cost compared to automobiles have driven demand, resulting in a significant increase in production. Given that more than 98% of motorcycles sold in Brazil are manufactured in the Manaus Free Trade Zone (ZFM), it is essential to assess the maturity level of Industry 4.0 in this segment. Understanding this level of development is crucial for analyzing the progress in implementing digital technologies and automation in production processes, as well as measuring the effectiveness and competitiveness of organizations. This analysis allows for the identification of areas that require improvements or additional investments, guiding the strategic planning of companies to focus efforts and resources where they are most needed.

Finally, assessing the maturity level of Industry 4.0 not only contributes to digital transformation but also helps companies better position themselves in the market. This approach enables rapid adaptation to technological innovations and strengthens competitiveness by anticipating trends and sector demands, ensuring a prominent role in an increasingly technology and innovation-driven market.

The article aims to identify the impacts of implementing 4.0 technologies on the efficiency of a two-wheel industry in the PIM, applying a PIMM 4.0 technological maturity identification methodology, which considers six dimensions in its evaluation and outlines a strategy to achieve the ideal maturity level. The analysis of Industry 4.0 maturity in the PIM contributes to the sustainable and competitive development of local companies, allowing the creation of a strategic roadmap that directs efforts, resources, and investments in critical areas.

This article aims to identify the impacts of implementing 4.0 technologies on increasing the efficiency of a two-wheel industry in the Manaus Industrial Pole, initially applying a technological maturity identification methodology, and outlining a strategy to achieve the ideal maturity level.

The analysis of Industry 4.0 maturity within the context of the Manaus Industrial Pole offers valuable practical contributions to the sustainable and competitive development of local companies. A focused work on this theme allows, among other benefits, the creation of a strategic roadmap that guides companies on the path to achieving ideal technological maturity. This roadmap serves as a structured guide to direct efforts, resources, and investments in critical areas, maximizing the impact of digital transformation initiatives.

For the selection of the maturity model to be applied, the characteristics and peculiarities as well as the challenges of the PIM were considered. In this sense, the most suitable model was the PIMM 4.0, which constitutes a specific and contextualized tool to assess the degree of maturity and readiness of industries, especially those located in the Manaus Industrial Pole (PIM), regarding the adoption of Industry 4.0 technologies.

The adoption of PIMM 4.0 represents a highly strategic approach for the industries of the Manaus Industrial Pole, as it offers a detailed assessment adapted to the regional context. In addition to diagnosing the current level of digital maturity, the model provides clear direction for technological evolution, promoting competitiveness, sustainability, and preparation for future industry challenges.

2. Literature Review

The concept of Industry 4.0 goes beyond automated physical systems, also encompassing the possibility of autonomous and decentralized intelligent systems for decision-making. More than an adaptation, it should be preceded by a maturity assessment, considering the current state of the organization's points and needs for development in more strategic and critical areas, so that the impact of rapid decision-making on the results and evolution of these areas is understood.

Maturity in Industry 4.0 is a central concept for understanding how companies can adapt and thrive in an increasingly digital and connected industrial scenario. Industry 4.0 is characterized by the integration of advanced technologies such as the Internet of Things (IoT), artificial intelligence, big data, robotics, and cyber-physical systems (CPS) in production processes. This transformation aims to increase efficiency, flexibility, and customization of production, as well as promote sustainability and competitiveness of companies (Hermann et al., 2015; Zhou et al., 2015). However, to achieve these benefits, companies must assess their level of technological maturity and develop strategies to advance in their digital transformation journey.

Sonntag (2022) states that maturity models are essential for formulating business strategies, evaluating and comparing capabilities between units. In his study, he developed a maturity model to measure the adoption of Industry 4.0 technologies through Lean Manufacturing, using the methodology of De Bruin et al. (2005). Validated and applied in companies in the metal-mechanical sector, the model showed effectiveness in detecting different maturity levels and identifying improvement opportunities.

Another relevant model for assessing maturity in Industry 4.0 was proposed by Akdil et al. (2018). This model offers a comprehensive framework that considers various dimensions such as automation, connectivity, data analysis, and people management. By applying this model, companies can identify their current stage of adopting 4.0 technologies, understand their gaps, and outline a strategic roadmap to achieve ideal maturity. This approach is fundamental to ensure that technological investments are efficiently directed and that digital transformation processes are successful. However, unlike the model proposed by Akdil et al. (2018), which broadly addresses multiple sectors, the PIMM 4.0 model provides specific regional adaptations essential for capturing the unique operational and logistical contexts found in industrial environments, such as those in the Manaus Free Trade Zone. This contextualization allows for more precise diagnostics and actionable insights tailored to local industry characteristics.

The transition to Industry 4.0, however, is not without challenges. One of the main obstacles is the need for significant investments in technological infrastructure, such as sensors, actuators, networks, communication, and data analysis platforms. Additionally, personnel training and cultural change within organizations are critical aspects that need to be addressed (Hecklau et al., 2016). Interoperability between systems and cybersecurity are also issues that demand attention, especially in an environment where connectivity and data exchange are essential (Nascimento et al., 2023). On the other hand, the opportunities generated by Industry 4.0 are vast. Process optimization, cost reduction, and the ability to offer personalized products on a large scale are some of the benefits that can be achieved (Matt and Rauch, 2017).

Success in implementing Industry 4.0 depends on several factors. One of the fundamental pillars is organizational culture. With the increasing automation and digitalization of processes, it becomes essential for employees to develop new skills, especially in technology and data analysis areas. Simultaneously, leadership needs to adopt a more collaborative and innovation-oriented style (Müller et al., 2021). Human resource management should also take a holistic approach, considering not only technical training but also the well-being and motivation of teams.

Beyond the internal environment of organizations, the success of Industry 4.0 also requires the engagement of different social actors, such as unions, the industrial sector, public authorities, and academia, which have effectively collaborated in recent years. Technologies such as the Internet of Things (IoT) and cyber-physical systems have become common in factories, promoting greater connectivity and real-time monitoring. The so-called "smart factories" incorporate concepts like Plug and Produce and digital twins, enabling greater individualization and efficiency in processes. In an increasing number of industrial sectors, the demand for advanced solutions aimed at preventing unplanned production downtimes, such as supervised control systems and predictive maintenance technologies, has become increasingly critical to ensure operational continuity and efficiency (Kagermann et al., 2013).

Sustainability is another important pillar of Industry 4.0. The adoption of digital technologies allows for waste reduction, resource optimization, and the promotion of more responsible industrial practices (Avelar-Sosa et al., 2019). At the same time, the competitiveness of companies is strengthened by their ability to quickly adapt to market changes and anticipate trends. This is especially relevant in a global scenario where innovation and agility are determining factors for success (Zhou et al., 2015).

Practical cases and applications of Industry 4.0 in different sectors highlight the significant benefits of this digital transformation. In the manufacturing sector, for example, the integration of cyber-physical systems has enabled the automation of production lines and mass customization, meeting the growing consumer demand for customized products (Liu and Xu, 2017; Zawadzki and Zywicki, 2016).

These advances are not limited to isolated examples but reflect a broader strategic movement, especially in industrial regions like the Manaus Industrial Pole (PIM). Industry 4.0 offers concrete opportunities to increase competitiveness and reduce waste through strategies that reconcile productivity with technological innovation. In this context, accelerating the development of digital maturity becomes essential. Such maturity is directly related to the ability of companies to efficiently integrate technologies, promoting automated, interconnected, and sustainable production. Collaboration between government, companies, and academia is fundamental in this process, contributing to positioning the PIM as a reference in digital transformation (Itikawa and Santiago, 2021).

Maturity in Industry 4.0 is a continuous process that requires the adoption of advanced technologies, process transformation, and people training. Models such as those proposed by Akdil et al. (2018) provide valuable tools to evaluate and guide this journey, while studies by Hermann et al. (2015) and Zhou et al. (2015) highlight the impacts and challenges of this digital transformation. In this context, Santiago (2020) proposes a specific model to assess the maturity of Industry 4.0. Based on consolidated theoretical frameworks, such as the Industry 4.0 concepts of Kagermann et al. (2013), Santiago's model considers essential dimensions such as technology, processes, people, and strategy. Additionally, by emphasizing sustainability, competitiveness, and people management, the model reinforces that the integration of digital technologies can bring significant benefits to different industrial sectors. Thus, the approach proposed by Santiago stands out as an essential resource for companies seeking to adapt and thrive in an increasingly dynamic and digital environment.

Applying the model, the study by Itikawa and Santiago (2022) evaluated the level of Industry 4.0 maturity in a company benefiting from the Informatics Law in the Manaus Free Trade Zone. The research validated the PIMM4.0 maturity model through a case study and statistical analysis, offering a relevant tool to diagnose the current stage of technological adoption. Evaluations like this are crucial for PIM companies to clearly understand their position in the digital transformation journey and identify priority areas for investment and continuous improvement.

Looking to the future, Industry 4.0 is expected to continue evolving rapidly, driven by the advancement of emerging technologies such as artificial intelligence, machine learning, and cloud computing. Research and development of new technological solutions will play a decisive role in consolidating this new phase of the industrial revolution, enabling companies to face the challenges of an increasingly dynamic, complex, and competitive productive environment (Cimini et al., 2018; Oztemel and Gursev, 2020).

3. Methodology

This study adopts a qualitative approach to assess digital maturity in the context of Industry 4.0, using the PIMM 4.0 model as its methodological basis. Data collection is conducted through digital questionnaires structured around three fundamental axes: (1) respondent profile, (2) the company's industrial sector - crucial information for sectoral comparative analyses - and (3) organizational size (number of employees). This initial screening allows the results to be contextualized within a specific evaluation framework for each production segment.

This sectoral customization is precisely the differential of PIMM 4.0. Unlike generic digital maturity models, the tool was developed to capture the specific nuances of production chains such as motorcycles and electronics, considering everything from manufacturing infrastructure to logistical challenges. Its comprehensive scope evaluates nine key technological dimensions - including cultural, technological, and data management aspects - offering not only an accurate diagnosis of installed capabilities but also a personalized strategic plan for digital evolution.

Among the evaluated dimensions, sustainability stands out as a transversal element, reflecting the growing demand for responsible industrial practices. This integrated approach generates valuable insights for increasing competitiveness, especially when complemented by the benchmarking functionality that allows companies to compare their performance with peers in the Manaus Industrial Pole. Such comparisons not only identify best practices but also reveal specific operational bottlenecks - whether in technological park modernization or personnel training - allowing for strategic resource allocation.

Within a context of accelerated digital transformation, these functionalities make PIMM 4.0 particularly relevant for the Brazilian scenario. Its adaptation to the particularities of the Manaus Free Trade Zone, for example, considers unique characteristics such as the strong concentration in motorcycle production. This regional contextualization transforms the tool into more than just a diagnostic system: it becomes a strategic navigation system that guides companies in their digital transition, avoiding disconnected investments and maximizing technological returns.

As a result, the implementation of PIMM 4.0 represents a qualitative leap for local industries. In addition to measuring the current stage of digital maturity, the model provides a clear roadmap to achieve higher levels of competitiveness, aligning technological development with sustainability and preparing the productive sector for the challenges of global Industry 4.0. The educational version was selected due to its streamlined functionality appropriate for academic studies, providing an ideal balance between comprehensiveness and ease of interpretation for preliminary assessments.

3.1 The PIMM 4.0 Model

The PIMM 4.0 Method is divided into 8 dimensions: Products and Services, Manufacturing and Operations, Strategy and Organization, Supply Chain, Business Model, Interoperability, People and Culture, and Sustainability. The PIMM 4.0 methodology (Integrated Manufacturing Measurement Platform) is a comprehensive tool for assessing the maturity of companies concerning Industry 4.0. It is structured around eight main dimensions, each focused on specific aspects that contribute to digital transformation and the adoption of advanced technologies.

In the Products and Services dimension, the focus is on how the company integrates digital technologies into the development, production, and delivery of products and services. This includes the ability to offer smart, personalized, and connected products, as well as the use of tools like IoT (Internet of Things) and data analytics to enhance customer experience and add value to products. The Manufacturing and Operations dimension focuses on modernizing production and operational processes. This dimension evaluates the adoption of technologies such as automation, robotics, cyber-physical systems, and additive manufacturing (3D printing). It also considers the efficiency, flexibility, and adaptability of production processes to market demands.

In the Strategy and Organization dimension, the analysis is on how the company aligns its corporate strategy with Industry 4.0 principles. This includes defining clear goals, organizational structure, data governance, and leadership capacity to promote digital transformation. The dimension also evaluates the existence of an innovation culture and the ability to adapt to technological changes. The Supply Chain dimension examines the integration and digitalization of the supply chain. It assesses visibility, traceability, and collaboration among suppliers, partners, and customers, using technologies such as blockchain, supply chain management (SCM) systems, and advanced planning tools. The goal is to ensure an agile, resilient, and efficient supply chain. In the Business Model dimension, the methodology explores how the company innovates in its business model to adapt to new Industry 4.0 opportunities. This includes adopting service-based models (servitization), digital platforms, subscriptions, and other approaches that generate value from data and connectivity. The dimension also evaluates the ability to monetize new business opportunities.

The Interoperability dimension assesses the ability of systems, machines, and processes to communicate and work in an integrated manner. This includes adopting open standards, communication protocols, and integration systems such as IIoT (Industrial Internet of Things) and APIs (Application Programming Interfaces). Interoperability is essential for ensuring efficient data exchange between different parts of the organization and the value chain.

The People and Culture dimension focuses on the role of employees and organizational culture in digital transformation. It evaluates the level of employee training and skills development, the adoption of new digital skills, and the promotion of an innovation and collaboration culture. It also considers change management and the ability to engage employees in the transformation process.

The Sustainability dimension analyses how the company integrates sustainable practices into its operations and strategies, aligned with Industry 4.0 principles. This includes adopting technologies that reduce environmental impact, such as energy efficiency, waste management, and the circular economy. It also evaluates the company's commitment to sustainability and social responsibility goals.

The PIMM 4.0 methodology not only defines the eight essential dimensions for assessing the maturity of Industry 4.0 but also establishes four maturity levels that help organizations understand their current stage and chart a path for evolution. These levels - Digital, Technological, Transition, and Advanced - are directly related to the dimensions, as each evolves as the company progresses through maturity stages. This classification varies according to a set of scores to be achieved for each level, with the Digital level being the most basic, scoring between 0 and 1, the Technological level between 1 and 2, the Transition level scoring between 2 and 3, and the Advanced level, the highest level, scoring between 3 and 4 points, all considering the 8 dimensions of the methodology, as presented in the following Table 1:

Table 1. Relationship between Scores, Maturity Levels, and Dimensions

Level	Digital	Technological	Transition	Advanced
Dimensions	**Base grade by technological level**			
Products and Services	0 - 1,0	1,0 - 2,0	2,0 - 3,0	3,0 - 4,0
Manufacturing and Operations				
Strategy and Organization				
Supply Chain				
Business Model				
Interoperability				
People and Culture				
Sustainability				

Explaining the levels, at the Digital level, for example, dimensions such as Manufacturing and Operations and Interoperability are at an initial stage, with low connectivity and system integration. At the Technological level, automation initiatives and improvements in data collection begin to emerge, positively impacting dimensions such as Supply Chain and Products and Services. At the Transition level, high integration between systems and large-scale automation reflects significant advances in dimensions such as Strategy and Organization and Business Model, with greater visibility and predictive capacity. Finally, at the Advanced level, all dimensions reach their peak, with full interoperability, self-optimized processes, and an organizational culture aligned with Industry 4.0, demonstrating how maturity in each dimension contributes to complete digital transformation. This connection between maturity levels and PIMM 4.0 dimensions allows companies to identify not only their overall stage but also how each specific area can evolve, offering a holistic and strategic view for digital transformation.

The application of PIMM 4.0 is carried out through questionnaires, statistical analyses, and case studies, allowing for the identification of gaps and improvement opportunities. These questionnaires are available through a web system, with 3 versions: Demo, Educational, and Full. The Demo version is aimed at demonstrating and understanding the system with limited resources and a questionnaire, but it delivers a summary report at the end with the maturity according to the inserted evaluation. The Educational version has some additional functionalities, such as reports and graphs, like the Demo version, and the questionnaire also has a reduced number of questions compared to the Full version, which, according to the author, has a more detailed questionnaire and a higher level of information and reports. The version used in this work was the educational version, which has an academic scientific focus and can be found on the PIMM 4.0 portal: (Available at https://pimm40.tech/educa/pesquisa/questionario/view/index.php).

Within the dimensions and the provided questionnaire, questions related to each dimension are evaluated, such as the level of product customization, system and process integration, investments in research and development, the level of data integration and availability by the company, the level of employee knowledge regarding technologies and data tools, among other questions.

4. Data Collection

In this context, the model was applied in one of the largest motorcycle manufacturers in Brazil, located in the Manaus Free Trade Zone. The research focused on a strategic segment of production - the engine factory - composed of three interconnected production units: casting, machining, and assembly of engines of various displacements.

This industrial unit stands out for its modern infrastructure and verticalized production processes, positioning itself as a key player in the development of the two-wheel sector in the country. In addition to large-scale production capacity, the company differentiates itself through continuous investments in technology and innovation, ensuring high standards of efficiency and quality. Another relevant aspect is the organization's commitment to sustainable practices and social responsibility, manifested through environmental initiatives and community development programs in the region.

For the research, a qualitative approach was chosen, allowing for a detailed and contextualized analysis of the collected data. The process began with the insertion of data into the PIMM 4.0 system, an educational version, a tool developed to assess the maturity and readiness of companies about Industry 4.0. After the initial data collection, the results generated by the system were analysed, providing insights into the current maturity stage of the studied company. This step was essential to identify gaps and improvement opportunities.

To ensure the reliability and validity of the data, six specialists were involved, each with expertise in specific areas such as production/manufacturing, logistics, information technology, projects, and sustainability. These professionals have experience ranging from 4 to 20 years, enriching the analysis with diverse technical and practical perspectives. Each specialist completed the PIMM 4.0 questionnaire, contributing their unique perspective. The triangulation of data, with multiple perspectives, allowed for robust validation of the information and a more comprehensive analysis of the results.

The qualitative methodology, combined with the use of PIMM 4.0 and the participation of specialists, provided an accurate and reliable assessment of the company's maturity with Industry 4.0. In addition to identifying the current stage, the research highlighted priority areas for investments and improvements, offering a solid foundation for the development of digital transformation strategies aligned with the organization's needs. This methodological approach reinforces the credibility of the results and contributes to the company's advancement towards the fourth industrial revolution, maintaining its prominent position in the sector.

4. Results and Discussions

In a preliminary stage of the research, the author himself completed the PIMM 4.0 model questionnaire based on his professional experience as a collaborator and project manager in technology and innovation within the organization. His work over the past four years, especially in initiatives related to Industry 4.0 and digital transformation, provided a solid technical and practical foundation for the evaluation.

After completing the instrument, the information was processed by the PIMM 4.0 digital platform, considering the automotive sector's reference parameters. The results indicated that the company performs above the segment average in most of the evaluated dimensions, except for two categories where the scores were below the sector benchmark. For comparative analysis purposes, a bar chart shown in Figure 1 illustrates the company's performance across the eight dimensions of the model, allowing visualization of the gap between the base level (organization's score as evaluated by the researcher) and the segment average (industry benchmark). This visualization facilitates the identification of strengths and improvement opportunities in the company's digital maturity process.

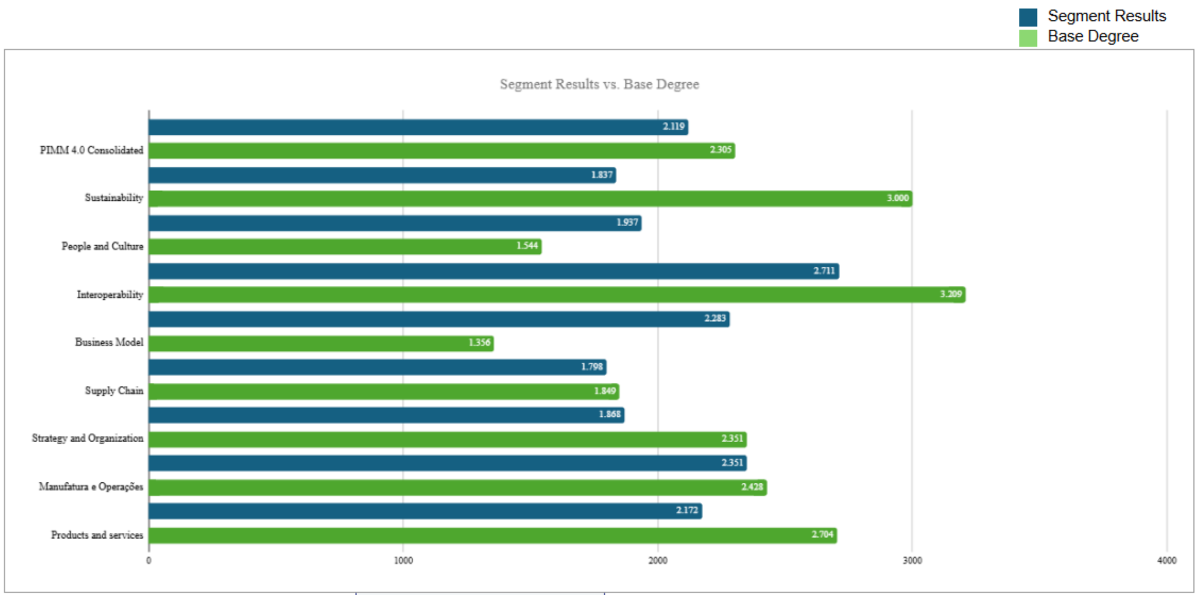

Figure 1. Comparison of Base Level with Segmented Level of Evaluation.

The final evaluation of the PIMM 4.0 System indicated that the maturity level of the assessed factory is at the Technological position, where integrated information technology with production systems is adopted. There are some important system initiatives, with reduced interoperability, the beginning of automation in operational areas, and evidence of low visibility.

The results presented by the methodology are consistent with the reality of the factory within the company evaluated. However, to broaden the perception of the evaluation and verify the reliability of the result, five employees from different specialties within the assessed factory (engine factory) and support sectors were invited to respond to the questionnaire. The results of each user's evaluations are presented in Table 2.

Table 2. PIMM 4.0 Results for Engine Assembly Line and Support Sectors

	Products and Services		Manufacturing and Operations		Strategy and Organization		Supply Chain		Business Model		Interoperability		People and Culture		Sustainability		PIMM 4.0 Consolidated	
Evaluator	Baseline Level	Segment Level	Baseline Level	Segment Level	Baseline Level	Segment Level	Baseline Level	Segment Level	Baseline Level	Segment Level	Baseline Level	Segment Level	Baseline Level	Segment Level	Baseline Level	Segment Level	Baseline Level	Segment Level
Author	2.704	2.172	2.428	2.351	2.351	1.868	1.849	1.798	1.356	2.283	3.209	2.711	1.544	1.937	3	1.837	2.305	2.119
IT/Logistics	2.39	2.172	2.606	2.351	1.882	1.868	3.383	1.798	3.158	2.283	3.209	2.711	2.154	1.937	3	1.837	2.723	2.119
Environmental	3.338	2.172	2.988	2.351	2.819	1.868	2.474	1.798	2.241	2.283	3.209	2.711	3.129	1.937	4	1.837	3.025	2.119
Foundry	3.018	2.172	2.057	2.351	3.292	1.868	1.856	1.798	1.794	2.283	1.595	2.711	2.194	1.937	3	1.837	2.351	2.119
Machining	2.698	2.172	2.434	2.351	2.351	1.868	1.534	1.798	2.249	2.283	3.209	2.711	1.91	1.937	3	1.837	2.423	2.119
Final Engine	1.195	2.172	1.676	2.351	1.882	1.868	2.165	1.798	1.356	2.283	2.244	2.711	1.219	1.937	2	1.837	1.717	2.119
Average	2.704	2.172	2.431	2.351	2.351	1.868	2.011	1.798	2.018	2.283	3.209	2.711	2.154	1.937	3	1.837	2.387	2.119

Considering the six evaluators, the analysis revealed that the company's consolidated average was 2.387, surpassing the evaluated industrial segment average of 2.119. Four of the six evaluators reached the "Transition" maturity level, with scores close to each other, reflecting some homogeneity in the perception of digital maturity. One evaluator achieved the "Advanced" level, while another was classified at the "Digital" level, revealing different perspectives on the adoption of Industry 4.0 practices among sectors. The overall average of the evaluations also remained within the Transition level, the same as verified by the author of the research.

The dimensions with the best performance were Interoperability (3.209), Sustainability (3.0), and Products and Services (2.704), highlighting significant advances in technological integration and environmental responsibility. On the other hand, the lowest performances were observed in Business Model (2.018) and People and Culture (2.154), indicating challenges related to strategic management and cultural adaptation to digital transformations.

The results suggest a good level of digital maturity but also reinforce the need to improve organizational and leadership aspects regarding Industry 4.0 concepts. It was also observed that the subjectivity and level of familiarity of the evaluators with Industry 4.0 concepts directly influenced the responses. Notably, evaluators linked to the final stages of the production chain - identified in the framework as "Final Engine" - presented a more critical view, resulting in the lowest overall score and classification at the "Digital" level. This perception may be related to the greater impacts felt by these sectors due to the absence of digitalization. As highlighted by Tessarini and Saltorato (2018), the non-application of Industry 4.0 technologies tends to significantly affect factory floor operators, production managers, and supply chains, resulting in manual processes, a lack of real-time visibility, and a loss of operational efficiency.

Additionally, as highlighted by Tessarini and Saltorato (2018), even though users further removed from direct operations of the production chain may not feel the impacts of the absence of Industry 4.0 technologies as immediately, they are also affected by the lack of systemic integration, especially in highly connected industrial environments. This finding can be observed in the evaluation conducted by the Environmental Evaluator, whose perception was more optimistic compared to the other evaluators, suggesting that the distance from direct operation may positively influence the perception of the organization's digital maturity.

The other evaluations showed high consistency with the author's perception, evidenced by the convergence in the identified maturity level (Technological level) and the similarity in the assigned scores. This uniformity in the results reinforces the reliability of the evaluation conducted.

Additionally, to quantify the degree of similarity between the evaluators' perceptions, Pearson's Correlation was used, a statistical coefficient that measures the strength and direction of the linear relationship between two quantitative variables. The coefficient value ranges from -1 to +1, where values close to +1 indicate strong positive correlation, values close to -1 indicate strong negative correlation, and values close to 0 indicate no linear correlation. The application of this metric allows verifying the alignment between the evaluators regarding the dimensions evaluated in the PIMM 4.0 model, providing quantitative support for the analysis of the reliability of the obtained data. Figure 2 shows the levels of Pearson's r coefficient. In Table 3, the results of the correlation evaluation and Pearson's r coefficient are shown, where the results and data provided in Table 3 were evaluated using JASP (Just Another Statistical Program), which is a free and open-source software aimed at statistical analysis.

Table 3. Intensity versus Pearson's r Coefficient Values

Intensity	Value of r	Direction
Very Strong	0.9-1.0	Positive/Negative
Strong	0.7-0.9	Positive/Negative
Moderate	0.5-0.7	Positive/Negative
Weak	0.3-0.5	Positive/Negative
None	0.0-0.3	Negative

Figure 2 results reveal significant relationships among three fundamental dimensions for the implementation of Industry 4.0: Products and Services, Manufacturing and Operations, Strategy and Organization, People and Culture, and Interoperability. Pearson's coefficient analysis demonstrated a strong positive correlation ($r = 0.751$) between the dimensions of Products and Services and Manufacturing and Operations, Interoperability and Manufacturing and Operations ($r = 0.728$), indicating a marked interdependence between these areas. The same applies to People and Culture and Products and Services, with the highest correlation in the evaluation.

Figure 2. Correlation Evaluation and Pearson's r Coefficient

Pearson's Correlations

Variable		Products and Services	Manufacturing and Operations	Strategy and Organization	Supply Chain	Business Model	Interoperability	People and Culture
1. Products and Services	Pearson's r	—						
	p-value	—						
2. Manufacturing and Operations	Pearson's r	0.751	—					
	p-value	0.052	—					
3. Strategy and Organization	Pearson's r	0.724	0.166	—				
	p-value	0.066	0.722	—				
4. Supply Chain	Pearson's r	−0.102	0.345	−0.407	—			
	p-value	0.828	0.448	0.365	—			
5. Business Model	Pearson's r	0.299	0.593	−0.184	0.698	—		
	p-value	0.515	0.160	0.693	0.081	—		
6. Interoperability	Pearson's r	0.252	0.728	−0.451	0.253	0.444	—	
	p-value	0.585	0.064	0.309	0.584	0.318	—	
7. People and Culture	Pearson's r	0.794	0.797	0.542	0.306	0.532	0.236	—
	p-value	0.033	0.032	0.209	0.504	0.219	0.610	—

The Products and Services dimension, which encompasses aspects such as customization, digital product features, and product data usage, demonstrated an explanatory power ($r^2 = 0.564$), indicating that 56.4% of the variability observed in the Manufacturing and Operations dimension can be associated with changes in the former. This latter dimension, in turn, evaluates critical elements such as the level of automation, process and system integration, and methods of collecting and using operational data.

This significant correlation indicates that innovations in Products and Services drive improvements in manufacturing, and vice versa. The digitalization of products demands the modernization of production lines, while automated processes contribute to increased added value. Continuous and efficient data integration between these areas is fundamental for operational excellence. Similarly, the Interoperability dimension, which evaluates the implementation of management systems, their integration with other systems, logistics chain connectivity, and data protection protocols, also demonstrated significant correlation with Manufacturing and Operations. This finding reinforces the premise that the digital maturity of information systems is intrinsically related to productive efficiency. The incorporation of digital attributes in products requires the modernization of production lines, while automation favors the development of higher-value solutions. Continuous data integration between these areas is crucial for operational efficiency.

The study revealed a very strong positive correlation ($r = 0.794$) between the People and Culture and Products and Services dimensions, indicating a significant interdependence relationship. The coefficient of determination ($r^2 = 0.630$) shows that approximately 63% of the variability observed in Products and Services can be explained by changes in People and Culture (or vice versa). The high correlation suggests that companies with skilled teams and agile culture tend to develop more innovative products/services adapted to digital demands. While the correlation between Products/Services and Manufacturing/Operations ($r = 0.751$) reflects technical synergies, the relationship with People and Culture ($r = 0.794$) highlights the human factor as a critical element for innovation. This underscores that digital transformation is not only technological but also cultural and organizational, and that Industry 4.0 strategies should integrate training, cultural change, and product development simultaneously.

6. Conclusion

This study addressed organizational transformation considering Industry 4.0 principles, emphasizing the integration of digital technologies and innovative strategies in the engine production chain of a two-wheel automotive sector company located in the Manaus Free Trade Zone. In this context, the importance of incorporating Industry 4.0 concepts and practices as an integral part of organizational culture is highlighted.

To meet the demands of the new industrial scenario, it is essential to optimize manufacturing and operations processes through the expansion of digital data collection and analysis, advanced automation, and interoperability between systems and machines. The strategic use of these technologies enables the continuous identification of improvement opportunities, resulting in efficiency gains and operational cost reductions. However, such advances are only sustainable when accompanied by consistent alignment between organizational strategy and Industry 4.0 objectives, requiring leadership to continuously assess organizational readiness, as argued by Hermann et al. (2015).

The application of the PIMM 4.0 model allowed for an accurate assessment of the digital maturity of the analysed factory, classifying it at the "Technological" level and demonstrating performance exceeding segment averages in several dimensions. The inclusion of multiple evaluators reinforced the reliability of the obtained data, revealing convergence in perceptions about the organization's current stage, as well as the identification of persistent challenges, such as the need to strengthen Industry 4.0 concepts and practices at operational and managerial levels.

Pearson's correlation analysis highlighted relevant interdependencies between the evaluated dimensions, with strong correlations between Products and Services, Manufacturing and Operations, and People and Culture. These results indicate that technological innovation should occur in an integrated manner with operational efficiency and human development. The Products and Services dimension showed a significant impact on Manufacturing and Operations, explaining 56.4% of its variability. Complementarily, the Interoperability dimension presented a strong association with productive efficiency, emphasizing the role of systemic integration in consolidating digital maturity. On the other hand, the lowest scores obtained in the Business Model and People and Culture dimensions suggest the need for strategic and cultural interventions to drive organizational progress.

The findings reinforce that digital maturity transcends the punctual adoption of technologies, demanding a systemic approach that integrates processes, people, and culture. Additionally, the study highlights the relevance of considering the perceptions of different actors in the production chain, as their direct or indirect experiences with digitalization processes substantially affect their evaluations. However, the successful implementation of these technologies fundamentally depends on continuous investments in workforce training. Qualification programs focused on programming, data analysis, and emerging technologies, combined with the development of specific digital skills for manufacturing and logistics contexts, are crucial to ensure organizational adaptation to the demands of the new industrial paradigm.

In summary, the transition to Industry 4.0 necessitates a strategic alignment between technological integration, process optimization, and the enhancement of human capital. The synergistic interaction among these pillars is essential for fostering organizational competitiveness, sustainability, resilience, and innovation in response to complex global challenges. Nevertheless, while preliminary insights derived from Pearson's correlation analysis offer an initial understanding of the interrelationships among maturity dimensions, more sophisticated statistical approaches, such as multiple regression and exploratory or confirmatory factor analysis, are recommended to elucidate underlying causal mechanisms and strengthen the robustness of findings. Moreover, future studies should consider longitudinal research designs to capture the temporal evolution of digital maturity, enabling a more comprehensive assessment of the long-term impacts and effectiveness of Industry 4.0 implementation strategies within specific regional industrial ecosystems.

References

Akdil, A. Ustundag, and E. Cevikcan, “Maturity and readiness model for industry 4.0 strategy,” in Industry 4.0: Managing the digital transformation, Springer, Cham, pp. 61–94, 2018.
Azevedo and S. B. Santiago, “Design of an assessment industry 4.0 maturity model: An application to a manufacturing company,” in Proc. Int. Conf. Ind. Eng. Oper. Manage., IEOM Society, pp. 1–12. [Online]. Available: https://ieomsociety.org/toronto2019/papers/59.pdf, 2019.
Cimini et al., “Industry 4.0 technologies impacts in the manufacturing and supply chain landscape: An overview,” in Proc. Int. Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing, Springer, Cham, pp. 109–120, 2018.
De Bruin et al., “Understanding the main phases of developing a maturity assessment model,” in Proc. Australasian Conf. Inf. Syst. (ACIS), Australasian Chapter of the Association for Information Systems, pp. 8–19, 2005.
Hecklau et al., “Holistic approach for human resource management in Industry 4.0,” Procedia CIRP, vol. 54, no. 1, pp. 1–6, 2016.
Hermann, T. Pentek, and B. Otto, “Design Principles for Industrie 4.0 Scenarios: A Literature Review,” Working Paper No. 01, 2015.
https://doi.org/10.3390/sci4030026.
Itikawa and S. B. Santiago, “A Systematic Review on Industry 4.0 Maturity Metrics in the Manaus Free Trade Zone,” Int. J. Adv. Eng. Res. Sci., vol. 8, p. 1, 2021.
Itikawa and Santiago, S. B. “Industry 4.0 Maturity: A case study of a maturity model applied to the Manaus Free Trade Zone company,” Int. J. Dev. Res., vol. 12, no. 08, pp. 58238–58245, Aug. 2022. https://doi.org/10.37118/ijdr.25190.08.2022.

Kagermann, W. Wahlster, and J. Helbig, “Recommendations for Implementing the Strategic Initiative Industrie 4.0,” Final Report of the Industrie 4.0 Working Group. Available: https://en.acatech.de/publication/recommendations-for-implementing-the-strategic-initiative-industrie-4-0-final-report-of-the-industrie-4-0-working-group/. Accessed on: Feb 19, 2025, 2013,

KIM, Jaewoo et al. M2M service platforms: Survey, issues, and enabling technologies. IEEE Communications Surveys and Tutorials, v. 16, n. 1, p. 61-76, 2013

Liu and X. Xu, “Cyber-physical machine tool—the era of machine tool 4.0,” Procedia CIRP, vol. 63, pp. 70–75, 2017.

Matt and E. Rauch, “Designing assembly lines for mass customization production systems,” in Mass Customized Manufacturing, CRC Press, pp. 33–54, 2017.

Müller, J. M., Buliga, O., and Voigt, K. I. *Industry 4.0 Implementation: The Critical Role of Organizational Culture and Workforce Adaptation*. Technological Forecasting and Social Change, 162, 2021, https://doi.org/10.1016/j.techfore.2020.120323

Nascimento, T. H. R. do, Matos, W. M., Figarela, E. A. B., Souza, E. C., and Leite Júnior, J. É. *Desafios e oportunidades da Indústria 4.0 na Engenharia de Controle e Automação Industrial*. Revista Faculdade de Tecnologia – ISSN 1678-0817, v. 27, ed. 123. Available at: https://revistaft.com.br/desafios-e-oportunidades-da-industria-4-0-na-engenharia-de-controle-e-automacao-industrial/. Accessed on: April, 25, 2023.

Oztemel and S. Gursev, “Literature review of Industry 4.0 and related technologies,” J. Intell. Manuf., vol. 31, no. 1, pp. 127–182, 2020.

OZTEMEL, Ercan; GURSEV, Samet. Literature review of Industry 4.0 and related technologies. Journal of Intelligent Manufacturing, v. 31, n. 1, p. 127-182, 2020.

Santiago, S. B. PIMM 4.0 Industry 4.0 Diagnostic Portal, Model implemented in several industries in the states of Brazil! (s.d.). Available at https://pimm40.tech/educa/pesquisa/questionario/view/index.php

Sonntag, Desenvolvimento de modelo de maturidade da indústria 4.0 fundamentado no lean manufacturing, Universidade Federal do Paraná, 2022.

Tessarini, G., and Saltorato, P. Impactos da indústria 4.0 na organização do trabalho: Uma revisão sistemática da literatura. *Revista Produção Online, 18*(2), 743–769, 2018, https://doi.org/10.14488/1676-1901.v18i2.2967

Zawadzki and K. Zywicki, “Smart product design and production control for effective mass customization in the Industry 4.0 concept,” Management and Production Engineering Review, 2016.

Zhou, T. Liu, and L. Zhou, “Industry 4.0: Towards future industrial opportunities and challenges,” in Proc. 2015 12th Int. Conf. Fuzzy Systems and Knowledge Discovery (FSKD), IEEE, pp. 2147–2152, 2015.

Biographies

André Luiz Viana da Silva is Control and Automation Engineer, graduated from the School of Mines at the Federal University of Ouro Preto (UFOP) in 2020. He began his academic journey in 2013, participating in an extension project on urban mobility using VANET simulation in the SUMO simulator, under the guidance of Professors Wellington Passos and Prof. Dr. Thiago Oliveira (UFSJ). In 2014, he conducted a scientific initiation project with Prof. Dr. Gustavo Peixoto (UFOP), researching metaheuristics applied to parallel machine scheduling, a study presented at the VIII UFOP Career Fair. He participated in academic initiatives through the junior enterprise Automic Jr (2016), under the supervision of Prof. Dr. Agnaldo Reis, and joined the FEMU-UFOP Formula Team, advised by Professors Sávio Lopes and Profa. Dra Elisângela Leal. In 2020, he completed an academic and professional exchange in Darmstadt, Germany, working at the electrical engineering consultancy Mollmann Beratende Ingenieure. He holds a postgraduate degree in Project Management from Fundação Getulio Vargas (FGV, 2023) and an MBA in Junior Leadership and Business Management with a focus on behavioral competencies from the BBI of Chicago (2020). Currently, he is completing a specialization in Industrial Engineering and Management at CETELI/UFAM. He works professionally as a Digital Innovation Specialist at a multinational company in the automotive sector, contributing to projects focused on digital transformation and Industry 4.0.

Professor Daniel Reis Armond de Melo is Ph.D. in Business Administration from the Federal University of Bahia (2012). Holds a Master’s degree in Production Engineering (2006) and a Bachelor's degree in Business Administration from the Federal University of Amazonas (2002). Currently, he is an Associate Professor at the Federal University of Amazonas. He coordinated the Professional Master's Program in Intellectual Property and Technology Transfer for Innovation (PROFNIT) from 2018 to 2021, where he was also responsible for the course "Concepts and Applications of Technology Transfer." He served as Executive Secretary at the Secretariat of Administration and Management (SEAD/Amazonas) from 2017 to 2019. He has experience in business consulting, working mainly in the following areas: Project Management, Innovation Management, and Information Systems. He participates in several university research groups and is the leader of GEPPETTO/UFAM and NUPAD/UFAM. He also serves as a reviewer for academic journals in the field of Business Administration. In 2013, he received the CAPES Thesis Award in the area of Business Administration for his dissertation titled "University-Industry Relationship in Brazil: The Role of Academia in Coinvention Networks." He completed a postdoctoral fellowship in Innovation Management at the School of Economics, University of Porto, Portugal (2016–2017).

Professor Sandro Breval Santiago is a Postdoctoral researcher at the Polytechnic School of the University of São Paulo (USP), in the field of Mechatronics Engineering (ongoing). Completed a postdoctoral program at the Faculty of Engineering, University of Porto, specializing in Industrial Management / Industry 4.0. Holds a Ph.D. in Industrial Engineering from the Federal University of Santa Catarina (UFSC) and a Bachelor's degree in Business Administration from the Federal University of Amazonas (UFAM).
Has received international training in management from the University of Chicago, Wharton School, INSEAD, ESADE, and RWTH Aachen University. Also completed international training in Digital Transformation at Porto Business School and the i40mc – Expert Training program at Acatech/RWTH Aachen University in Germany.
Has extensive experience in advanced manufacturing projects, industrial management, and technological services. Currently serves as an Associate Professor at the Federal University of Amazonas (UFAM) and is an accredited professor at Fundação Dom Cabral (FDC).