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MATURIDADE DA INDÚSTRIA 4.0 NO POLO INDUSTRIAL DE MANAUS POLO:
Aplicação do modelo pimm4.0 no setor de eletrônica empresa

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INDUSTRY 4.0 MATURITY IN THE MANAUS INDUSTRIAL POLE: Application of the PIMM 4.0 model in an electronics sector company

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Abstract:

Background: The advent of Industry 4.0 has ushered in a novel technological paradigm characterized by enhanced connectivity, automation, and data-driven decision-making frameworks. Despite the global progression of industries toward digital transformation, enterprises situated in the Manaus Industrial Pole (PIM) encounter distinctive challenges pertaining to logistics, infrastructure, and the adaptation of technological innovations. A comprehensive understanding of the maturity level of Industry 4.0 implementation within this specific context is imperative for informing strategic decision-making processes and fostering competitive advantages.

Materials and Methods: This study applied the PIMM 4.0 maturity assessment framework to evaluate an electronics-sector enterprise within the PIM. A quantitative case study methodology was executed, collecting data from 86 employees representing various organizational tiers. The assessment tool scrutinized three pivotal dimensions—Manufacturing and Operations, Supply Chain, and Interoperability—utilizing an ordinal scale ranging from 1 to 4, indicative of the organization's technological preparedness and degree of integration.

Results: The results reveal that the organization is situated at an incipient phase of Industry 4.0 implementation, with the majority of subdimensions in Manufacturing and Operations classified at Levels 1 and 2. The Supply Chain dimension exhibited an intermediate level of maturity in terms of Lead Times and Visibility, whereas Interoperability attained the highest performance metrics, with a preponderance of indicators reaching Level 4. Notable deficiencies were identified in IT security and integration within the supply chain, both of which fell significantly short of the anticipated benchmarks for advanced digital transformation.

Conclusion: While the organization demonstrates notable advancements toward digitalization—particularly concerning system integration and the utilization of manufacturing data—its overarching maturity level is confined to Level 2. Focused enhancements in cybersecurity, the digitalization of the supply chain, and strategic alignment are crucial for progression toward Level 3 of Industry 4.0 maturity. Ongoing investment in technological integration and the development of organizational capabilities will be vital for maintaining competitive standing and facilitating a thoroughly interconnected industrial ecosystem.

Key Word: Industry 4.0; Maturity Model; Interoperability; Digital Transformation; PIMM 4.0.

I. Introduction

The Industrial Revolution, according to historical records, began in England in the second half of the 18th century and represented a decisive milestone in the technological, economic, and organizational development of society. This period radically transformed production methods, giving rise to new management models, work organization, and factory structuring.

Traditionally, it is divided into three phases: the First Industrial Revolution, driven by the steam engine and mechanization of the textile industry; the Second, marked by the expansion of industrialization, the use of new energy sources such as electricity and oil; and the Third, characterized by the automation of production processes, driven by computing, robotics, and biotechnology.

Industry 4.0, also known as the Fourth Industrial Revolution, represents a major shift in manufacturing and industry through the integration of new technologies, such as the Internet of Things (IoT), cyber-physical systems, and advanced data analytics. It is composed of six principles: interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity, which support flexibility, adaptability, and efficiency in manufacturing, creating intelligent and interconnected production systems.

The Manaus Industrial Pole (PIM), which is widely acknowledged as one of the most sophisticated and advanced industrial complexes located in the entirety of Latin America, is characterized by the presence of more than 500 diverse enterprises, all of which collectively contribute to its significant role in fostering both regional and national

development, as noted by scholars Alanís and Silva in their 2023 study. At the present moment, the foremost priority for stakeholders and policymakers involved with the PIM resides in the strategic alignment of this industrial hub with the foundational principles and innovative concepts of Industry 4.0, with a particular emphasis on the necessity for modernization and technological adaptation, which are regarded as essential mechanisms to maintain the ongoing relevance and facilitate the expansion of the regional economy in an increasingly competitive global landscape. The preparedness and responsiveness of the industrial sector within Manaus to the transformative paradigms presented by Industry 4.0 are already manifesting in tangible ways, clearly illustrating a proactive and anticipatory adjustment to the prevailing global industrial trends that are reshaping production and operational frameworks worldwide.

II. Theoretical Framework

The integration of Industry 4.0 technologies instigates a profound transformation in the management of organizational change by establishing novel frameworks, professional roles, and requisite competencies, while concurrently amplifying the necessity for adaptive, interactive, and sociotechnical methodologies. To achieve successful integration of Industry 4.0, organizations are compelled to reevaluate both their technological infrastructures and their human resource management strategies to efficaciously facilitate change (8). The effective management of the substantial transformations instigated by the advent of Industry 4.0 necessitates the implementation of interactive organizational processes that foster an environment conducive to continuous learning and adaptive responses as novel technologies are systematically integrated into existing workflows and practices. Nonetheless, the process of implementing these groundbreaking innovations frequently gives rise to internal tensions, particularly in the context of balancing competing demands, such as those for ongoing learning and high performance, as well as the need for structured organizational frameworks and a strong sense of belonging among employees, among various other considerations. Successfully addressing these challenges requires the strategic development of comprehensive approaches that effectively reconcile the immediate pursuit of short-term results with the imperative to consolidate and enhance long-term organizational capabilities and competencies (9,10).

Industry 4.0 Impacts

The advent of Industry 4.0 has profoundly enhanced production efficiency within the electronics industry through the amalgamation of innovative technologies such as the Internet of Things (IoT), artificial intelligence, and big data analytics. These advanced technologies facilitate instantaneous data interchange, predictive maintenance, and optimized resource allocation, culminating in diminished production timelines and elevated product quality (11). For instance, the deployment of IoT-enabled devices and sensors empowers manufacturers to oversee production processes in real time, fostering anticipatory maintenance and minimizing the frequency of unanticipated operational interruptions (12).

Moreover, the establishment of smart factories has demonstrated beneficial effects on operational performance and cost efficiency, as substantiated by empirical studies of manufacturing enterprises that have embraced Industry 4.0 technologies (13). The incorporation of sophisticated robotics and automation has streamlined production methodologies, facilitating swifter adaptations to market fluctuations and consumer demands, thus enhancing overall productivity (14,15).

Maturity Analysis in Industry 4.0

The concept of Industry 4.0 maturity pertains to the extent of preparedness and capability of organizations to embrace and assimilate sophisticated technologies linked to the Fourth Industrial Revolution. Evaluating this maturity is pivotal for enterprises to measure their advancement in the adoption of digital technologies and to discern deficiencies that can inform their transformative strategies.

Maturity models, including those predicated on fuzzy logic and multicriteria methodologies, facilitate more nuanced diagnostics by considering the intrinsic uncertainty of human judgment and the intricacies of industrial processes, thereby aiding the transition towards intelligent operations and supply chains (16,17). Approaches that incorporate multidimensional indicators evaluate Industry 4.0 readiness through a weighted aggregation of diverse metrics, thereby enabling organizations to ascertain their present condition and preparedness for implementation (18).

The Manaus Industrial Pole (PIM)

The Manaus Industrial Pole (PIM) serves as a principal economic driver within the Northern region of Brazil, established to facilitate regional advancement through the provision of fiscal and industrial incentives. Research indicates that the PIM demonstrates considerable economic vitality, characterized by rapid productivity

enhancement propelled by economies of scale and technological advancement, in accordance with the Kaldor-Verdoorn law, particularly within the manufacturing domain (19). Enterprises operating within this pole have endeavored to implement contemporary management methodologies, such as lean manufacturing, thereby attaining favorable outcomes in operational efficiency and the adoption of principles derived from the Toyota Production System (20).

Nonetheless, environmental management remains constrained, encountering obstacles due to the inadequate execution of public policies and challenges in enforcing regulations aimed at the conservation of natural resources, despite advancements in environmental consciousness and recycling efforts (21).

Entities within the PIM have also allocated resources towards innovative strategies, including the integration of Industry 4.0 technologies in supply chain operations and the deployment of solar energy systems to curtail expenses and enhance sustainability (22,23). However, logistical challenges persist as a pivotal concern, predominantly reliant on port infrastructure. The productivity of local ports remains subpar compared to the national average, adversely impacted by operational disruptions predominantly stemming from inadequate road conditions, environmental and climatic factors such as seasonal droughts, and a multitude of other significant impediments (24).

These logistical difficulties in Manaus, particularly within the PIM, constitute substantial hindrances to the region's progress. The geographic seclusion of the area diminishes competitiveness and inhibits the comprehensive implementation of Industry 4.0 practices. The current advancements towards Industry 4.0 are limited, and addressing these logistical challenges is imperative for enhancing operational efficiency and promoting the expansion of local enterprises (25).

III. Material And Methods

This investigation is predicated upon research executed within a corporation situated in the Manaus Industrial Pole (PIM), which operates within the electro-electronic sector. Utilizing the PIMM 4.0 methodological framework, the data collection process was implemented across various hierarchical strata, scrutinizing functionalities, governance, and strategic initiatives, along with the stakeholders embedded within the value chain, encompassing both customers and suppliers. Links to the email addresses of personnel engaged in the production process were disseminated, thereby facilitating the acquisition of quantitative data and corroborative evidence.

PIMM 4.0 constitutes a maturity assessment model aimed at appraising the efficacy with which organizations are assimilating Industry 4.0 technologies, with particular emphasis on real-time inventory management and operational efficacy in industrial settings such as PIM (26).

The methodological framework employed in this inquiry encapsulates the exploration of seven pivotal dimensions within the corporate milieu: Products and Services, Manufacturing and Operations, Strategy and Organizational Structure, Supply Chain, Business Model, Interoperability, and People and Organizational Culture. These dimensions are methodically disaggregated into 47 subdimensions, which constitute the foundation of the data collection instrument utilized.

In the instance of the organization under examination, the empirical dataset comprised responses obtained from 86 employees who engaged in the survey process via a structured questionnaire.

Responses were evaluated using an ordinal scale ranging from 1 to 4, signifying varying degrees of technological and organizational maturity concerning the tenets of Industry 4.0. Specific evaluative criteria were delineated for this objective, which are systematically organized in the subsequent table.

Level	Classification	Description
1	Digital	Insufficient organizational outreach in the amalgamation of the production chain with technological frameworks and the interconnections among both vertical and horizontal processes.
2	Technological	Existence of systems that amalgamate certain organizational dimensions, featuring automation within production; however, these systems exhibit minimal alignment with the industry 4.0 paradigm and exhibit a deficiency in comprehensive integration.
3	Transition	System integration facilitates visibility through substantial initiatives in automation.
4	Advanced	Enhancement of respective processes, alongside integrated interoperability across varying organizational strata.

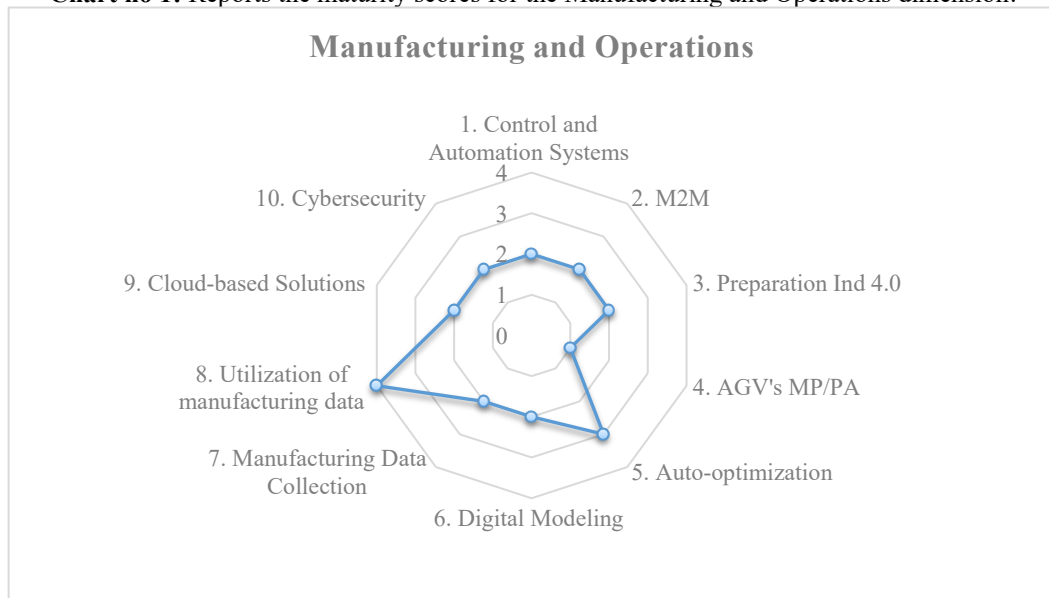
Table no 1: Defines measurement criteria for the study.

The current research endeavor seeks to investigate three pivotal dimensions pertinent to Industry 4.0: Manufacturing and Operations, Supply Chain, and Interoperability. Through this investigation, the intention is to evaluate the maturity level of the organization in each dimension, employing the PIMM 4.0 framework.

IV. Result

The analysis of the data was executed through the examination and interpretation of radar charts constructed from the empirical data gathered during the study. The three dimensions were appraised based on the scores allocated to each subdimension, with the mode derived from the 86 valid responses secured. Subsequently, the charts were generated utilizing these modal values, which encapsulate the most prevalent data points.

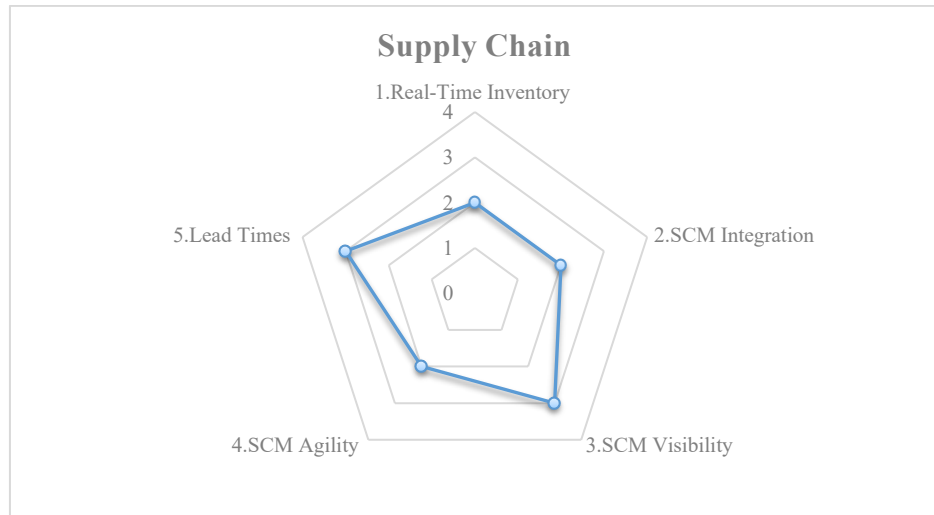
Chart no 1: Reports the maturity scores for the Manufacturing and Operations dimension.



The radar chart adhered to the parameters established by the study, wherein Level 1 (innermost) signifies the preliminary digital stage, and Level 4 (outermost) denotes a superior level of maturity. The evaluation of Chart 1, pertaining to “Manufacturing and Operations”, indicates that the majority of subdimensions are concentrated at Levels 1 and 2, suggesting minimal compliance with Industry 4.0 principles. However, Subdimension 8 is distinguished at Level 4, signifying a substantial degree of optimization and integration in the utilization of manufacturing data. This denotes the incorporation of devices and sensors, facilitating real-time data collection and analysis, which augments decision-making and operational efficacy (28).

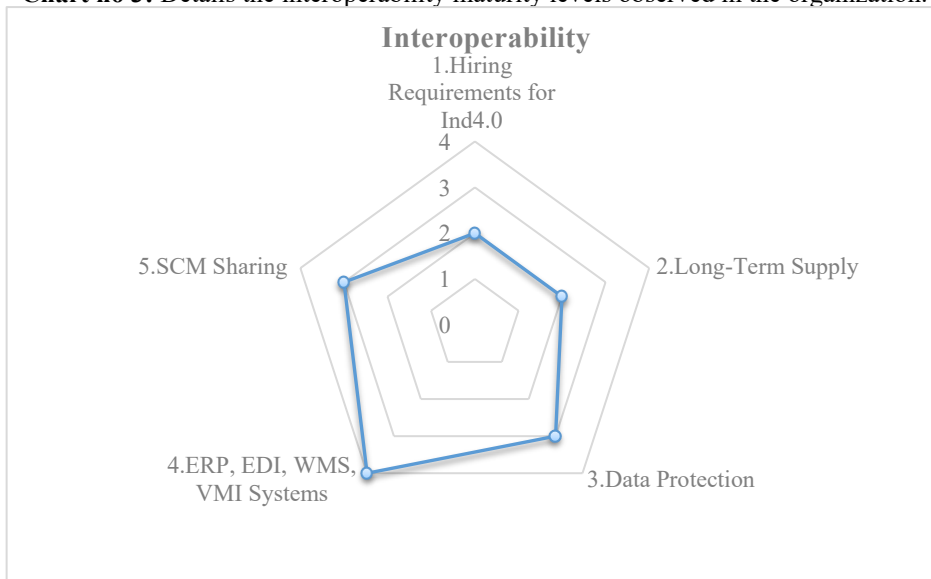
Despite the alignment of manufacturing data utilization with the ideal model of Industry 4.0, Subdimension 10, which pertains to IT Security, reveals potential for enhancement, as it is a crucial element in system integration and has a direct influence on digital transformation and operational performance.

Chart no 2: Displays the maturity scores related to the Supply Chain dimension.



In the context of the “Supply Chain” dimension, none of the subdimensions are situated at Level 1 or Level 4, suggesting a partial progression toward complete integration with Industry 4.0 standards. Two subdimensions, Lead Times and Supply Chain Visibility, are categorized at Level 3, indicating intermediate advancement. These results reflect a trend toward comprehensive supply chain integration and the existence of interoperability across processes. Improved visibility facilitates enhanced transparency in decision-making, which is vital for agile responses to consumer demands (29).

Chart no 3: Details the interoperability maturity levels observed in the organization.



In contrast to the preceding dimensions, Chart 3, which corresponds to “Interoperability”, illustrates that the organization exhibits a high degree of system integration, achieving Level 4 compliance with Industry 4.0 principles. Furthermore, the subdimension associated with data protection is positioned at Level 3, indicating satisfactory performance, albeit with avenues for enhancement.

In summary, the findings denote that while the organization exhibits progressive advancements toward digital transformation, particularly in manufacturing integration and system interoperability, significant deficiencies remain in IT security and supply chain digital maturity. Fortifying these areas would enable a more holistic adoption of Industry 4.0 standards, thereby promoting greater operational synergy, data-driven decision-making, and sustained competitiveness.

V. Discussion

The results of this investigation elucidate a heterogeneous distribution of Industry 4.0 maturity across the evaluated dimensions, indicating that while the organization has commenced the integration of digital technologies into its operational framework, the advancement remains inconsistent across the assessed domains. The elevated

level of interoperability observed signifies that the organization has made considerable progress in systems integration, a finding that aligns with scholarly research accentuating that integrated digital environments are frequently the initial indicators of Industry 4.0 maturity [28]. Nevertheless, the prevalence of Levels 1 and 2 within the Manufacturing and Operations dimension reveals considerable deficiencies in automation, cyber-physical connectivity, and information technology security. These outcomes are in concordance with previous investigations that illustrate how technological adoption is often impeded by structural and organizational obstacles [8,9].

Moreover, the intermediate performance exhibited in the Supply Chain dimension underscores a partial advancement towards real-time visibility and agility, while simultaneously exposing enduring challenges in synchronizing supply chain partners and digital platforms. As articulated in prior literature, the integration of supply chains typically progresses at a slower pace than internal automation owing to its reliance on external stakeholders and shared infrastructures [29]. Our findings corroborate this trend by demonstrating that despite the presence of certain initiatives, comprehensive alignment with Industry 4.0 standards has yet to be realized.

In summary, the cross-dimensional analysis indicates that the organization occupies a transitional phase of digital maturity. Progressing towards elevated levels will necessitate investments not solely in infrastructure and automation but also in cybersecurity, workforce training, and long-term operational strategies. These considerations resonate with the assertion that Industry 4.0 transformations require holistic methodologies capable of harmonizing technological advancement with organizational readiness [10].

VI. Conclusion

Upon a thorough examination of the three distinct dimensions that have been investigated within the context of the case study, it can be reasonably inferred that the company exhibits a degree of alignment with the fundamental principles associated with Industry 4.0 in certain specific areas of its operations and strategic framework. However, it is essential to acknowledge that there remain several sectors within the organization that possess considerable opportunities for enhancement and optimization. The presence of evidence indicating progress in various subdimensions strongly suggests a promising potential for further advancement, particularly if the organization implements adequate strategic frameworks and undertakes targeted investments in key areas. Considering the overall average score attained, which currently positions the company at a maturity level classified as Level 2, it is anticipated that, with sustained efforts and commitment, achieving Level 3 will be within reach, thereby signifying a more sophisticated stage of digitalization and technological integration within the company's operational paradigm.

The findings derived from this comprehensive analysis accentuate the critical importance of formulating and developing adaptive management strategies that possess the capability to effectively address and navigate the multifaceted challenges posed by the seamless integration of emerging new technologies into existing business processes. Organizations are faced with the imperative task of striking a delicate balance between the immediate performance pressures that necessitate attention to short-term results and the equally essential requirement to cultivate and enhance long-term capabilities, which are vital for not only surviving but thriving in the dynamically evolving landscape characterized by Industry 4.0 advancements.

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