

Industry 4.0 Practices in the Amazon Region: An Operations Management Perspective

Práticas da Indústria 4.0 na Região Amazônica: uma Perspectiva da Gestão de Operações

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ABSTRACT

The adoption of Industry 4.0 (I4.0) in peripheral regions, such as the Brazilian Amazon, remains underexplored. This study analyzes I4.0 practices in Amazonian manufacturing industries from an operations management perspective, assessing their implementation, the adequacy of an assessment protocol, and the maturity levels observed. A multiple-case study was conducted in two companies: a thermal power plant with continuous production and 60 employees, and a plastic injection molding company with batch production and 400 employees. A structured protocol comprising eight constructs and 57 open-ended questions was applied, combining document analysis, on-site observation (10 days per company), and 20 interviews totaling 30 hours. Data were analyzed using Bardin's content analysis framework. The results indicate that both companies exhibit maturity levels between the computerization and connectivity stages (1-2), corresponding to Industry 2.0 and Industry 3.0, with no advanced implementation of I4.0. The thermal power plant exhibits greater sensor integration and horizontal integration than the batch production company. Basic sensors and supervisory control systems are the predominant technologies, whereas the Internet of Things (IoT), big data, digital twins, and artificial intelligence are absent. The findings indicate that the production system influences I4.0 maturity in the companies analyzed. The protocol proved suitable for the qualitative assessment of these practices, providing a replicable diagnostic tool. Social implications include differences in employees' understanding of I4.0 and concerns about job displacement. This study contributes to operations management by expanding knowledge of digital transformation in underexplored industrial contexts.

Keywords: Industry 4.0. Operations management. Manufacturing industries. Amazon region. Maturity assessment.

RESUMO

A adoção da Indústria 4.0 (I4.0) em regiões periféricas, como a Amazônia brasileira, permanece pouco explorada. Este estudo analisa práticas de I4.0 em indústrias manufatureiras amazônicas sob a perspectiva da gestão de operações, avaliando sua implementação, a adequação de um protocolo de avaliação e os níveis de maturidade observados. Realizou-se um estudo de casos múltiplos em duas empresas: uma usina termelétrica, com produção contínua e 60 funcionários, e uma empresa de injeção plástica, com produção por lotes e 400 funcionários. Aplicou-se um protocolo estruturado com oito construtos e 57 questões abertas, combinando análise documental, observação in loco (10 dias por empresa) e 20 entrevistas, totalizando 30 horas. Os dados foram analisados por meio da análise de conteúdo de Bardin. Os resultados indicam que ambas as empresas apresentam níveis de maturidade entre os estágios de computadorização e conectividade (1-2), correspondentes às Indústrias 2.0 e 3.0, sem implementação avançada de I4.0. A usina termelétrica apresenta maior integração de sensores e integração horizontal em comparação à empresa de produção por lotes. Sensores básicos e sistemas supervisórios são as tecnologias predominantes, enquanto Internet das Coisas (IoT), big data, gêmeos digitais e inteligência artificial estão ausentes. Conclui-se que o sistema produtivo influencia a maturidade em I4.0 nas empresas analisadas. O protocolo mostrou-se adequado à avaliação qualitativa dessas práticas, oferecendo um instrumento diagnóstico replicável. As implicações sociais incluem diferenças na compreensão da I4.0 entre funcionários e preocupações com a substituição de postos de trabalho. O estudo contribui para a gestão de operações ao ampliar o conhecimento sobre a transformação digital em contextos industriais pouco investigados.

Palavras-chave: Indústria 4.0. Gestão de operações. Indústrias manufatureiras. Região Amazônia. Avaliação de maturidade.

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1 INTRODUCTION

Industrial production was transformed first by steam power in the 19th century, then by electricity in the early 20th century, and finally by automation in the 1970s. However, these waves of technological advancement have not reduced overall employment. While the number of manufacturing jobs has declined, new jobs have emerged and the demand for new skills has grown. Today, another workforce transformation is on the horizon, as manufacturing experiences a fourth wave of technological advancement: the emergence of new digital industrial technologies that are collectively known as Industry 4.0 (Lorenz et al., 2015).

The Fourth Industrial Revolution is characterized by the increasing digitization and interconnection of products, value chains, and business models. It is characterized by the fusion of technologies that blur the lines between the physical, digital, and biological spheres. There are three reasons these transformations are not just an extension of the third industrial revolution: (1) speed, (2) scope, and (3) systems impact. The speed of current disruptions, which is without historical precedent when compared to previous revolutions, means the Fourth Revolution involves an exponential rather than a linear pace. It influences almost all industries and countries, signifying that the breadth and depth of these changes herald the transformation of entire systems of production, management, and governance (Koch et al., 2014; Schwab, 2015).

The term Industry 4.0 (I4.0) has been used since 2011 to describe the widespread integration of information and communication technology into industrial manufacturing. The term "Industrie 4.0" was introduced in 2011 by the Communication Promoters Group of the Industry Science Research Alliance to describe the widespread integration of information and communication technology into industrial production. The origins of the idea can be found in the German government's 2006 High Tech Strategy. Some of the features of I4.0 were identified in Germany's industrial policy in 2010 and in 2012 the government made I4.0 one of the 10 future projects part of its High Technology Strategy (Schuh et al., 2020; Smith et al., 2016).

I4.0 represents a paradigm shift from "centralized" to "decentralized" production, that is, made possible by technological advances that constitute a reversal of the logic of the conventional production process. Thus, this means that the industrial production machinery no longer simply "processes" the product, but that the product communicates with the machinery to inform it exactly. I4.0 involves the development of independent systems capable of making their own decisions using machine learning. Therefore, this industry allows for the exploration of pillars such as the Internet of Things (IoT), Big Data and data analytics, collaborative robots, additive manufacturing, cloud computing, artificial intelligence, 5G networks, and others (Bunse et al., 2014; Ortiz et al., 2020).

The research literature on I4.0 has grown considerably in recent years. This growth in the subject has been documented in research reviews conducted on various topics, such as the capacity of I4.0 technologies (Justus et al., 2018); evaluation model for SMEs (Essakly et al., 2019; Kolla et al., 2019; Rauch et al., 2020); macroeconomic assessment of I4.0 (Roland Berger, 2014); skills and competencies for I4.0 (Cotet et al., 2017; Pacaux-Lemoine et al., 2021; Perini et al., 2017); and interface between lean manufacturing and I4.0 (Kolla et al., 2019).

In conclusion, the Manaus Free Trade Zone (ZFM) emerged in 1967 as a development model with the objective of fostering the economic development of the region, integrating the states of the Northern Region and promoting the occupation of this region. Currently, there are approximately 500 companies installed in the Industrial Pole of Manaus (PIM) and more than 120 thousand direct jobs. The PIM recorded revenue of R\$ 204.39 billion in 2024, which is equivalent to a nominal growth of 16.24% over the value obtained in 2023 (R\$ 175.83 billion). Computer goods (9.93%), electronics (11.71%) and two-wheelers (18.32%) were the PIM segments with the largest participation (Superintendência da Zona Franca de Manaus [SUFRAMA], 2025b).

Therefore, the gap addressed by this study lies in conducting qualitative research to understand managers' and employees' perceptions of Industry 4.0 practices within the production environment, specifically involving operations management. Therefore, the following research questions were developed for investigation:

RQ1: Do companies implement Industry 4.0 practices in their production environment?

RQ2: Does the survey framework provide an adequate assessment of practices related to Industry 4.0?

RQ3: What is the observed Industry 4.0 maturity level in these companies, according to the literature?

Thus, this study aims to understand practices related to Industry 4.0 in the manufacturing industries in the Amazon region. This research employed a multiple-case study as an epistemological approach, based on a protocol for understanding Industry 4.0 practices to support organizations in their pursuit of a new productive and technological trajectory. The second section deals with concepts related to Industry 4.0, its dimensions, and the research reviews existing in the literature in recent years. Section three discusses the study's methodology and research structure; section four deals with the presentation of the case study companies; section five presents the results and the discussion carried out throughout the study. Finally, the last section presents the conclusion with the final position of the study.

2 BACKGROUND

2.1 Concepts of Industry 4.0 and its dimensions

The term Industry 4.0 has been used since 2011 to describe the widespread integration of information and communication technology into industrial manufacturing. Consequently, the importance of Industry 4.0 lies in the pivotal role of information processing in enabling rapid organizational adaptation. The faster an organization can adapt to an event that alters its circumstances, the greater the benefits of adaptation (Schuh et al., 2020).

The Fourth Revolution represents a new level of organization and control across the entire value chain throughout product life cycles. This cycle focuses on increasingly personalised customer demands, encompassing everything from conception to order processing, development, production, and delivery to the end customer and ultimately, recycling including all associated services. Its specific potential lies in highly flexible production, high productivity, and low resource consumption, enabling the manufacture of highly individualised products under the economic conditions of mass production. Engineering, production, logistics, services, and marketing are ultimately interconnected within dynamic, inter-company

networks, optimised in real time to generate added value (Cologne Institute for Economic Research – IW, 2015).

While Industry 3.0 focuses on automating individual machines and processes, I4.0 focuses on end-to-end digitization of all physical assets and integration into digital ecosystems with value chain partners. Data generation, analysis, and communication underpin the gains promised by I4.0, which networks a wide range of new technologies to create value. Therefore, Industry 4.0 is driven by (Reinhard et al., 2016):

1. Digitization and integration of vertical and horizontal value chains;
2. Digitization of product and service offers;
3. Digital Business Models and Customer Access.

The essence of the I4.0 vision is the ubiquitous connection of people, things, and machines. This connection aims to produce a variety of new goods and services. Products, means of transport, or tools are expected to “negotiate” within a virtual market about which production elements could best perform the next production step (Koch et al., 2014).

Industry 4.0 encompasses six design principles in its framework: decentralization, virtualization, interoperability, modularity, real-time capability, and service orientation. These principles are called “design principles” because they contribute to the design process or transition from a common industry (3.0), to Industry 4.0 (Hermann et al., 2015).

This network within an “internet of things, services, data, and people” will transform the future of manufacturing. Several authors use the term “Industry 4.0” to refer to the fourth industrial revolution with four main characteristics (Deloitte, 2015, 2016):

1. The vertical network of intelligent production systems, such as factories and intelligent products, a network of intelligent logistics, production, marketing, and intelligent services, with a strong need-oriented, individualized, and customer-specific production operation;
2. Horizontal integration through a new generation of global value creation networks, including integration of business partners and customers, and new business models and cooperation across countries and continents;
3. Through engineering across the entire value chain, encompassing not just the production process but also the final product, i.e., the entire product life cycle;
4. Acceleration through exponential technologies that, while not new in terms of their development history, are only now capable of mass-market application as their cost and size have decreased (e.g., sensor technology) and their computing power has increased enormously.

Several disruptive technologies are related to I4.0, enabling the digitization of an organization. These technologies involve (1) data, computational power, and connectivity; (2) analytics and intelligence; (3) human-machine interaction; and (4) physical-to-digital conversion. The I4.0 allows us to explore certain pillars, such as the Internet of Things (IoT); Big Data and data analysis; augmented reality; cybersecurity; collaborative robots; additive production; cloud computing; artificial intelligence; and 5G networks (Oztemel & Gursev, 2020; Wee et al., 2015).

Therefore, I4.0 describes the organization of production processes based on technology and devices that communicate autonomously along the value chain in virtual computer models. It involves a series of disruptive innovations in production and leaps in industrial processes, resulting in significantly higher productivity. The value of the Industry 4.0 concept can

be enhanced by clarifying the role played by technologies that facilitate the physical manipulation of objects. Among the various technologies, the Internet of Things (IoT) stands out; IoT is a crucial element of Industry 4.0. This concept has gained momentum in recent years as the importance of connectivity, both in the creation of products and services and in increasing customer and consumer satisfaction, has become better understood (Smith et al., 2016; Sniderman et al., 2016).

The uses of I4.0 often require the use of investments in new technologies that do not pay for themselves in the same year. However, these investments can be minimized by applying the minimum viable product (MVP) approach, that is, thinking about the smallest possible implementation, but delivering relevant commercial value in a given area. In Industry 4.0 transformations, easy-to-implement pilots are often at the fringes of the operation's key value creation processes. Adopting a "technology-forward" approach instead of an "impact-backward" selection of Industry 4.0 solutions can lead to pilot projects that demonstrate unclear commercial value (Tschiesner et al., 2019).

In conclusion, the use of Industry 4.0 technologies in manufacturing can boost productivity and mitigate the environmental impact of industrialisation, potentially creating employment rather than displacing it – thereby fostering inclusive development. However, these technologies may fail to redistribute wage advantages in manufacturing from emerging economies to industrialised nations. To counter this, tailored science, technology and innovation (STI) policies must be implemented, commensurate with each country's developmental stage. Such policies should prepare both businesses and workforces for an era of rapid transformation, while establishing a robust and diversified industrial base (UNCTAD, 2022).

2.2 Assessment in Industry 4.0

Concerning the assessment in I4.0, the consultancy Roland Berger (2014) mapped the extent of progress with the implementation of I4.0 in different EU Member States in terms of two criteria: "industrial excellence" and "value networks"; the article by Schumacher et al. (2016) proposed a new empirically grounded model and its implementation to assess Industry 4.0 maturity in industrial enterprises within the domain of discrete manufacturing. The primary objective was to broaden the dominant technological focus of recently developed models by incorporating organizational aspects. The dimensions "Products", "Customers", "Operations", and "Technology" were established to evaluate fundamental enablers. Furthermore, the dimensions "Strategy", "Leadership", "Governance", "Culture", and "People" allow for the inclusion of organizational aspects in the assessment.

Cotet et al. (2017) identified and assessed the core of the various complex skills required in the I4.0 environment using a psychological instrument to assess transversal capabilities; and Perini et al. (2017) present a Training Data Evaluation Tool (TDET), which is based on the integration of a Training Evaluation Ontology (TEO) with a Training Analytical Model (TAM) for defining workers' skill levels.

Vaidya et al. (2018) provided an overview of Industry 4.0, along with an understanding of its nine pillars. The nine pillars of Industry 4.0 are explained with examples to illustrate the application of Industry 4.0, as well as to identify the challenges and issues associated with its implementation; Justus et al. (2018) stand out. They evaluate the capacity

of Industry 4.0 technologies against the functional requirements, specifically focusing on the Proof of Concept (PoC) for Predictive Maintenance in the automotive industry for the construction of a Referential Architecture; and Colli et al. (2018) provided a new digital maturity assessment approach (360 Digital Maturity Assessment) based on problem-based learning (PBL).

Colli et al. (2019) indicate the need to support companies in this transformation is currently covered by several maturity models, usually operationalized through standardized questionnaires; and Essakly et al. (2019) developed a performance metrics framework for the holistic assessment of the impact of I4.0 solutions on SMEs.

Additionally, Sharpe et al. (2019) analyzed the evaluation of RAMI4.0, a Research Architecture (RA) designed for I4.0, through the representation of the core functionality of an existing Cybernetic-Physical System (CPS). Lin et al. (2019) release the Smart Industry Readiness Index (SIRI). SIRI is one of the I4.0 maturity models that help industrial companies identify opportunities moving towards I4.0. Kolla et al. (2019) provided state of the art literature on existing assessment models and mapped lean and I4.0 components to the specific characteristics of manufacturing SMEs.

Rauch et al. (2020) developed an assessment model for SMEs that provides a clear overview of existing Industry 4.0 concepts; Yüksel (2020) investigated the applications of I4.0 in companies in Turkey, a developing country; Dikhanbayeva et al. (2020) identified research gaps concerning Industry 4.0 design, based on their analysis of 12 maturity models derived from eight basic design principles; Liebrecht et al. (2021) evaluated available I4.0 methods to select the most suitable for an individual company; and Pacaux-Lemoine et al. (2021) evaluated the design methodology called Cognitive Work Analysis (CWA) and its applicability when designing an assistance system to support humans in controlling the Intelligent Manufacturing System in I4.0.

El Baz et al. (2022) investigated how sustainability drivers can be taken into account when implementing Industry 4.0 technologies. The authors propose addressing sustainability-oriented Industry 4.0 implementation through three main stages: approach, deployment, and outcomes (externalities). Anshari and Hamdan (2022) identified critical new skills and capabilities required among organizational personnel to maintain competitiveness, innovation and relevance regarding KM's role in developing new skill sets or capabilities within the Fourth Industrial Revolution context. Belhadi et al. (2022) developed a self-assessment model to evaluate the systemic level of circular economy and Industry 4.0 integration within organizations using a dynamic capabilities perspective.

Govindan and Arampatzis (2023) propose a framework to assist industries in adopting Industry 4.0 through two phases. In the initial phase, the company's readiness level is assessed. In the second phase, existing barriers to Industry 4.0 implementation (based on the company's readiness evaluated in the first phase) are analysed. Hajoary et al. (2023), with further developments in Hajoary et al. (2024), developed a novel multidimensional analytical framework and indicators to assess Industry 4.0 maturity and readiness across six dimensions and 32 indicators. Sajjad et al. (2024) developed and validated a comprehensive, compatible modified lean manufacturing maturity model for Industry 4.0 (LM4I4.0).

In conclusion, Rakiman et al. (2024) determined the readiness level for Industry 4.0 in the manufacturing sector and identified Industry 4.0 implementation barriers within manufacturing industries. Sulistyo et al. (2025) developed an integrated Lean 4.0 readiness assessment tool to bridge

the gap between Lean readiness and Industry 4.0 readiness. McDermott et al. (2024) investigated Industry 4.0 readiness and comprehension within the pharmaceutical industry, while McDermott et al. (2025) subsequently assessed the Industry 4.0 readiness status in their medical device manufacturer case study.

2.3 Manaus Industrial Park (PIM) and Amazonas Economic Development

The Manaus Free Trade Zone (Zona Franca de Manaus – ZFM) was established with the objective of creating a free-trade area for the storage, processing, and export of products originating from abroad. On February 28, 1967, ten years later, the government expanded this legislation, and President Castello Branco signed Decree-Law No. 288, which reformulated the model and established tax incentives for 30 years to implement a development hub in the Amazon region. This decree-law defined the ZFM as an industrial, commercial, and agricultural center.

Over its more than 50 years of existence, the Manaus Free Trade Zone model has undergone at least five phases concerning regional development theories. The first phase (1967–1975) was characterized by the stimulation of import substitution of final goods and the formation of the internal market. The second phase (1975–1990) was marked by measures to foster the national input industry. The third phase (1991–1996) had as its main characteristics the opening of the country's economy, the reduction of import taxes, and an emphasis on quality and productivity. The fourth phase (1996–2002) was defined by the adaptation of companies and the model to the globalized economy, as well as adjustments arising from the Plano Real (Brazil's economic stabilization plan). Finally, the fifth phase (2003 to the present) has seen the model seek greater productive efficiency, valuing companies' innovation capacity, and fostering export expansion (Silva et al., 2019; SUFRAMA, 2025a).

Botelho (2006) indicates that, even considering the relative success of the ZFM project from the perspective of the industrialization model based on import substitution – which drove the economic growth of the city of Manaus – economic development was not achieved. The ZFM populated the city of Manaus, and migrants from the countryside and riverine communities moved to Manaus, forming a contingent of cheap labor, leading to upward population growth, an increase in the number of slums, land invasions, and degradation of water bodies. Neighborhoods emerged with urbanization devoid of citizenship, marked by social discrimination and inefficient public services (Gonçalves, 2012; Nascimento, 2013).

One of the strong appeals for the creation of the ZFM – which generated intense migratory flows to the capital – was the objective of bringing development through job creation for the population and, consequently, better quality of life in the urban space. This motivated migration because it opened a possibility of hope in the city with promising proposals, among them the possibility of achieving homeownership (Brianezi, 2018; Giatti et al., 2015; Silva & Scudeller, 2022).

Cities in the interior did not possess the economic power to retain this workforce, which remained abandoned due to the lack of investment in those locations. These populations became attracted to the transformation process concentrated in Manaus as a "possible dream" – the possibility of having better access to health, education, housing, and, above all, employment with better living conditions. This disparity between the capital and the

interior resulted in high migratory pressure and a tendency for the city to continue growing demographically, through unplanned growth and the worsening of social injustices in the interior, beyond its capacity to provide living conditions for the population. In other words, industrialization energized the capital but emptied the interior and its capacity to generate economic activity (Brianezi, 2018; Costa, 2021; Giatti et al., 2015).

3 DATA AND METHOD

3.1 Research design

In this study, a case study design was chosen to explore the phenomenon and establish a strong foundation for the epistemological approach. Multiple case studies provide a comparison of data collection through different websites, which can be useful to improve our understanding of the phenomenon under study (Eisenhardt & Graebner, 2007). Furthermore, the purpose of this research was to conduct exploratory case studies (McCutcheon & Meredith, 1993) in which the conclusions obtained from the analysis of the data will be based on empirical evidence. Cases were selected based on theoretically convenient sampling criteria.

The case study is suitable for analyzing longitudinal change processes (Eisenhardt, 1989) and for gaining a holistic as opposed to a reductionist perspective of a phenomenon (Gummesson, 1991). The case study offers a research methodology that needs to be taken into account by a science whose objective is to satisfy the most pressing needs for a greater understanding of the society it serves (Villarreal, 2017; Villarreal & Calvo, 2015; Villarreal & Landeta, 2010). The process of conducting the research case studies followed the steps of Voss et al. (2002): (1) rationale for case research; (2) developing the research framework; (3) case selection; (4) developing the research protocol; (5) conducting the research; (6) data documentation and coding; and (7) data analysis, hypothesis development, and testing.

3.2 Epistemological approach

The study used a protocol for understanding practices related to I4.0 considering the characteristics presented in Deloitte (2015, 2016), Koch et al. (2014), Smith et al. (2016), Lee et al. (2017), Schuh et al. (2020), Lorenz et al. (2015), Bunse et al. (2014), Wee et al. (2015), Cologne Institute for Economic Research - IW (2015), Reinhard et al. (2016), Roland Berger (2014), and Oztemel and Gursev (2020). The Protocol aims to understand the current status of the companies' production systems regarding Industry 4.0.

In total, there are eight constructs, with the analyzed criteria detailed in Table 1, comprising 57 open questions designed to provide an adequate evaluation of the productive system. In the end, a radar chart was prepared with the scores of the two companies (scores from 1 to 4), where this score reflects the stage of implementation of the practices observed in the application of the protocol:

1. Practice not considered, rarely occurring, or not applicable to the company's reality;

2. Practice where there is some awareness of its use, yet it occurs in a disorderly or occasional manner (e.g., through informal systems);
3. Practice that occurs consciously, based on appropriate formal systems, however, can still be improved; and
4. Practice is based on effective and highly developed systems, with autonomous capacity for improvement and development.

Table 1
Relationship between constructs and source

Constructs	Source
Cyber-physical production systems (A)	Deloitte (2015); Koch et al. (2014); Smith et al. (2016); Lee et al. (2017)
Smart factory (B)	Schuh et al. (2020); Cologne Institute for Economic Research - IW (2015); Smith et al. (2016).
People (C)	Lorenz et al. (2015); Cologne Institute for Economic Research - IW (2015).
Vertical network (D)	Koch et al. (2014); Deloitte (2015); Cologne Institute for Economic Research - IW (2015); Oztemel and Gursev (2020).
Horizontal integration (E)	Bunse et al. (2014); Koch et al. (2014); Deloitte (2015); Cologne Institute for Economic Research - IW (2015); Oztemel and Gursev (2020).
Through-Engineering (F)	Deloitte (2015, 2016).
Exponential technologies (G)	Lorenz et al. (2015); Wee et al. (2015); Deloitte (2015); Oztemel and Gursev (2020).
Industry 4.0 environment (H)	Reinhard et al. (2016); Roland Berger (2014); Cologne Institute for Economic Research - IW (2015); Oztemel and Gursev (2020).

Source: Authors.

3.3 Companies

Case 1. Thermal power plant

The first case represents a thermal power plant, operating since 2002. The company has an installed capacity of 9 MW, with a continuous production process, and with a high level of automation. Currently, the plant located in the Amazon has approximately 60 employees.

Case 2. Plastic injection molding company

The second case represents a plastic injection molding company, being an important national player in the segment of plastics for the electronics, home appliances, automobile, and electrical products industries. Currently, the plant located at the PIM has approximately 400 employees.

3.4 Data collection

The organizational intervention was conducted from 2018 to 2024 as part of a large-scale research project on Industry 4.0 practices in the Amazon

region. Data collection focused on two manufacturing companies located in the Manaus Industrial Pole: a thermal power plant (continuous production, 60 employees) and a plastic injection molding company (batch production, 400 employees).

A structured protocol was employed, based on Deloitte (2015, 2016), Koch et al. (2014), Smith et al. (2016), Lee et al. (2017), Schuh et al. (2020), Lorenz et al. (2015), Bunse et al. (2014), Wee et al. (2015), Cologne Institute for Economic Research – IW (2015), Reinhard et al. (2016), Roland Berger (2014), and Oztemel and Gursev (2020). The protocol comprised eight constructs and 57 open-ended questions designed to assess I4.0 practices across the companies' productive systems.

Three complementary research techniques were used, following Marconi and Lakatos (2002) and Vergara (2009):

1. Indirect documentation: documentary and bibliographic research was conducted, including the analysis of standard operating procedures (SOPs), production plans, check sheets, PQCDsME indicators (Productivity, Quality, Cost, Delivery, Safety, Morale, Environment), and PDCA records. These documents provided insights into formalized practices and continuous improvement routines.
2. Intensive direct observation: on-site observation was carried out over 10 days per company, covering both productive and administrative areas. This allowed the research team to capture informal practices, human-machine interactions, and the actual implementation of I4.0-related technologies.
3. Open structured interviews: a total of 20 interviews were conducted, with an average duration of 40 to 90 minutes each, totaling approximately 30 hours of interviews. The respondents were selected to represent different strategic and operational levels, including: 2 operations managers, 2 industrial managers, 4 engineers, 2 industrial analysts, 3 production leaders, and 7 machine operators. This diversity ensured that the assessment captured both strategic policy execution and shop-floor perceptions.

Each of the 57 questions was scored on a 4-point Likert-type scale, as follows: (1) Score 1: practice not considered, rarely occurring, or not applicable to the company's reality; (2) Score 2: practice where there is some awareness of its use, yet it occurs in a disorderly or occasional manner (e.g., through informal systems); (3) Score 3: practice that occurs consciously, based on appropriate formal systems, however, can still be improved; (4) Score 4: practice based on effective and highly developed systems, with autonomous capacity for improvement and development.

Scores were first assigned per question by the research team based on triangulation of documentary evidence, observational notes, and interview responses. Subsequently, the perceptions and strategic importance attributed by the respondents were incorporated into the final scoring, ensuring that the assessment reflected not only technical implementation but also the actors' understanding of I4.0 phenomena. Scores were then aggregated by construct (eight constructs in total), and an arithmetic mean was calculated for each construct per company. Finally, a radar chart was generated for each company to visualize the maturity profile across all eight I4.0 dimensions. A summary of the methodological procedures used is presented in Table 2.

Table 2
Summary of the methodological procedures

Stage	Method	Source	Comments
Approach to the problem	Qualitative	Gummeson (1991); Miles and Huberman (1994); Maxwell (1998)	Interpretation of the opinion of the interviewees Use of productive qualitative data
Type of Research	Exploratory case study (Multiple cases)	Villarreal (2017); Villarreal and Calvo (2015); Villarreal and Landeta (2010); Voss et al. (2002)	Thermal power plant and Plastic injection molding company located in the Amazon
Procedure	Indirect documentation Intensive direct observation Extensive direct observation	Guérin et al., 2001; Marconi & Lakatos, 2002; Vergara, 2009	External and internal reports and procedures
Data gathering	Multiple case study In loco observation = 10 days each Open structured interview = 30 hours of interview Protocol application = 20 days	Guérin et al., 2001; Marconi & Lakatos, 2002; Vergara, 2009	Quality department Operations management department Industrial engineering department Observation in the productive and administrative area Interviews with company managers and employees Protocol application with company managers and employees
Analysis of data	Analysis of content	Bardin, 1977	Understanding and perception of respondents about the phenomenon studied from the following steps: (1) pre-analysis, (2) data exploration, and (3) treatment of results, inference, and interpretation.

Source: Authors.

Data triangulation (Eisenhardt, 1989; Yin, 2018) was achieved by cross-referencing the three sources: documents, observations, and interviews. For qualitative data, content analysis was performed following Bardin's (1977) framework, which comprises three steps: (1) pre-analysis (systematization and establishment of interpretation indicators), (2) data exploration (coding, classification, and categorization), and (3) treatment of results, inference, and interpretation. This combination of quantitative scoring and qualitative discourse analysis enabled a holistic and in-depth understanding of I4.0 practices in the Amazonian context.

4 RESULTS

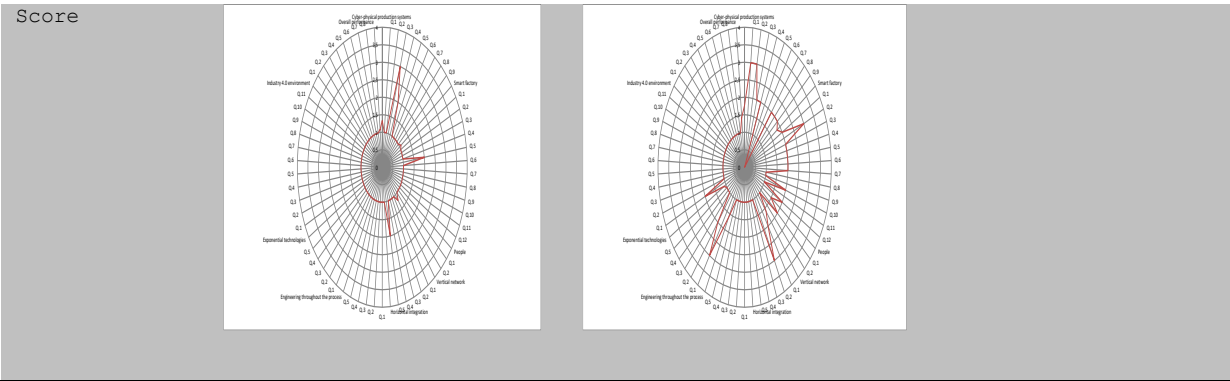
The main results and implications observed from the analysis of the case studies regarding the I4.0 criteria are discussed in this section and summarized in Table 3. The score of each case is also presented for observation of the level of implementation of practices related to I4.0 based on the understanding of the actors involved and the adopted protocol.

Table 3
Case study results

Criteria	Thermal power plant	Plastic injection molding company
Cyber-physical production systems	It uses a supervisory system designed to capture and store information about the production process in a database. The information comes from sensors that capture the process variables of the industrial plant.	It has performance, production, and problem control based on operator reports, which immediately send the collected data to the production control telemetry system. There is an integrated sensing system that notifies the needs of the asset in real time, sending the information to an easily accessible panel that can be viewed at various points of the production line by machine operators.
Smart factory	Approximately 15% of the process still involves human-machine interaction, such as in the operation of wood chippers and supervisory tasks, where small human interventions are necessary. The company lacks sensors aimed at achieving zero defects and predictability, thus hindering the improvement of maintenance management, including a predictive approach.	The factory has some automated processes, but when faced with all existing sub-processes, there is still a small level of automation. It has a well-installed preventive and corrective maintenance system, the machines already undergo constant sensorial integration to the quality and control process, accompanied by the company's engineering team, however, it is not possible to monitor and control the entire process from a single point in time. Digitalized in real-time.
People	Human resources need to be better valued by the organization, in the sense of qualification, training, and staff engagement. The impact of automation on the workforce was observed due to the reduction in the number of employees.	The teams work autonomously to create and implement continuous improvement methods within their sectors to improve their information and problem-resolution chains.
Vertical network	There is a deficiency in the integration of	The process has efficient data collection from the machines that are integrated into the entire

	information systems. There is no integration of networked resources and products, as well as materials and components of the process, making it difficult to locate them anywhere and at any time in the production process. The collection, analysis, and management of data are done only for the production system and not for the entire company.	plant system, providing diverse information on maintenance and productivity, with certain points in the process being able to be monitored through cell phones carried by authorized employees.
Horizontal integration	There is not a constant process of optimizing the production process and the business model to respond quickly to problems and failures, as there is not enough productive flexibility to respond to changes, problems, and failures.	The company has an internal program for optimizing the production process in response to periodic problems and failures. However, this improvement process does not extend to the company's business model, which has remained constant in recent years.
Through-Engineering	There is no monitoring of the entire product/service life cycle by engineering, it is concentrated in certain sectors that require a more technical opinion.	The process is customized by the client and sent ready-made, or to be subject to adaptation by the company's engineering team, which sometimes works to solve problems in the most efficient way possible, within the technical limitations of its staff, and integrates the project into its production capacity.
Exponential technologies	Most exponential technologies do not fit the needs of the current context of the company. From the exponential technologies to the only one used by the company are the sensors, which act in the conversion of the physical phenomena of the industrial plant, heat, movement, vibration, and sounds into electrical signals.	Robots are already utilized in the manufacturing cells for product removal from injectors. However, sensing is limited to the control of these production robots, which helps reduce failures and increase productivity.
Industry 4.0 environment	The concepts of a smart building, social web, business web, smart logistics, products	The concepts of a smart building, social web, business web, smart logistics, products and/or services connected to the concept of smart homes, product digitalization process, and service

and/or services connected to the concept of smart homes, product digitalization process, and service portfolio, are also outside the analyzed organizational reality.



Source: Authors.

The thermal power plant achieved the following scores: cyber-physical production systems (2.5), smart factory (1.8), people (1.5), vertical network (1.5), horizontal integration (2.0), through-engineering (1.0), exponential technologies (1.5), and Industry 4.0 environment (1.0). Its overall average score was 1.60.

The plastic injection molding company achieved the following scores: cyber-physical production systems (2.0), smart factory (2.2), people (2.5), vertical network (2.0), horizontal integration (2.5), through-engineering (2.0), exponential technologies (2.0), and Industry 4.0 environment (1.5). Its overall average score was 2.09.

Scores range from 1 (practice not considered, rarely occurring, or not applicable to the company's reality) to 4 (practice based on effective and highly developed systems, with autonomous capacity for improvement and development).

5 DISCUSSION

The main results and implications observed in the case studies regarding the considered dimensions are presented in Table 3. The scores reflect the level of understanding of the organizational actors added to the other research techniques adopted in the protocol.

The radar scores reveal a clear maturity gap between the two companies. The thermal power plant achieved an overall average of 1.60, placing it between "practice not considered" (score 1) and "occasional/disorderly awareness" (score 2). Its highest score (2.5) was in cyber-physical systems, due to the presence of supervisory control and data acquisition (SCADA) – a legacy of its continuous production system. Its lowest scores (1.0) were observed in through-engineering and I4.0 environment, indicating that product lifecycle management and digital ecosystems are entirely absent.

The plastic injection molding company achieved an overall average of 2.09, approaching "conscious use with formal systems, still improvable"

(score 3). Its highest score (2.5) was in the "People" dimension, reflecting autonomous work teams and a culture of continuous improvement. Its lowest score (1.5) was in I4.0 environment, similar to the thermal power plant, suggesting that external digital ecosystems (e.g., smart logistics, connected products) remain beyond the current reality of Amazonian manufacturers.

The radar visualization (Table 3) allows for quick comparison: the injection molding company outperforms the thermal power plant in six out of eight dimensions, with the largest gaps in "People" (+1.0) and "Exponential technologies" (+0.5). This suggests that production system characteristics (continuous vs. batch) influence not only automation levels but also organizational culture and workforce readiness.

RQ1: Do companies implement Industry 4.0 practices in their production environment?

Regarding the 'cyber-physical production systems' dimension, both companies are in the initial stage of connecting information generated within their production processes. The thermal power plant, by adopting a continuous production system, the thermal power plant achieves better monitoring of its production process, as it has sensors located at various stages. The plastic injection molding company, however, still relies on employees to manually collect data and feed it into the telemetry system. The panel adopted by the company only provides information on products in process, that is, various information from the production process is either manually informed or does not yet have real-time monitoring. Consequently, companies exhibit an early-stage understanding and perception of the concepts presented by Deloitte (2015, 2016); Koch et al. (2014); Smith et al. (2016); and Lee et al. (2017).

As for the "smart factory" dimension, both companies have a significant part of the production process without the use of sensors or intelligent machines to monitor the performance of machines and products in the process. While maintenance management in both companies shows advancements in preventive and predictive maintenance, it is not yet possible to plan machine maintenance remotely or digitally. Companies are in the initial stages (stage one - computerization and stage two - connectivity) dialoguing with Schuh et al. (2020) and Smith et al. (2016).

In the "people" dimension, the thermal power plant needs to go through a workforce update process aimed at adopting the skills required by I4.0. The plastic injection molding company, while fostering a culture that enables work teams' autonomy for process improvement, also needs to enhance workforce training to acquire the necessary skills for Industry 4.0 (Lorenz et al., 2015). In the thermal power plant, the score reflected a workforce not yet prepared for I4.0 requirements. Operators reported fear of automation-driven layoffs, and no formal upskilling program was in place. In contrast, the plastic injection molding company scored higher due to autonomous work teams that continuously propose improvements. However, even in this company, training on digital skills (e.g., data interpretation, basic programming) remained absent. The main difference between the two companies lies in organizational culture: the injection molding company has a longer tradition of team-based problem-solving, which facilitates future I4.0 adoption.

The "vertical network" dimension indicates both companies need to digitize and connect more functions along the value chain. This means greater integration from order processing and product development to integrated customer service. It is observed that in both companies, integration has only advanced internally. Both upstream and downstream processes in organizations are not integrated within the value chain (Deloitte, 2015; Koch et al., 2014).

As for the "horizontal integration" dimension, the thermal power plant, by using a continuous production system, achieves greater horizontal integration (Bunse et al., 2014; Deloitte, 2015; Koch et al., 2014), while the plastic injection molding company can only integrate a few stages of the main production process. In both cases, it is necessary to seek greater integration between the departments to achieve greater production efficiency. This is one of the dimensions with the best performance in the evaluation.

Concerning the "through-engineering" dimension, the thermal power plant needs to improve the follow-up of the product's life cycle; currently, this monitoring only occurs at the most technical levels. The plastic injection molding company has better monitoring of the product life cycle, however, it does not have autonomy for decision-making in aspects related to the product development process that is under the responsibility of its customers. A closer relationship between the company and the customer is necessary to better monitor the life cycle of products, according to Deloitte (2015).

The "exponential technologies" dimension indicates the need for both companies to adopt more technologies related to I4.0 in their production processes. It is observed that companies are still in a stage of automation of the production process, needing to adopt several technologies, such as digital twin, the Internet of things, and big data, among others to improve the efficiency of internal processes and the entire chain of value (Deloitte, 2015; Lorenz et al., 2015; Wee et al., 2015). The thermal power plant uses only basic sensors for process variables (temperature, pressure, vibration). No IoT, cloud computing, or digital twin was identified. The plastic injection molding company employs collaborative robots for product removal from injectors, representing a more advanced – albeit still initial – stage. However, sensing is limited to production robots only, and data is not integrated across the production line. Neither company uses big data analytics or artificial intelligence.

Finally, the "Industry 4.0 environment" dimension demonstrates that several concepts that are related to the I4.0 environment (Reinhard et al., 2016; Roland Berger, 2014) are outside the reality of the companies studied. This may be a reflection of the current technological process they are in. Also added to this scenario is the local reality of the economic and social aspects of the Amazon region.

RQ2: Does the survey framework provide an adequate assessment of practices related to Industry 4.0?

The research framework enabled an understanding of Industry 4.0 practices in two manufacturing industries in the Amazon region. While most studies on Industry 4.0 evaluation emphasize quantitative aspects, this study employed qualitative research techniques to understand perceptions of Industry 4.0 practices, making it an original contribution to operations management.

The use of varied qualitative research techniques (open structured interview, structured observation, content analysis, and documentary research) provided a broader and deeper understanding of the phenomenon within the companies studied, as pointed out in Voss et al. (2002), Miguel (2012), Creswell (2009), and McCutcheon and Meredith (1993).

The application of open structured interviews together with structured observation and documentary research enabled an in-depth case that contributes to the literature by deepening the real situations in which the various aspects of I4.0 are used.

The internal validity of the case study is confirmed by a systematic comparison of the literature about the research framework. The reliability of the study is justified by the systematization of the database which was organized, integrated, and synthesized from the information obtained from different sources of evidence resulting from the various research techniques employed (Villarreal, 2017; Villarreal & Calvo, 2015; Villarreal & Landeta, 2010).

RQ3: What is the observed Industry 4.0 maturity level in these companies, according to the literature?

Regarding the current maturity level of these companies, the case studies reveal that they are in a stage between computerization and connectivity, as indicated by Schuh et al. (2020). In the case of the thermal power plant, the continuous production system facilitates the adoption of sensors and supervisory systems throughout the production process, which results in greater connectivity. The plastic injection molding company, as it is part of a more dynamic activity that involves the use of cutting-edge technologies in its production process, is also suitable for a stage between computerization and connectivity. The study also enables comparison of results with the Industry 4.0 factory typology presented in Tschiesner et al. (2019), where based on key value drivers - (1) number of product variants manufactured in a factory and (2) average batch size - it was observed that the thermal power plant is characterised as high-volume production, while the plastic injection molding company represents mass-customised production.

The results indicate that companies are positioned between Industry 2.0 and Industry 3.0, in a similar fashion to the work of Hajoary et al. (2024). This study aligns with the research by McDermott et al. (2024, 2025) through its adoption of qualitative approaches to assess Industry 4.0 practices. That is to say, evaluation methods employing qualitative techniques remain limited despite the growing body of work addressing Industry 4.0 assessment across diverse industrial sectors.

Table 3 presents the radar scores per construct for both companies. The thermal power plant achieved the following scores: cyber-physical production systems (2.5), smart factory (1.8), people (1.5), vertical network (1.5), horizontal integration (2.0), through-engineering (1.0), exponential technologies (1.5), and Industry 4.0 environment (1.0). Its overall average score was 1.60.

The plastic injection molding company achieved the following scores: cyber-physical production systems (2.0), smart factory (2.2), people (2.5), vertical network (2.0), horizontal integration (2.5), through-engineering (2.0), exponential technologies (2.0), and Industry 4.0 environment (1.5). Its overall average score was 2.09.

Scores range from 1 (practice not considered, rarely occurring, or not applicable to the company's reality) to 4 (practice based on effective and highly developed systems, with autonomous capacity for improvement and development).

6 CONCLUSION

This study aimed to understand practices related to Industry 4.0 in two manufacturing industries in the Amazon region. A research framework was developed, considering that most studies on Industry 4.0 evaluation emphasize quantitative aspects. This research utilized qualitative techniques to

understand the perception and adoption of Industry 4.0 practices, thereby making an original contribution to operations management.

6.1 Detailed findings by dimension

The radar scores revealed distinct patterns across the eight I4.0 dimensions. Regarding “cyber-physical production systems”, the thermal power plant outperformed the injection molding company (2.5 vs. 2.0), due to its continuous production process enabling broader sensor deployment. In the “smart factory” dimension, both companies scored below 2.5, indicating that predictive maintenance and real-time centralized monitoring remain incipient. The “people” dimension showed the largest gap between companies (1.5 vs. 2.5), reflecting that organizational culture and workforce readiness vary significantly even within the same region.

Both companies scored lowest in “through-engineering” (1.0 and 2.0) and “Industry 4.0 environment” (1.0 and 1.5), indicating that product lifecycle management, digital ecosystems, smart logistics, and connected products are entirely absent from their current reality. Exponential Technologies” scored at most 2.0 in both cases, with only basic sensors and collaborative robots identified; no IoT, big data, digital twin, or artificial intelligence was observed. “Vertical and horizontal integration” scored between 1.5 and 2.5, suggesting that internal data connectivity exists but does not extend to upstream or downstream value chain partners.

These results demonstrate that Amazonian manufacturers are positioned between Industry 2.0 and 3.0, with maturity concentrated in basic automation and isolated connectivity, while advanced I4.0 pillars remain unreached. The production system (continuous vs. batch) influences cyber-physical and integration dimensions, but does not affect weaknesses in through-engineering and I4.0 environment, which appear structural to the regional context.

6.2 Theoretical contribution

The theoretical contribution lies in expanding the limited body of knowledge concerning Industry 4.0, particularly regarding operations management and the understanding of Industry 4.0 practices by managers and employees in a productive environment. The eight constructs applied in the protocol present in the epistemological approach make it possible to visualize practices related to I4.0 based on the understanding of the actors involved in the process (managers and employees). The protocol made it possible to understand the current state of the companies concerning the subject, supporting the development of research in the Amazonian context.

6.3 Managerial contribution

As for the managerial contribution, the study could serve for the implementation or improvement of I4.0 in other manufacturing industries, in addition to the possibility of adaptation to the reality of micro and small manufacturing companies. The results indicate that an organization's adopted production system can directly influence its Industry 4.0 maturity level.

6.4 Social implication

As for the social implication, the application protocol, especially the open structured interviews, provided an interpretation of the I4.0 phenomenon based on people's perceptions. Unlike other operations management approaches (e.g., quality management and lean manufacturing), which often show a consistent understanding across different organizational and educational levels, this study observed a lack of uniformity in understanding of Industry 4.0, even among individuals at the same organizational and educational levels. This result may have broad sociological and organizational behavior implications for individuals regarding the advantages (training, higher wages) or disadvantages (layoffs, unemployment) of adopting Industry 4.0 and the man-machine relationship in the face of the elimination or precariousness of work (Compan et al., 2021; Biencourt et al., 2021; Gamkrelidze et al., 2021; Zouinar, 2020).

6.5 Limitations and future research

The research limitation is associated with the sample size (limited). However, the study was carried out in the form of an in-depth case, which allowed a greater depth of the organization's reality. It was also not possible to carry out a longitudinal analysis that would help in a greater understanding of the organizational reality over time. For future studies, it is recommended to conduct similar research in a specific sector, so it will be feasible to analyze the peculiarities of the I4.0 implementation in a specific industrial sector.

REFERENCES

- Anshari, M., & Hamdan, M. (2022). Understanding knowledge management and upskilling in Fourth Industrial Revolution: transformational shift and SECI model. *VINE Journal of Information and Knowledge Management Systems*, 52(3), 373-393. <https://doi.org/10.1108/VJIKMS-09-2021-0203>
- Bardin, L. (1977). *L'analyse de contenu*. Presses Universitaires de France.
- Belhadi, A., Kamble, S. S., Chiappetta Jabbour, C. J., Mani, V., Khan, S. A. R., & Touriki, F. E. (2022). A self-assessment tool for evaluating the integration of circular economy and industry 4.0 principles in closed-loop supply chains. *International Journal of Production Economics*, 245, Article 108372. <https://doi.org/10.1016/j.ijpe.2021.108372>
- Biencourt, M., Gaillard, I., Mollo, V., Barthe, B., Carlier, A., & Charvillat, V. (2021). Transformations du travail par l'Intelligence Artificielle : Quels enjeux pour l'ergonomie ? Exemple d'une recherche-action dans le secteur du tri de déchets. Dans *Société d'Ergonomie de Langue Française (Dir.), Actes du 55ème Congrès de la SELF. L'activité et ses frontières : Penser et agir sur les transformations de nos sociétés* (pp. 324-329). SELF. <https://univ-tlse2.hal.science/hal-03450140>
- Botelho, A. J. (2006). *Redesenhando o projeto ZFM - um estudo de alerta (uma década depois)*. Editora Valer.
- Brianezi, T. (2018). *Zona Franca de Manaus: Ame-a ou deixe-a em nome da floresta*. Editora Valer.
- Bunse, B., Kagermann, H., & Wahlster, W. (2014). *Industrie 4.0: Smart manufacturing for the future [Report]*. Germany Trade & Invest. <http://www.gtai.de/GTAI/Navigation/EN/Invest/Service/Publications/business-information,t=industrie-40--smart-manufacturing-for-the-future,did=917080.html>

- Colli, M., Berger, U., Bockholt, M., Madsen, O., Møller, C., & Wæhrens, B. V. (2019). A maturity assessment approach for conceiving context-specific roadmaps in the Industry 4.0 era. *Annual Reviews in Control*, 48, 165-177. <https://doi.org/10.1016/j.arcontrol.2019.06.001>
- Colli, M., Madsen, O., Berger, U., Møller, C., Wæhrens, B. V., & Bockholt, M. (2018). Contextualizing the outcome of a maturity assessment for Industry 4.0. *IFAC-PapersOnLine*, 51(11), 1347-1352. <https://doi.org/10.1016/j.ifacol.2018.08.343>
- Cologne Institute for Economic Research (IW), Lichtblau, K., Stich, V., Bertenrath, R., Blum, M., Bleider, M., ... Schroter, M. (2015). *Industrie 4.0 readiness*. IMPULS-Stiftung.
- Compan, N., Coutarel, F., Brissaud, D., & Rix-Lièvre, G. (2021). Contribution de l'ergonomie à la conception des nouvelles technologies dans l'industrie 4.0 : vers la conception de situations capacitantes. Dans *Société d'Ergonomie de Langue Française (Dir.), Actes du 55ème Congrès de la SELF. L'activité et ses frontières : Penser et agir sur les transformations de nos sociétés* (pp. 330-335). SELF. <https://shs.hal.science/halshs-03109103>
- Costa, J. B. (2021). *A Amazônia e a Zona Franca de Manaus: Caminhos independentes*. Amazonas Et Al.
- Cotet, G. B., Balgiu, B. A., & Negrea, V. C. Z. (2017). Assessment procedure for the soft skills requested by Industry 4.0. *MATEC Web of Conferences*, 121, Article 07005. <https://doi.org/10.1051/mateconf/201712107005>
- Creswell, J. W. (2009). *Research design: Qualitative, quantitative, and mixed methods approaches* (3. ed.). Sage.
- Deloitte. (2015). *Industry 4.0: Challenges and solutions for the digital transformation and use of exponential technologies*.
- Deloitte. (2016). *Growing the business: Applying Industry 4.0 to build revenue*.
- Dikhanbayeva, D., Shaikholla, S., Suleiman, Z., & Turkyilmaz, A. (2020). Assessment of Industry 4.0 maturity models by design principles. *Sustainability*, 12(23), Article 9927. <https://doi.org/10.3390/sul2239927>
- Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of Management Review*, 14(4), 532-550. <https://doi.org/10.5465/amr.1989.4308385>
- Eisenhardt, K. M., & Graebner, M. E. (2007). Theory building from cases: Opportunities and challenges. *Academy of Management Journal*, 50(1), 25-32.
- El Baz, J., Tiwari, S., Akenroye, T., Cherrafi, A., & Derrouiche, R. (2022). A framework of sustainability drivers and externalities for Industry 4.0 technologies using the Best-Worst Method. *Journal of Cleaner Production*, 344, Article 130909. <https://doi.org/10.1016/j.jclepro.2022.130909>
- Essakly, A., Wichmann, M., & Spengler, T. S. (2019). A reference framework for the holistic evaluation of Industry 4.0 solutions for small- and medium-sized enterprises. *IFAC-PapersOnLine*, 52(13), 427-432. <https://doi.org/10.1016/j.ifacol.2019.11.093>
- Gamkrelidze, T., Barcellini, F., & Zouinar, M. (2021). Intelligence Artificielle dans les activités professionnelles: quelles visions des acteurs concernés? In *Actes du 55e Congrès de la SELF: L'activité et ses frontières. Penser et agir sur les transformations de nos sociétés* (pp. 531-537). SELF.
- Giatti, L. L., Freitas, C. M., Desmoulière, S. J. M., Medeiros, M. S., Silva, M. B. C., & Chagas, M. B. R. (2015). Manaus, Cidade-Região e Capital da Amazônia: modelo de desenvolvimento e pressões sobre os ecossistemas, seus serviços e saúde humana. In C. M. Freitas & L. L. Giatti (Orgs.),

Sustentabilidade, ambiente e saúde na cidade de Manaus (pp. 49-72). Edua; Fiocruz.

Gonçalves, C. W. P. (2012). *Amazônia, Amazônias* (3. ed.). Contexto.

Govindan, K., & Arampatzis, G. (2023). A framework to measure readiness and barriers for the implementation of Industry 4.0: A case approach. *Electronic Commerce Research and Applications*, 59, Article 101249. <https://doi.org/10.1016/j.eelerap.2023.101249>

Guérin, F., Laville, A., Daniellou, F., Duraffourg, J., & Kerguelen, A. (2001). *Compreender o trabalho para transformá-lo: A prática da ergonomia*. Edgard Blücher. Gummesson, E. (1991). *Qualitative methods in management research*. Sage.

Hajoary, P. K., MA, A., & Garza-Reyes, J. A. (2024). Industry 4.0 maturity assessment: a multi-dimensional indicator approach. *International Journal of Productivity and Performance Management*, 73(4), 981-1004. <https://doi.org/10.1108/IJPPM-07-2022-0325>

Hajoary, P. K., Balachandra, P., & Garza-Reyes, J. A. (2023). Industry 4.0 maturity and readiness assessment: an empirical validation using Confirmatory Composite Analysis. *Production Planning & Control*. Advance online publication. <https://doi.org/10.1080/09537287.2023.2210545>

Hermann, M., Pentek, T., & Otto, B. (2015). Design principles for Industrie 4.0 scenarios: A literature review [Working paper]. Technische Universität Dortmund.

Justus, A. D. S., Ramos, L. F. P., & Loures, E. de F. R. (2018). A capability assessment model of Industry 4.0 technologies for viability analysis of PoC (proof of concept) in an automotive company. In *Advances in Transdisciplinary Engineering* (Vol. 7, pp. 936-945). IOS Press. <https://doi.org/10.3233/978-1-61499-898-3-936>

Koch, V., Kuge, S., Geissbauer, R., & Schrauf, S. (2014). Industry 4.0: Opportunities and challenges of the industrial internet. Strategy& PwC.

Kolla, S., Minufekr, M., & Plapper, P. (2019). Deriving essential components of lean and Industry 4.0 assessment model for manufacturing SMEs. *Procedia CIRP*, 81, 753-758. <https://doi.org/10.1016/j.procir.2019.03.189>

Lee, J., Jin, C., & Bagheri, B. (2017). Cyber physical systems for predictive production systems. *Production Engineering*, 11(2), 155-165. <https://doi.org/10.1007/s11740-017-0729-4>

Liebrecht, C., Kandler, M., Lang, M., Schaumann, S., Stricker, N., Wuest, T., & Lanza, G. (2021). Decision support for the implementation of Industry 4.0 methods: Toolbox, Assessment and Implementation Sequences for Industry 4.0. *Journal of Manufacturing Systems*, 58, 412-430. <https://doi.org/10.1016/j.jmsy.2020.12.008>

Lin, W. D., Low, M. Y. H., Chong, Y. T., & Teo, C. L. (2019). Application of SIRI for Industry 4.0 Maturity Assessment and Analysis. In *IEEE International Conference on Industrial Engineering and Engineering Management* (pp. 1450-1454). IEEE Computer Society. <https://doi.org/10.1109/IEEM44572.2019.8978720>

Lorenz, M., Rüßmann, M., Strack, R., Lueth, K. L., & Bolle, M. (2015). *Man and machine in Industry 4.0: How will technology transform the industrial workforce through 2025?* Boston Consulting Group.

Marconi, M. A., & Lakatos, E. M. (2002). *Técnicas de pesquisa: planejamento e execução de pesquisas, amostragens e técnicas de pesquisa, elaboração, análise e interpretação de dados* (5. ed.). Atlas.

Maxwell, J. A. (1998). Designing a qualitative study. In L. Bickman & D. J. Rog (Eds.), *Handbook of applied social research methods*. Sage.

- McCutcheon, D. M., & Meredith, J. R. (1993). Conducting case study research in operations management. *Journal of Operations Management*, 11(3), 239-256. [https://doi.org/10.1016/0272-6963\(93\)90002-7](https://doi.org/10.1016/0272-6963(93)90002-7)
- McDermott, O., Stam, D. L., Duarte, S., & Sony, M. (2025). Readiness for Industry 4.0 in a Medical Device Manufacturer as an Enabler for Sustainability, a Case Study. *Sustainability*, 17(1), Article 357. <https://doi.org/10.3390/su17010357>
- McDermott, O., Wojcik, A. M., Trubetskaya, A., Sony, M., Antony, J., & Kharub, M. (2024). Pharma industry 4.0 deployment and readiness: a case study within a manufacturer. *The TQM Journal*, 36(9), 456-476. <https://doi.org/10.1108/TQM-04-2024-0160>
- Miguel, P. A. C. (Org.). (2012). *Metodologia de pesquisa em engenharia de produção e gestão de operações* (2. ed.). Elsevier; ABEPRO.
- Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook* (2. ed.). Sage Publications.
- Nascimento, E. M. D. (2013). *Parque Municipal do Mindu: um olhar para a sua problemática ambiental*. Edua.
- Ortiz, H., Marroquin, G., & Cifuentes, Z. (2020). Industry 4.0: Current Status and Future Trends. In *Industry 4.0 - Current Status and Future Trends*. IntechOpen. <https://doi.org/10.5772/intechopen.90396>
- Oztemel, E., & Gursev, S. (2020). A Taxonomy of Industry 4.0 and Related Technologies. IntechOpen. <https://doi.org/10.5772/intechopen.90122>
- Pacaux-Lemoine, M. P., Berdal, Q., Guérin, C., Rauffet, P., Chauvin, C., & Trentesaux, D. (2021). Designing human-system cooperation in industry 4.0 with cognitive work analysis: a first evaluation. *Cognition, Technology & Work*. <https://doi.org/10.1007/s10111-021-00667-y>
- Perini, S., Arena, D., Kiritsis, D., & Taisch, M. (2017). An ontology-based model for training evaluation and skill classification in an industry 4.0 environment. In *IFIP Advances in Information and Communication Technology* (Vol. 513, pp. 314-321). Springer. https://doi.org/10.1007/978-3-319-66923-6_37
- Rakiman, U., Thiyagaraja, V., & Rasi, Z. (2024). Readiness of Industry 4.0 in manufacturing industry. *International Journal of Research and Innovation in Social Science*, 8(8), 998-1012.
- Rauch, E., Unterhofer, M., Rojas, R. A., Gualtieri, L., Woschank, M., & Matt, D. T. (2020). A maturity level-based assessment tool to enhance the implementation of industry 4.0 in small and medium-sized enterprises. *Sustainability*, 12(9), Article 3559. <https://doi.org/10.3390/SU12093559>
- Reinhard, G., Jesper, V., & Stefan, S. (2016). *Industry 4.0: Building the digital enterprise-2016 Global Industry 4.0 Survey*. PwC. www.pwc.com/industry40
- Roland Berger. (2014). *Industry 4.0: The new industrial revolution-How Europe will succeed*.
- Sajjad, A., Ahmad, W., Hussain, S., Chuddher, B. A., Sajid, M., Jahanjaib, M., ... Jawad, M. (2024). Assessment by Lean Modified Manufacturing Maturity Model for Industry 4.0: A Case Study of Pakistan's Manufacturing Sector. *IEEE Transactions on Engineering Management*, 71, 6420-6434. <https://doi.org/10.1109/TEM.2023.3259005>
- Schuh, G., Anderl, R., Gausemeier, J., Hompel, M. ten, & Wahlster, W. (2020). *Industrie 4.0 maturity index*. acatech. www.acatech.de/publikationen
- Schumacher, A., Erol, S., & Sihn, W. (2016). A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. *Procedia CIRP*, 52, 161-166. <https://doi.org/10.1016/j.procir.2016.07.040>

- Schwab, K. (2015, December 12). The Fourth Industrial Revolution: What it means and how to respond. *Foreign Affairs*. <https://www.foreignaffairs.com/articles/2015-12-12/fourth-industrial-revolution>.
- Sharpe, R., van Lopik, K., Neal, A., Goodall, P., Conway, P. P., & West, A. A. (2019). An industrial evaluation of an Industry 4.0 reference architecture demonstrating the need for the inclusion of security and human components. *Computers in Industry*, 108, 37-44. <https://doi.org/10.1016/j.compind.2019.02.007>
- Silva, J. R. C., & Scudeller, V. V. (2022). The Amazon rubber booms and the Free Trade Zone of Manaus: urban expansion and watersheds degradation. *Research, Society and Development*, 11(6). <https://doi.org/10.33448/rsd-v11i6.29103>
- Silva, M. L. A., Barbosa, M., & Costa, M. F. (2019). Análise do modelo Zona Franca de Manaus com base nas teorias de desenvolvimento regional. In *Anais do IX Seminário Internacional sobre Desenvolvimento Regional* (pp. 23-34). Editora da UNISC.
- Smith, J., Kreutzer, S., Moeller, C., & Carlberg, M. (2016). Industry 4.0 [Study for the ITRE Committee]. European Parliament, Policy Department A: Economic and Scientific Policy. [https://www.europarl.europa.eu/RegData/etudes/STUD/2016/570007/IPOL_STU\(2016\)570007_EN.pdf](https://www.europarl.europa.eu/RegData/etudes/STUD/2016/570007/IPOL_STU(2016)570007_EN.pdf)
- Sniderman, B., Mahto, M., & Cotteleer, M. J. (2016). Industry 4.0 and manufacturing ecosystems: Exploring the world of connected enterprises. Deloitte University Press. https://www2.deloitte.com/content/dam/insights/us/articles/manufacturing-ecosystems-exploring-world-connected-enterprises/DUP_2898_Industry4.0ManufacturingEcosystems.pdf
- Sulistyo, A. B., Karningsih, P. D., & Alvandi, S. (2025). Developing an Industry-Specific Lean 4.0 Readiness Assessment Tool: A Case for the Chemical Sector. *Jurnal Optimasi Sistem Industri*, 23(2), 283-298. <https://doi.org/10.25077/josi.v23.n2.p283-298.2024>
- Superintendência da Zona Franca de Manaus. (2025a). História da Zona Franca de Manaus. <https://www.gov.br/suframa/pt-br/assuntos/historia-da-zona-franca>
- Superintendência da Zona Franca de Manaus. (2025b). PIM fatura montante recorde de R\$ 204 bilhões em 2024. [https://www.gov.br/suframa/pt-br/assuntos/noticias/pim-fatura-montante-recorde-de-r-204-bilhoes-em-2024#:~:text=bilh%C3%B5es%20em%202024-,PIM%20fatura%20montante%20recorde%20de%20R%24%202024%20bilh%C3%B5es%20em%202024,\(US%24%2035.27%20bilh%C3%B5es\)](https://www.gov.br/suframa/pt-br/assuntos/noticias/pim-fatura-montante-recorde-de-r-204-bilhoes-em-2024#:~:text=bilh%C3%B5es%20em%202024-,PIM%20fatura%20montante%20recorde%20de%20R%24%202024%20bilh%C3%B5es%20em%202024,(US%24%2035.27%20bilh%C3%B5es)).
- Tschiesner, A., Hallerstedte, S., Christoph, S., Christian, J., & Garms, F. (2019). Industry 4.0: Capturing value at scale in discrete manufacturing. McKinsey and Company Global Institute. Retrieved from <https://www.mckinsey.com/industries/industrials-and-electronics/our-insights/capturing-value-at-scale-in-discrete-manufacturing-with-industry-4-0>
- UNCTAD. (2022). Industry 4.0 for inclusive development. United Nations Conference on Trade and Development.
- Vaidya, S., Ambad, P., & Bhosle, S. (2018). Industry 4.0 - A glimpse. *Procedia Manufacturing*, 20, 233-238. <https://doi.org/10.1016/j.promfg.2018.02.034>
- Vergara, S. C. (2009). Métodos de coleta de dados no campo. Atlas.
- Villarreal, O. (2017). Is it desirable, necessary and possible to perform research using case studies? *Cuadernos de Gestión*, 17(1), 147-172.

- Villarreal, O., & Calvo, N. (2015). From the triple helix model to the global open innovation model: a case study based on international cooperation for innovation in Dominican Republic. *Journal of Engineering and Technology Management*, 35, 71-92.
- Villarreal, O., & Landeta, J. (2010). Case study as a scientific research methodology in business economics and strategic management. An application to internationalisation. *Investigaciones Europeas de Dirección y Economía de la Empresa*, 16(3), 31-52.
- Voss, C., Tsikriktsis, N., & Frohlich, M. (2002). Case research in operations management. *International Journal of Operations and Production Management*, 22(2), 195-219. <https://doi.org/10.1108/01443570210414329>
- Wee, D., Kelly, R., Cattel, J., & Breunig, M. (2015). *Industry 4.0: How to navigate digitization of the manufacturing sector*. McKinsey & Company.
- Yin, R. K. (2018). *Case study research and applications: Design and methods* (6th ed.). SAGE Publications.
- Yüksel, H. (2020). An empirical evaluation of industry 4.0 applications of companies in Turkey: The case of a developing country. *Technology in Society*, 63. <https://doi.org/10.1016/j.techsoc.2020.101364>
- Zouinar, M. (2020). Évolutions de l'Intelligence Artificielle: quels enjeux pour l'activité humaine et la relation Humain-Machine au travail ? *Activités*, 17(1). <https://doi.org/10.4000/activites.4941>