




Industry 4.0 Readiness Assessment – A Comparative Analysis of Portuguese and Brazilian Companies

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Abstract. Purpose: This paper aims to present a comparative analysis of the Industry 4.0 (I4.0) maturity levels between Portuguese and Brazilian industrial companies. This study focuses on identifying significant differences across various evaluation dimensions using a standardized maturity model (MM).

Methodology: The same evaluation model, developed by the German Mechanical Engineering Industry Association (VDMA), was applied to Portuguese and Brazilian companies, specifically in the State of Espírito Santo (ES). The research encompassed 370 Portuguese industrial companies and 46 Brazilian ones. The VDMA platform was used to process individual results, indicating the levels across six model dimensions and providing an overall score on a scale of 0–5. The data collected were then tabulated to enable a comparative analysis between the two countries.

Findings: The study revealed that, on average, Brazilian companies have a lower maturity level (0.95) than Portuguese companies (1.22) on the 0–5 scale for I4.0 readiness. Notably, significant differences were observed in the dimensions of Smart Operations and Employees. Based on these differences, this study outlines potential pathways for these companies to enhance their I4.0 maturity levels.

Originality/value: This research provides a unique comparative perspective on industrial companies' I4.0 maturity levels in Portugal and Brazil, using a standardized and widely recognized MM. The findings offer valuable insights into the specific areas where companies in these countries can focus their efforts to advance their readiness for I4.0, highlighting the importance of tailored strategies for different national contexts.

Keywords: Industry 4.0; digital readiness; Portugal; Brazil.

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1. Introduction

Since 2011, Industry 4.0 (I4.0) has proven to be a crucial path for the research and development of flexible production systems. The increase in production complexity, driven by various business factors, presents challenges in the fourth industrial revolution era, such as intensified global competition among companies, product diversity and customization to meet customer needs. However, I4.0 proposes comprehensively integrating information technologies into production processes, enabling smarter, dynamic and versatile production. Yet, current production systems require a cohesive and careful migration throughout the transformation processes (Brecher *et al.*, 2021).

In modern industries, managing these challenges presents increasing complexity and can represent a competitive advantage, especially for small and medium-sized enterprises (SMEs), in a context marked by constant changes. Although modern companies that adopt I4.0 technologies have the opportunity to simplify the sharing of information and knowledge among employees, few SMEs implement such technologies for this purpose (Li *et al.*, 2019).

Industrial companies worldwide face challenges due to the extensive transformation of their processes in terms of digitalization and other characteristics of I4.0 (Nenadál *et al.*, 2022). I4.0 has significantly shaped the social, economic and technological environment, subject to digital transformation. However, there is a scarcity of studies on the relevant opportunities and challenges for implementing I4.0 in industrial companies (Vuksanović Herceg *et al.*, 2020). Social, economic and technological developments are leading companies to face new production challenges through information and communication technologies that offer physical and virtual structures for rapid adaptation along the entire value chain (Alcácer *et al.*, 2022).

SMEs, considered the backbone of a country's economic growth, must incorporate advanced technology into their businesses and operations to increase their productivity (Chonsawat and Sopadang, 2021). I4.0 has attracted the attention of industrial companies in recent years. Despite efforts in research and knowledge transfer to practice, introducing concepts and technologies of I4.0 remains a significant challenge for many companies, especially SMEs. Many of these companies do not have an overview of existing I4.0 concepts and technologies and do not know how to implement them in their own companies (Rauch *et al.*, 2020).

In the context of the fourth industrial revolution, the adoption of I4.0 in the daily life of SMEs faces expected challenges, especially in its integration. The more advanced maturity levels are difficult to achieve, due to the inadequacy of existing maturity models (MMs) to assess companies with low maturity levels, like most existing SMEs (Amaral and Peças, 2021). Given the rapid development of technologies and the production environment, companies need to keep up with the evolution of innovations to survive in this competitive environment by integrating information technology (IT) and industry (Kiraz *et al.*, 2020).

Due to limited resources, SMEs face significant challenges in implementing a successful digitalization strategy. It is crucial to use MMs as a valuable tool to assess and guide the digitalization transition of companies (Zilli *et al.*, 2023). To keep up with the state of I4.0, the use of readiness models allows for analyzing the state of implementation of I4.0 technologies, quantifying and qualifying their level of readiness considering different dimensions. Some companies cannot keep up with the evolution of I4.0 with their business models, resulting in a lack of proper self-assessment about understanding the level of readiness achieved (Alcácer *et al.*, 2021). Therefore, it is important to understand how companies face the challenges of digital transformation and to know their perception of the enabling technologies of I4.0.

Companies need to be more aware of their current maturity in I4.0 and pave the way for this fourth industrial revolution in a more modern and challenging manner.

I4.0 has been transforming global value chains adaptively, driving companies to remain more competitive, which requires greater flexibility in reorganizing business structures and developing employee competencies (Götz, 2019). It is extremely important for companies to adopt a forward-thinking design of value-added processes, such as factory planning, I4.0 implementation, digitalization, and sustainability. Applying an MM allows identifying strengths and weaknesses regarding these future production themes and, if necessary, introducing activities to promote modern and economical production (Wessing and Müller, 2022). The success of implementing digital solutions in a particular region or country depends significantly on SMEs' adoption of these processes (Brodny and Tutak, 2022).

1.1. *Overview of Brazilian and Portuguese industries and their contexts*

The Brazilian and Portuguese industries present distinct contexts, yet share challenges and opportunities in the global economic landscape. Both countries increasingly focus on incorporating I4.0 technologies to enhance efficiency, productivity, and competitiveness. Digitalization, automation, the Internet of Things (IoT), and data analytics are key areas of development for both Portuguese and Brazilian industries, aiming to create intelligent factories adaptable to the demands of the global market.

In Portugal, the industry plays a significant role in the economy, contributing a substantial share of the Gross Domestic Product (GDP), accounting for about 21% according to INE (2024), and employing a significant portion of the country's workforce. The Portuguese industry is recognized for its specialization in textiles, footwear, cork, wine, tourism and technology. Portugal has undergone significant transformation in recent decades, adopting policies to promote innovation and the internationalization of businesses. Additionally, being part of the European Union provides access to markets and financial resources. However, it faces challenges such as a lack of scale in many sectors, dependence on imports of raw materials, and the ongoing need for modernization and digitalization.

On the other hand, in Brazil, the industry also plays a significant role in the economy, contributing substantially to the GDP, with 25.5% of the total (CNI, 2024), and employing a large portion of the country's active population. The Brazilian industry is diversified, covering sectors such as automotive, agribusiness, petrochemicals, technology and food. However, it faces challenges such as bureaucracy, inadequate infrastructure, high tax burden and issues related to international competitiveness.

Although the Portuguese and Brazilian industries have specific characteristics and challenges, both share the common goal of adapting to technological advancements and promoting sustainable economic growth. Understanding these contexts is essential for assessing maturity in I4.0 and identifying opportunities for collaboration and mutual learning between the two countries.

1.2. Problem statement and study objective

The identified problem lies in the significant differences in the level of I4.0 maturity between companies based in Portugal and Brazil. Both countries are immersed in the context of I4.0 and face similar challenges and opportunities for digital transformation in the industrial sector, with notable variations in the stage of adoption of technologies and practices associated with I4.0 among the companies in each country.

These differences can manifest in various aspects, including implementing digital technologies, process automation, system integration, use of data for decision-making, and an organizational culture oriented toward innovation. Understanding these disparities is crucial to identifying gaps and improvement opportunities in both contexts.

Thus, the problem statement emphasizes the need to investigate and understand the underlying reasons for the differences in the level of I4.0 maturity between Portuguese and Brazilian companies, aiming to provide relevant insights to promote the evolution and enhancement of the industry in both regions.

The proposed study aims to conduct a comparative analysis of I4.0 maturity among companies in Portugal and Brazil, considering key indicators such as digital technology adoption, integration of industrial processes, and use of data for decision-making. It seeks to identify significant differences in I4.0 maturity between companies in the two countries, exploring each context's specific economic, cultural, regulatory, and structural factors. This study will analyze the influencing factors of the observed differences in I4.0 maturity between Portugal and Brazil, including investment in innovation, government policies supporting digitalization, technological infrastructure, and organizational culture. Case studies will be conducted to analyze success stories in both countries to highlight companies with a high level of I4.0 maturity and the strategies adopted for this success, providing practical insights for other organizations.

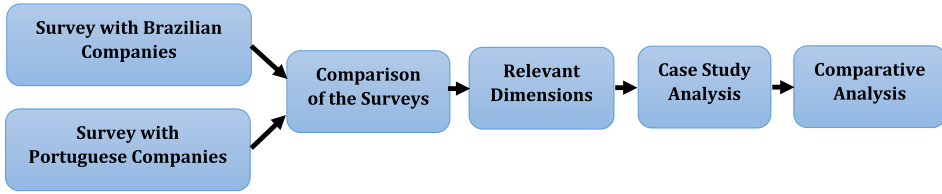


Fig. 1. Stages of the methodology applied in the study.

2. Methodology

The methodology used in the study followed the steps outlined in Fig. 1. To perform the comparative analysis of I4.0 maturity among Portuguese and Brazilian companies, the results of two surveys conducted in both countries were used, which had the same methodological basis. The surveys utilized the assessment model for the I4.0 maturity level defined by the German Mechanical Engineering Industry Association (VDMA). This model is known as “Industrie 4.0 Readiness”, which evaluates companies’ preparedness regarding the fundamentals of I4.0 (VDMA/IMPULS, 2015).

In these surveys, each company individually responded to the VDMA model questions, adapting them to their reality and with the support of researchers. The individual results were processed by the platform, revealing the levels of each of the six dimensions of the model and the overall result on a scale of 0–5. The presented data were tabulated, allowing for comparison of the results from Portuguese and Brazilian industrial companies.

The survey results were compared considering the six dimensions of the VDMA model (which will be presented ahead), identifying significant differences, and considering relevant dimensions by comparing averages. Based on this result, it was possible to identify the differences that characterize the maturity level of the two groups of companies. To support these conclusions, three companies from each country in the furniture sector were studied to try to understand the aspects that portray maturity differences and causal factors. Thus, in addition to measuring and comparing the maturity level, a qualitative analysis of the reality of each group of companies was conducted, and possible pathways for the evolution of these companies regarding I4.0 were identified.

3. Industry 4.0 and Assessment of Maturity Level

In I4.0, various fundamental concepts are redefining the way companies operate. This includes the IoT, which connects devices to the Internet to enhance operational efficiency; Big Data and Analytics, which allow for the analysis of large volumes of data for valuable insights; Artificial Intelligence (AI), which automates tasks and personalizes services; Additive Manufacturing (3D Printing), which offers customization and waste reduction; Augmented Reality (AR), which improves visualization

and training; and Cyber-Physical Systems (CPS), which integrate computational systems with physical processes for effective automation and management. These concepts transform the industry, making it more efficient, flexible and future-oriented (Weill and Woerner, 2015).

In assessing maturity in I4.0, various fundamentals are considered to understand companies' readiness and integration level. This includes the adoption of emerging technologies, the ability to integrate systems, the digitization of processes, flexibility and adaptability, organizational culture and cybersecurity. These elements are essential to successfully transition to I4.0, enabling more efficient, personalized and secure production.

Several models have been developed to assess company adaptation to I4.0. Given that this study aimed to conduct a comparative analysis of survey results assessing the maturity of Portuguese and Brazilian companies in I4.0, identifying significant differences in the various dimensions of the MM used, it was crucial to use a model that presented assessment results applicable to, or closer to, the business reality.

Various models that could contribute to the purposes of the research were detected and analyzed. Among the various models proposed for assessing the maturity level in I4.0, four models were chosen that showed greater relevance to the study's objectives, as demonstrated in Table 1.

The model selected for use in the field research was developed by VDMA/IMPULS, named Industrie 4.0 Readiness (VDMA/IMPULS, 2015). This choice was based on specific criteria, namely: (a) Consideration of business reality, (b) Ease of use, (c) Availability of an online assessment platform and lastly, (d) Possibility of comparison with other companies in the sector.

Table 1. Maturity and readiness models and respective dimensions.

Model	Dimensions	
IMPULS Industrie 4.0 Readiness (Lichtblau <i>et al.</i> , 2015)	<ul style="list-style-type: none"> – Strategy and organization – Smart factory – Smart operations 	<ul style="list-style-type: none"> – Smart products – Data-driven services – Employees
Industrie 4.0 Maturity Index (Schuh <i>et al.</i> , 2017)	<ul style="list-style-type: none"> – Computerization – Connectivity – Visibility 	<ul style="list-style-type: none"> – Transparency – Predictability – Adaptability
Maturity Model for Assessing I4.0 Readiness and Maturity of Manufacturing Enterprises (Schumacher <i>et al.</i> , 2016)	<ul style="list-style-type: none"> – Strategy – Leadership – Customers – Products – Operations 	<ul style="list-style-type: none"> – Culture – People – Governance – Technology
The Connected Enterprise Maturity Model (Rockwell Automation, 2014)	<ul style="list-style-type: none"> – Information infrastructure – Controls and devices 	<ul style="list-style-type: none"> – Networks – Security policies
Smart Manufacturing Systems Readiness Level (SMSRL) (Jung <i>et al.</i> , 2016)	<ul style="list-style-type: none"> – Organizational maturity – Information technology maturity 	<ul style="list-style-type: none"> – Performance maturity – Information connectivity maturity

Compared to other frameworks, such as the I4.0 Maturity Index (Schuh *et al.*, 2017), Schumacher *et al.* (2016) and the Rockwell Automation Model (2014), the VDMA/IMPULS model offers a more straightforward and more practical approach, especially for industrial companies. The Acatech model is very detailed but can be too complex for SMEs and less suited for cross-country studies. Schumacher's model is conceptually strong but lacks standardized tools and sector adaptability. The VDMA/IMPULS model is straightforward, easy to use and structured around six dimensions, allowing for benchmarking between companies and sectors. Its wide use in industry and the availability of an online tool make it particularly practical. These features made it a suitable choice for this study, comparing companies from developed and emerging economies.

The VDMA/IMPULS Industrie 4.0 Readiness model allows for the assessment of maturity in I4.0 and is based on six dimensions and specific criteria, as presented in Table 2.

The model indicates the readiness of the company in six levels, on a scale from 0 to 5, designated as follows: Level 0 – Outsider, Level 1 – Beginner, Level 2 – Intermediate, Level 3 – Experienced, Level 4 – Expert and Level 5 – Top performer. These six levels are grouped into three categories: Newcomers (0 and 1), Learners (2) and Leaders (3–5), as illustrated in Fig. 2.

The scheme of the main industrial and technological aspects of digitization was published in the VDMA guideline (Dössel *et al.*, 2014). The classification of products

Table 2. Dimensions and criteria of the MM evaluation in I4.0 of the VDMA (Lichtblau *et al.*, 2015).

Dimensions	Criterion
Strategy and Organization	<ul style="list-style-type: none"> – Implementation Status of the Industry Strategy 4.0 – Operationalization and Strategy review using a system of indicators – Industry Related Investments 4.0 – Use of technology and innovation management
Smart Factory	<ul style="list-style-type: none"> – Digital modeling – Equipment Infrastructure – Use of data – IT systems
Smart Operations	<ul style="list-style-type: none"> – Sharing Information – Cloud usage – IT Security – Autonomous processes
Smart Products	The readiness for smart products is determined by looking at the additional ICT functionality in the products and the extent to which usage phase data are analyzed
Data-driven Services	<ul style="list-style-type: none"> – Availability of data-driven services – Share of revenues derived from data-driven services – Sharing of used data
Employees	The readiness in the employees' dimension is determined by analyzing the skills of employees in various areas and by the company's efforts to acquire new skills

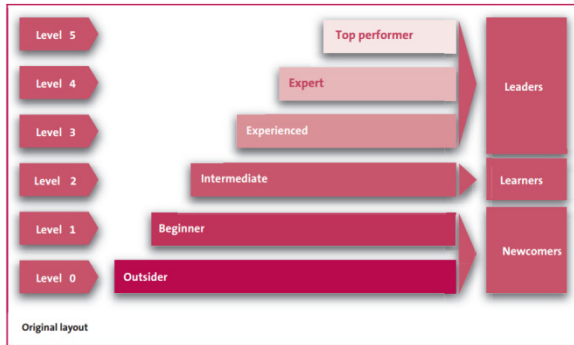


Fig. 2. The six dimensions of the “Industry 4.0 Readiness” model (Lichtblau *et al.*, 2015).

and processes in a business follows this scheme, displaying the level of digitization and the potential still untapped by companies in their digitization efforts.

4. Results

As presented in the study methodology, two surveys were conducted with Brazilian and Portuguese industries, using the same model and method to evaluate the maturity level in I4.0. The model used, as mentioned, was defined by VDMA, which assesses six dimensions of I4.0 on a scale of 0–5. The results obtained in each survey are presented below.

4.1. Maturity assessment of Portuguese companies

The Portuguese study involved the participation of 370 industrial companies from across the country, with 47% classified as small-sized, 46% as medium-sized and 7% as large-sized. The average result for Portuguese industrial companies was 1.22, on a scale of 0–5, indicating the Beginner level, classified as Newcomers. The general results of the readiness assessment of Portuguese companies in the six dimensions of the model are presented in Fig. 3.

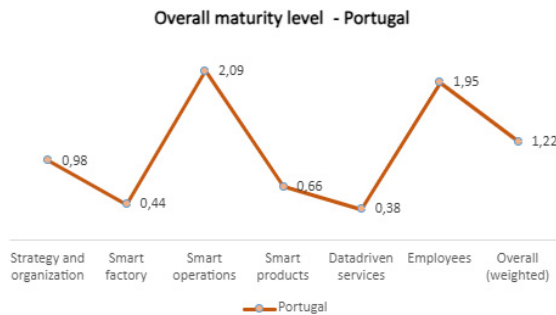


Fig. 3. Overall result of I4.0 maturity assessment of Portuguese companies by model dimension.

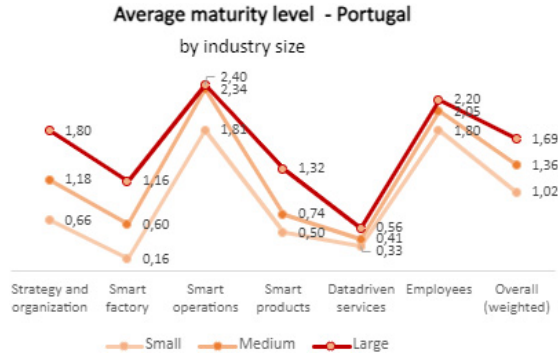


Fig. 4. Overall result of I4.0 maturity assessment of Portuguese companies by size of companies.

The analysis of I4.0 maturity level by industry size is presented in Fig. 4. Initially, an overview of the assessment by dimension and industry size is provided. The behavior of Portuguese industries is quite clear, with larger companies showing a higher level of maturity in each dimension. However, values are strongly converged for three dimensions: Smart Operations, Data-Driven Services and Employees, with very similar results across all three sizes.

4.2. Maturity assessment of Brazilian companies

The Brazilian study involved the participation of 46 industrial companies located in the State of Espírito Santo (ES). Of these companies, 50% were classified as small-sized, 28% as medium-sized and 22% as large-sized (Moura and Kohl, 2020). The average result for Brazilian (ES) industrial companies was 0.95 on a scale of 0–5, classified as Newcomers. The general results of the readiness assessment of Brazilian companies in the six dimensions of the model are presented in Fig. 5.

Regarding Brazilian industries, there is typical behavior in medium-sized industries, where some dimensions show higher results than those of large-sized ones (Employees), while in other dimensions, they have lower results than those of small-sized ones (Smart Products and Data-driven Services), as illustrated in Fig. 6.

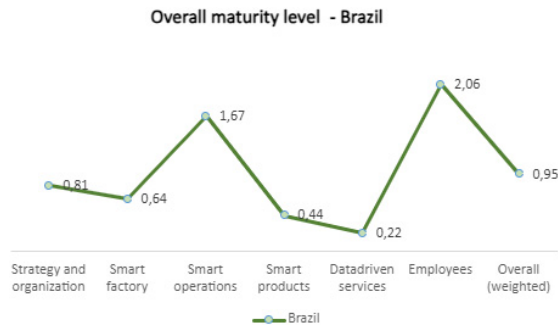


Fig. 5. Overall result of I4.0 maturity assessment of Brazilian companies by model dimension.

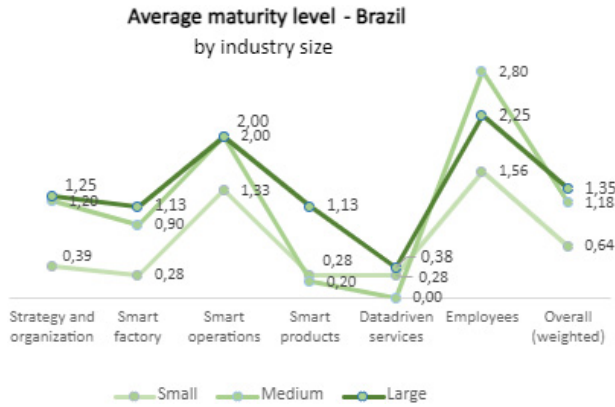


Fig. 6. Overall result of I4.0 maturity assessment of Brazilian companies by size of companies.

4.3. Comparison of industry 4.0 maturity levels between the two countries

The average general maturity level of Portuguese industries is 1.22, while that of Brazilian industries is 0.95. Portuguese companies, on average, present a higher maturity level by 0.27 points, representing 5.4% of the 5-point scale of the model used. The differences in the six dimensions of the model are detailed in Fig. 7.

The dimension of Smart Operations stands out with a difference of 0.42 points, equivalent to 8.4% of the total score. In other dimensions, Brazilian industries score higher in Smart Factory (0.2 = 4%) and Employees (0.11 = 2.2%). However, Portuguese industries still score higher in the dimensions of Strategy (0.17 = 3.4%), Smart Products (0.64 = 4%), and Data-driven Service (0.16 = 3.2%).

To identify the dimensions with significant differences between the two groups of companies, the absolute difference of values for each dimension was calculated and presented relative to the scoring scale of the model, ranging from 0 to 5. The results

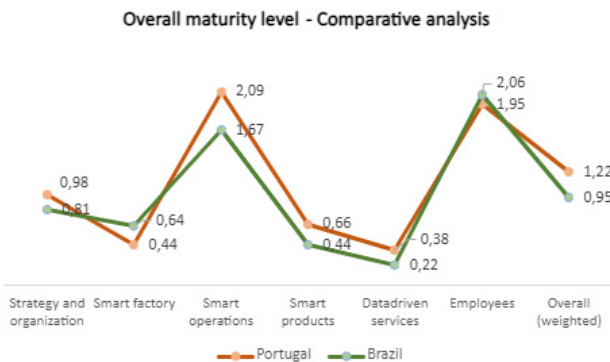


Fig. 7. Overall result of I4.0 maturity assessment across the six dimensions of the VDMA model.

Table 3. Differences between countries in the dimensions of the model.

Overall average	Strategy and organization	Smart factory	Smart operations	Smart products	Data-driven services	Employees	Overall (weighted)
Portugal	0.98	0.44	2.09	0.66	0.38	1.95	1.22
Brazil	0.81	0.64	1.67	0.44	0.22	2.06	0.95
Difference	0.17	-0.20	0.42	0.22	0.16	-0.11	0.27
Difference %	3.4%	-4.0%	8.4%	4.4%	3.2%	-2.2%	5.4%

Note: Relative difference (%) calculated in relation to the total points of each dimension, which is five points.

are shown in Table 3, with the score obtained in each dimension by country and the absolute and relative differences. A 5% threshold in relative value was considered for a difference to be considered relevant.

Among all the dimensions analyzed, the most significant difference is Smart Operations, with Portuguese industries standing out. Although the other dimensions do not exhibit differences exceeding 5%, which is the limit for comparison, Portuguese sectors have a better level of Strategy and Smart Products. Conversely, Brazilian industries excel in Smart Factory and Employees.

Figures 8–10 present a comparative analysis between the two countries by industry size. For small-sized industries, except for the Smart Factory dimension, Portuguese industries show higher maturity levels in the evaluated dimensions. On the other hand, regarding medium-sized industries, Brazilian industries have better results in the Smart Factory and Employees. For large-sized industries, the highlights are in the Strategy and Smart Operations dimensions, favoring Portuguese industries. The overall results of maturity levels across the three size categories highlight the superiority of Portuguese industries, reflected in the general values of 1.22 for Portuguese and 0.95 for Brazilian industries.

Table 4 presents the difference in maturity level between Portuguese and Brazilian industries, by business size and by dimension of the MM. To identify relevant differences, the comparison of the difference with the total points of each dimension,

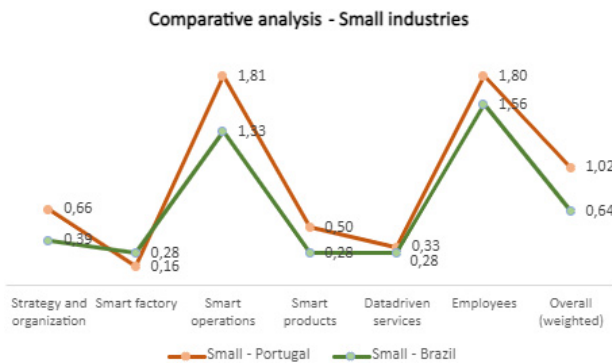


Fig. 8. Comparative analysis of maturity level – small-sized industries.

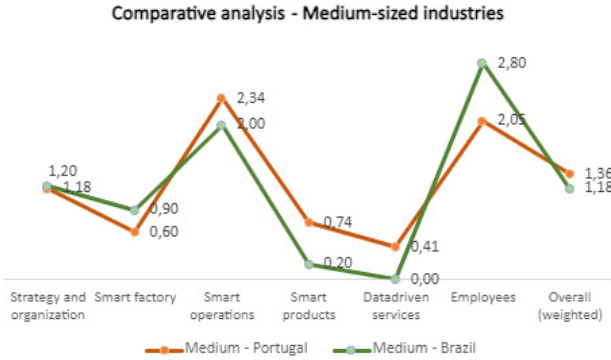


Fig. 9. Comparative analysis of maturity level – medium-sized industries.

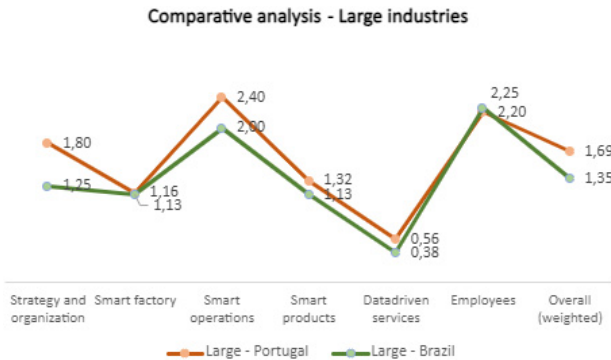


Fig. 10. Comparative analysis of maturity level – large-scale industries.

which is 5 points, was considered. Highlights are in red when the difference is greater than 5% for Portuguese industries and green when greater than 5% for Brazilian industries. Table 4 corroborates the emphasis on the Smart Operations dimension, where, for all sizes, Portuguese industries show better results than Brazilian ones. Thus, the model dimension that is considered to be relevant and analyzed is known as Smart Operations.

Table 4. Differences in maturity levels by industry size.

	Strategy and organization	Smart factory	Smart operations	Smart products	Data-driven services	Employees	Overall (weighted)
Small	5.4%	-2.4%	9.6%	4.3%	1.0%	4.9%	7.6%
Medium	-0.4%	-5.9%	6.7%	10.8%	8.3%	-15.0%	3.6%
Large	11.0%	0.6%	8.0%	3.8%	3.6%	-1.0%	6.9%

Note: In relation to the total points, the maturity level difference exceeds 5%. Red color for Portuguese industries and green color for Brazilian industries.

4.4. Analysis of the smart operations dimension – relevant difference between companies

Portuguese companies exhibited an overall maturity level of 1.22, categorized as **level 1 – Beginner**, whereas Brazilian companies scored 0.95, falling into **level 0 – Outsider**. Analyzing the six dimensions specifically, the differences in average results are very close in four dimensions: Strategy and Organization, Smart Factory, Smart Products, and Data-driven Services. However, the Smart Operations and Employees dimensions stand out with a significant difference.

As shown in Table 3, Portuguese companies present slightly higher values than Brazilian companies in the Strategy and Organization (3.4%), Smart Operations (8.4%), Smart Products (4.4%) and Data-driven Services (3.2%) dimensions, indicating a higher level of technology. Conversely, Brazilian companies showed slightly higher values in the Smart Factory and Employees dimensions. Figure 11 compares the differences in average values across the six dimensions of the model used.

The Smart Operations dimension has the highest absolute difference, with 0.43 points (see Fig. 11), and also in relative difference, with 8.4% (see Table 3). The other dimensions, as observed, have differences in measurement, but they were not considered relevant because the relative difference was less than 5%. According to Table 3 and the VDMA model, Brazilian companies achieved an average score of 1.67 in the Smart Operations dimension, categorized as **level 1 – Beginner**, while Portuguese companies obtained an average value of 2.09, classified as **level 2 – Intermediate** (see model levels in Fig. 1).

4.4.1. Characteristics of the smart operations dimension

According to the I4.0 reference model used in this study, developed by VDMA, the Smart Operations dimension is defined as follows: “Preparation for Industry 4.0 in the area of intelligent operations is determined using four criteria: (1) Information sharing, (2) Cloud usage, (3) IT security and (4) Autonomous processes” (VDMA/IMPULS, 2015). Integration is highlighted in this dimension, being fundamental for I4.0. It represents integrating all company components and systems,

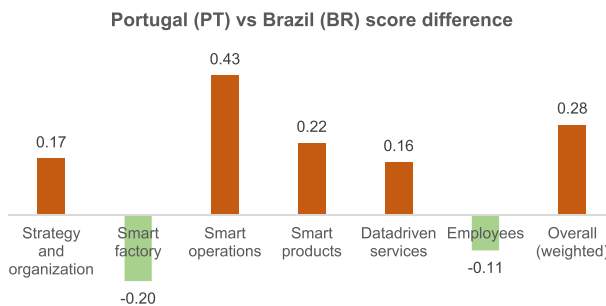


Fig. 11. The difference in overall scores across the six dimensions of PT compared to BR.

Table 5. Characteristics and challenges related to levels 1 and 2 of the smart operations dimension (VDMA/IMPULS, 2015).

	Smart operations	
	Level 1 – Beginner (BR)	Level 2 – Intermediate (PT)
Characteristics	<ul style="list-style-type: none"> • Initial steps toward internal information sharing, integrated into the system • Initial IT security solutions planned 	<ul style="list-style-type: none"> • Partially implemented internal information sharing • Multiple IT security solutions planned or initial solutions in development
Challenges	Little or no integrated information sharing within the company’s internal system (Vertical Integration)	No initial steps toward integrated information sharing with external partners (Horizontal Integration)

essential in achieving I4.0. It comprises both horizontal (external) and vertical (internal) integration of the value chain in which the company operates (PwC, 2014).

Table 5, based on the VDMA model, presents the main characteristics of this dimension at levels 1 and 2, where the studied companies are positioned, and indicates the main challenges these companies face.

Level 1 companies in the Smart Operations dimension are taking initial steps toward sharing external information integrated into the system and implementing IT security solutions. Level 2 companies have integrated internal information sharing into the system, and multiple IT security solutions are planned or already developed.

4.4.2. Smart operations in Portuguese companies (PT)

Portuguese industrial companies have invested more in Smart Operations than other dimensions in assessing their maturity. Despite this dimension weighting only 10% in the final calculation of the overall maturity level, it holds significant importance due to the focus on industrial companies that have given it in recent years. This includes cloud services, utilization of cloud-based software and data analysis and storage, scoring 3.74 on a scale of 0–5.

Portuguese industrial companies have also focused on organizing and securing IT, scoring 3.24. This is due to the establishment of specific IT departments in each operational area (production, product development, sales, etc.) in a centralized manner and the hiring of IT specialists for each operational area. The security of IT solutions involves internal data storage through cloud services, ensuring the security of internal data communications and the exchange of information with business partners.

The industrial processes of companies largely have experience in autonomous control of products throughout the production chain, scoring 3.34. These production processes sometimes autonomously respond to real-time changes in different production conditions.

However, information sharing by Portuguese companies still has a lower score, at 2.61. There is still some reluctance in sharing internal information among different departments and in the central system. Additionally, there is low receptivity to sharing information externally, including with customers and suppliers.

4.4.3. *Smart operations in Brazilian companies (BR)*

The Smart Operations dimension consists of four sub-dimensions: Information Sharing, Cloud Utilization, IT Security, and Autonomous Processes. In the Brazilian industry survey, it was impossible to identify the score of each sub-dimension, making a direct comparison with Portuguese industries at this level difficult. However, a more general analysis of the dimension is feasible.

This dimension is related to using IT to share internal and external information, utilize cloud environments, implement IT security systems and have autonomous processes. A lower result by Brazilian companies regarding the I4.0 maturity level suggests the need to increase investments in IT solutions. It's possible that industries still do not share their data sufficiently due to poorly integrated systems, hindering internal interaction. The situation is more complex regarding external data sharing with suppliers and customers.

Regarding the use of cloud systems, despite being a trend, there are still uncertainties about the total security of data traffic from companies to external environments. The cost should be considered, as it shifts from an investment in internal IT infrastructure to a service contract. If this hypothesis is true, industries should increase the use of information security services, which are also part of the Smart Operations dimension.

Regarding the Autonomous Processes sub-dimension, this may be the item with the greatest impact. In addition to the necessary investment in IT infrastructure and software, the implementation of autonomous processes is also directly related to operational labor costs, organizational culture and the availability of qualified teams. Brazilian industries may not yet have felt the need or may lack the appropriate culture to invest in IT and specialized personnel to equip their operations with autonomous processes.

4.4.4. *Comparative analysis of the smart operations dimension in Portuguese (PT) and Brazilian (BR) companies*

According to the VDMA model, Brazilian industries at level 1 in Smart Operations exhibit primary characteristics: Adopting internal sharing of integrated information systems and planning initial IT security solutions. This indicates that Brazilian industries, on average, are in the early phase of implementing integrated information systems and the initial phase of implementing information security systems. On the other hand, according to the same model, at level 2, where Portuguese companies are located, the characteristics include partially implemented internal information

sharing and the planning of multiple IT security solutions or the initial development of these solutions.

Portuguese industries, on average, are more advanced in terms of internal information sharing and make use of various information security solutions. However, these companies face the primary obstacle of not adequately integrating external information into the management system. On the other hand, Brazilian industries need to progress in the internal integration of information systems and also in IT security. The challenge for Portuguese industries, on the other hand, is to improve external integration, especially with suppliers and customers.

Market factors, corporate culture and distinct economic realities may influence these assessments. This result makes sense, considering that Portuguese industries operating in the competitive European market require a more well-defined I4.0 strategy and investments in management, planning, and operations control systems. On the other hand, Brazilian industries operating in a larger regional market need scale and, therefore, make greater use of automation. Regardless of this broader analysis, it is sure that there is a significant difference in maturity level in the Smart Operations dimension, with Portuguese industries standing out.

4.5. *Case studies of companies*

To understand the reality of the researched companies and attempt to grasp the situation beyond the statistics, case studies of both Portuguese and Brazilian companies were conducted. Three industries from each group were interviewed, all belonging to the same sector and across the three company sizes (small, medium and large), addressing issues such as the level of integration and sharing of systems and information, success and failure factors, and identifying lessons learned. The chosen sector was the furniture and wood sector, as it is common to both groups and includes small, medium and large industrial companies in the research. Companies with the best results in maturity assessment were selected to consider success cases from each group.

Table 6 presents the maturity levels of these studied industries. Even in this specific situation, studying cases of three companies per group compared to hundreds of researched companies, the coherence of the results in assessing maturity in I4.0 is evident, with Portuguese companies showing better results than Brazilian ones.

Table 6. Characteristics of participating companies in the case study.

Country	Company	Size	Business	Smart operations	Overall (weighted)
Portugal	A	Small	Custom furniture	3	1.240
	B	Medium	Mass production	3	1.630
	C	Large	Wooden boards	4	1.630
Brazil	D	Small	Custom furniture	1	0.424
	E	Medium	Children's furniture	2	1.213
	F	Large	Mass production	2	1.428

4.5.1. *Brazilian companies*

Three furniture industry companies in ES (BR), one of the country's most prominent sectors, were studied. The analyzed companies were identified as D, E and F. "Company D" operates in the custom furniture and joinery production segment. Despite being a small company, it has modern equipment with some level of automation, but without proper internal integration, both in equipment and systems. "Company E" manufactures standardized furniture for the children's segment. It is a medium-sized company with a good production volume, part of which is in serial systems, with some integration of ERP and PPC information with production. "Company F" is a large manufacturer of serial furniture for bedrooms and kitchens, such as wardrobes and cabinets. It has an automated production line with good system integration with factory operations and departments. These companies use updated machinery and stand out in the segment, seeking to modernize their facilities through investment in I4.0-related technologies.

Despite using modern machinery with embedded technology, these companies have a low level of internal integration. "Companies E and F" use an ERP in all operational and administrative activities and integrate with the PPC system. Only "Company F" has an operational control system, covering 50% of its operations, allowing it to achieve production control and flexibility. "Company D" has CAD and PPC systems, but control is done through manual records and spreadsheet use. There is still much to advance in vertical integration, starting with acquiring an ERP. External integration, referred to as horizontal, is carried out traditionally without any integration. The exception is "Company F", which has an extensive store network and integrates finished product stock.

Overall, these cases corroborate what was identified in the quantitative research and the references of the model used to analyze maturity in I4.0. They are taking the first steps toward internal sharing of information, integrated into the system, with little or no sharing of integrated details within the company's internal system (see Table 5).

4.5.2. *Portuguese companies*

Regarding the Portuguese companies, three industries in the furniture and wood sector were studied. "Company B" is renowned for its custom production of kitchens, wardrobes and bathroom furniture, being a medium-sized company that stands out for its emphasis on product customization. On the other hand, "Company A", a small-sized enterprise, specializes in custom interior carpentry and kitchen furniture manufacturing, showing a significant level of automation in its operations. "Company C", a large-scale company, operates in wood processing, producing a variety of wood panels such as particleboards and MDF, with a notable level of automation in its production lines. These companies exemplify the diversity and ongoing evolution in the Portuguese industry as they seek to adapt to the demands and opportunities of I4.0.

A general analysis of these companies reveals high software utilization for production management and control, including ERP, MES and SCADA systems. Consequently, they demonstrate extensive vertical integration of their systems up to the operational level. They employ operational systems for automated operation control, especially “Companies A and C”. The equipment used is modern and automated, facilitating integration among themselves. “Company C” achieves up to 90% autonomy in its operational processes, while “Company A” reaches 50%, and “Company B” reaches 20%. These companies are yet to establish external integration with suppliers and customers.

Based on the analysis of the three companies regarding Smart Operations, it was observed that success factors are intrinsically linked to the adoption of advanced technology, process automation, system integration, operational flexibility, effective data management and a continuous focus on meeting customer needs. These characteristics highlight the high level of internal data integration and sharing, reaffirming the maturity results and the model’s indicative value, while also posing the challenge of seeking integrated information sharing with external partners.

4.6. Analysis of results and pathways for evolution in industry 4.0

The comparative analysis of the surveys and the case studies has demonstrated that Portuguese companies exhibit a higher level of maturity in I4.0. The greatest difference was observed in the Smart Operations dimension, which entails using integrated systems in operations and internal data sharing. Table 7 summarizes this analysis.

Regardless of the superiority of Portuguese companies, there is still much to advance to achieve a satisfactory level of I4.0 maturity, both for Portuguese and Brazilian companies. While Brazilian companies need to invest more in systems that integrate ERP into operations, Portuguese companies need to consolidate the autonomy of operational processes and invest in horizontal integration. With this focus, the average level of companies in both groups can reach level 2 in the VDMA MM, with scores ranging between 2 and 2.99. It is evident that the efforts of Brazilian companies will be greater.

Pursuing improved maturity in I4.0 is crucial for companies in Portugal and Brazil, as both face similar challenges and opportunities in this context. To achieve this goal, some practices can be considered:

- (1) **Investment in Information Technology (IT):** Both countries can benefit from investing in IT solutions that promote efficient internal and external information sharing. This may include implementing integrated management systems and adopting secure cloud environments.
- (2) **Development of Internal Competencies:** Companies should prioritize the development of internal competencies necessary to handle the demands of I4.0. This includes training personnel in emerging technologies such as artificial intelligence, big data and automation.

Table 7. Summary of the comparative analysis of Portuguese and Brazilian companies.

Questions	Brazilian companies	Portuguese companies
General maturity level	0.95	1.22
Classification	0 – Outsider	1 – Beginner
Highlighted dimensions	Smart factory – 0.64 (>4.0%)	Strategy and Organization – 0.98 (>3.4%) Smart Operations – 2.09 (>8.4%)
	Employees – 2.06 (>2.2%)	Smart Products – 0.66 (>4.4%) Data-driven Services – 0.38 (>3.2%)
Level in Smart Operations	1.67	2.09
Characteristics	Nível 1 – Beginner	Nível 2 – Intermediate
	First steps toward internal information sharing, integrated into the system	Partially implemented internal information sharing
Challenges	Expand internal information sharing integrated into the company's internal system	Promote the sharing of integrated information with external partners

- (3) **Creation of an Innovation Culture:** Companies must cultivate an organizational culture focused on innovation. This involves encouraging experimentation, creative thinking and willingness to adopt new technologies and practices.
- (4) **Strategic Partnerships:** Seeking strategic partnerships with other companies, research institutions and government entities can be beneficial to drive innovation and adoption of I4.0 technologies.
- (5) **Focus on Information Security:** With increased digitization, companies need to prioritize information security. This includes implementing robust cybersecurity measures to protect their data and information.

Cooperation between the countries is possible considering the similarity in efforts to evolve in I4.0 maturity. In addition to the common language, the similarity in challenges related to I4.0 may lead to joint cooperation actions, both in academic research and by companies themselves. Thus, it is possible to envision contributions in the academic and business fields as follows:

- (1) **Development of Frameworks and Models:** The research contributes to the development of frameworks and models that enable companies to assess their level of maturity in I4.0 and identify areas for improvement.
- (2) **Identification of Best Practices:** By analyzing leading companies in terms of I4.0 maturity, the research helps identify best practices that can be adopted by other organizations to enhance their performance.

- (3) **Understanding of Success Factors and Barriers:** The research contributes to understanding the factors driving success in adopting I4.0 and the obstacles companies face during this process.
- (4) **Guidance for Public Policies:** Insights generated by the research can guide public policies and governmental strategies aimed at promoting I4.0 and developing ecosystems favorable to technological innovation.
- (5) **Professional Empowerment:** The research also plays an important role in empowering professionals and managers, providing them with the knowledge and skills to lead digital transformation in their organizations.

Across the Portuguese and Brazilian case studies, several success factors emerged. In Portugal, a common enabler was the presence of strong leadership committed to innovation and the existence of partnerships with technological providers. In Brazil, public incentives and participation in collaborative networks helped offset resource constraints. On the other hand, both groups of companies reported barriers such as limited digital skills among employees, high initial investment costs and the complexity of integrating legacy systems. Brazilian companies, in particular, highlighted greater difficulty accessing stable IT infrastructure and specialized technical support, reflecting broader structural challenges. These observations are consistent with findings from Zilli *et al.* (2023) and Brodny and Tutak (2022), which underline the importance of internal readiness and external ecosystem support in successful I4.0 adoption.

5. Discussion

5.1. *Theoretical contributions and literature comparison*

This study significantly contributes to production management theory, particularly in the context of I4.0, by identifying the “Smart Operations” dimension as a central element for the digital maturity of companies. The research advances theoretical understanding by revealing that horizontal and vertical integration of operations is fundamental for successful digital transformation, a point not always highlighted in previous studies (Kiraz *et al.*, 2020). This contribution is substantial as it offers a new perspective on how companies can optimize their internal and external operations to increase their competitiveness and efficiency and enhance their ability to respond quickly to market changes.

An unexpected finding was the higher average score achieved by Brazilian companies in the “Employees” dimension. While Portuguese companies generally exhibited greater maturity across most dimensions, this result suggests that Brazilian firms may have prioritized employee-related initiatives. One possible explanation lies in targeted workforce development programs such as SENAI, which support upskilling in digital technologies across the Brazilian industry. Additionally, the Brazilian sample includes firms with younger workforces and a higher emphasis on operational training, which may have boosted this dimension. In contrast, Portuguese SMEs often face

challenges linked to an aging workforce and more limited access to continuous training programs (Amaral and Peças, 2021). These contextual factors may explain the observed disparity and indicate that digital maturity is not always uniformly distributed across dimensions, but can be shaped by specific national policies and workforce characteristics.

Furthermore, the study adds to the field by exploring how economic and regulatory factors, such as access to financial resources and government support, influence the adoption of I4.0 technologies. In particular, Portuguese companies have demonstrated greater digital readiness due to a favorable economic environment and robust support policies (Amaral and Peças, 2021; Rauch *et al.*, 2020). These data advance the understanding of how the economic context can act as a facilitator or a barrier to technological innovation, something less addressed in studies focused exclusively on technological aspects (Götz, 2019; Brodny and Tutak, 2022). The research also explains technological adoption phenomena better by differentiating how these contextual variables directly influence companies' ability to implement advanced solutions. This approach allows for a better understanding of the conditions that favor the successful implementation of advanced solutions, overcoming the limitations of previous studies that predominantly focus on technical aspects.

5.2. *New theoretical perspectives*

Identifying “Smart Operations” as the most critical dimension for the digital maturity of companies contributes to the literature by clarifying the essential role of operational integration. It offers a new theoretical perspective on production management. This study demonstrates that effective integration of operations, internally and with external partners, improves efficiency and facilitates adaptation to emerging technologies, such as IoT, big data and artificial intelligence. This finding offers a new perspective by highlighting the importance of a holistic approach to production management, which considers technological infrastructure, management practices and organizational culture (Alcácer *et al.*, 2021; Wessing and Müller, 2022).

A more detailed look at some subdimensions helps to clarify the maturity differences between Portugal and Brazil. Portuguese companies scored higher in “System Integration” and “IT Security”, which may reflect more substantial investment in digital infrastructure and earlier compliance with European data protection standards. In contrast, Brazilian companies performed better in “Autonomous Processes”, especially those in export-oriented sectors, suggesting a focus on process automation. These contrasts highlight the value of analyzing specific technological aspects, which vary significantly depending on each country's context and priorities.

Additionally, the research emphasizes the importance of an organizational culture that promotes innovation and the capacity for change management as crucial factors for digital maturity. Companies that develop a culture of innovation and have leaders prepared to manage technological transformations are more successful in adopting new technologies. This suggests that the development of internal

competencies and leadership preparation are crucial for the digital evolution of companies, broadening the understanding of the organizational elements that support digital transformation (Zilli *et al.*, 2023). This perspective is supported by studies indicating that the ability to manage change is fundamental to digital evolution, offering a more comprehensive explanation of the factors contributing to the successful implementation of I4.0 technologies while also addressing gaps in the literature that have overlooked the influence of organizational culture.

5.3. *Methodological and contextual comparison*

The system integration methodology (VDMA/IMPULS, 2015) used in this study provides a more precise and contextualized view of companies' digital readiness, standing out from previous methods that do not comprehensively consider operational integration. This approach allows for a more practical and detailed assessment of companies' capabilities in adopting I4.0 technologies by including contextual variables such as economic and cultural factors (Weill and Woerner, 2015; Schuh *et al.*, 2017). The analysis of methodologies, definitions and studied contexts reveals significant nuances and differences between studies, providing a critical and in-depth view of the results.

The study also highlights the need to adapt digital readiness models to each country's specific economic, cultural and regulatory contexts. For example, Brazilian companies face unique challenges, such as lower availability of financial resources and less developed technological infrastructure. These structural barriers limit their capacity to adopt advanced technologies, resulting in lower digital maturity levels than Portuguese companies. This contrast underscores the importance of targeted public policies and investments in technological infrastructure to support digital transformation in Brazilian companies (Vuksanović Herceg *et al.*, 2020). This contextualized analysis clarifies the reasons for the disparities observed in digital maturity. It provides a solid basis for formulating more effective strategies to promote digital transformation in different national contexts. Therefore, the research contributes to a deeper understanding of the barriers and facilitators of digital transformation and offers practical insights for developing policies and business strategies.

6. Conclusions

6.1. *Practical implications*

The findings of this study highlight several practical implications for companies in Portugal and Brazil. While Portuguese companies are ahead in certain aspects of I4.0 maturity, particularly in the "Smart Operations" dimension, there is still significant room for improvement in integrating internal processes and strengthening information security. These companies should prioritize developing and implementing comprehensive ERP systems and data management frameworks to enhance

internal cohesion and data-driven decision-making capabilities. Furthermore, reinforcing cybersecurity measures is crucial to protect the increasing flow of data across integrated systems and ensure compliance with global standards.

For Brazilian companies, the study indicates an urgent need to elevate their I4.0 maturity, particularly by advancing from a basic level of digital integration. Implementing ERP systems that integrate operations across different business units is essential. These systems can streamline processes, improve data sharing and enhance operational efficiency. Brazilian companies should also consider investing in training programs to upskill employees, fostering a culture that embraces digital transformation. This will improve current operations and prepare companies for future technological advancements and market demands.

6.2. Study limitations

This study has several limitations that should be acknowledged. First, the research was geographically limited to industrial companies in Portugal and the State of ES, Brazil. This geographical constraint may not fully represent the diversity of I4.0 readiness in other regions of these countries, particularly in areas with different economic and industrial profiles. Additionally, this study's focus on specific sectors, such as the furniture and wood industry, may not capture the full spectrum of challenges and opportunities faced by companies in other sectors. Therefore, the findings may not be entirely generalizable to all industrial sectors or regions within the two countries.

A limitation of this study concerns the difference in sample sizes between the two countries. While the Portuguese sample is large and diverse ($n = 370$), the Brazilian sample is comparatively smaller ($n = 46$), which may affect the representativeness of the findings for the broader Brazilian industrial landscape. The Brazilian results should be interpreted as exploratory, offering initial data on digital maturity levels in a specific regional and sectoral context. Nevertheless, consistently using the same assessment model and methodology across both groups ensures a valid comparative perspective. Future research could extend this work with a more representative sample of Brazilian companies across multiple regions and industrial sectors.

6.3. Future research directions

To build on the insights obtained from this study, future research should focus on expanding the scope of analysis to include a broader range of sectors and regions within Portugal and Brazil. This would provide a more comprehensive understanding of the factors influencing I4.0 maturity in different industrial contexts. Additionally, exploring the impact of specific government policies, economic conditions and cultural factors on adopting I4.0 technologies could yield valuable insights into how these variables affect digital transformation efforts.

Another critical area for future research is the role of strategic partnerships and collaborations in facilitating the adoption of I4.0. Investigating how partnerships

between companies, academic institutions and government agencies can support developing and implementing digital technologies will be crucial. This research could identify best practices for fostering innovation ecosystems that promote the integration of advanced technologies in manufacturing.


Lastly, further studies should examine the impact of training and development programs on enhancing digital maturity. Understanding how investments in workforce skills can accelerate the adoption of I4.0 technologies will provide practical guidance for companies aiming to improve their competitive advantage through digital transformation. These studies could also explore the role of leadership in promoting cultural changes toward greater acceptance and utilization of new technologies.

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