

Article

Industry 4.0 and Sustainability: Empirical Validation of Constructs of Industry Technology and Sustainable Development

Lucas da Silva Melo ¹, Reimison Moreira Fernandes ¹, Denilson Ricardo de Lucena Nunes ² ,
Renata Melo e Silva de Oliveira ³ , Jonhatan Magno Norte da Silva ⁴ , Lucas Veiga Avila ⁵ ,
and Vitor William Batista Martins ^{1,*} 

- ¹ Departamento de Engenharia de Produção, Universidade do Estado do Pará, Belém 66095-015, Brazil; lucas.melo@aluno.uepa.br (L.d.S.M.); reimison.fernandes@aluno.uepa.br (R.M.F.)
- ² Departamento de Engenharia de Produção, Universidade do Estado do Pará, Castanhal 68745-000, Brazil; denilson.nunes@uepa.br
- ³ Departamento de Ciências Sociais Aplicada, Universidade do Estado do Pará, Belém 66095-015, Brazil; renata.oliveira@uepa.br
- ⁴ Campus do Sertão, Universidade Federal de Alagoas, Delmiro Gouveia 57480-000, Brazil; jonhatan.silva@delmiro.ufal.br
- ⁵ Departamento de Engenharia de Produção, Universidade Federal de Santa Maria, Santa Maria 97105-900, Brazil; lucas.avila@ufsm.br
- * Correspondence: vitor.martins@uepa.br



Citation: Melo, L.d.S.; Fernandes, R.M.; Nunes, D.R.d.L.; Oliveira, R.M.e.S.d.; Silva, J.M.N.d.; Avila, L.V.; Martins, V.W.B. Industry 4.0 and Sustainability: Empirical Validation of Constructs of Industry Technology and Sustainable Development. *Platforms* **2024**, *2*, 150–164. <https://doi.org/10.3390/platforms2040010>

Academic Editor: Adel Ben Youssef

Received: 3 September 2024

Revised: 16 September 2024

Accepted: 24 September 2024

Published: 26 September 2024

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Abstract: The study has as purpose to identify, analyze, and validate challenge constructs of Industry 4.0, which can affect the promotion of sustainability within the industry. A systematic literature review was conducted to identify challenges to the promotion of Industry 4.0 sustainability. A set of seventy challenges were grouped into the following eight constructs: finances, technology, organizational, human resources, legislation, geopolitical and economic factors, and both internal and external factors. Subsequently, the same constructs were validated using a survey involving industry professionals. The data were analyzed using the Lawshe method. Five constructs within the eight constructs were considered relevant to industry sustainability according to the experts' opinion. The validated set of constructs included: finance, technology, organizational, human resources, and internal factors. This study contributes to the literature in the field by addressing a research gap of constructs identification based on expert's opinions that impact Industry 4.0 in promotion of sustainable development. This study delivers theoretical and practical implications. From a theoretical standpoint, it contributes to expanding knowledge by providing valuable insights into the adoption of Industry 4.0 and its specific challenges concerning the pursuit of more sustainable practices. These implications extend to diverse research areas given the multidisciplinary nature of Industry 4.0.

Keywords: Lawshe method; constructs; Industry 4.0.; sustainable development

1. Introduction

In the context of Industry 4.0, the integration of digital technologies and sustainable practices holds potential for organizations to enhance their operational efficiency, reduce environmental impact, and contribute to overall sustainability. However, the validation of constructs related to industrial technologies and sustainable development within the Industry 4.0 paradigm is considered a gap in the literature for ensuring robust and reliable research findings. This article presents an empirical study aimed at validating key constructs associated with Industry 4.0 and sustainability. Through a rigorous methodology involving survey data collection and statistical analysis, the paper examines the relationships between industrial technologies, such as automation, robotics, and artificial

intelligence, and various dimensions of sustainable development, including environmental protection, economic growth, and social equity. The findings of this study contribute to the advancement of knowledge in the field of Industry 4.0 and sustainability, providing valuable insights for researchers, policymakers, and practitioners alike.

From a conceptual perspective, Industry 4.0 (I4.0) can be considered an ongoing technology transformation in the global industrial sector, characterized by the convergence of advancements in technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), big data, robotics, and cloud computing. Originating in Germany in 2011, Industry 4.0 has gained international recognition due to its potential impacts [1]. These impacts include optimizing supply chain flows, integrating chain links, reducing production costs, enabling personalized production, scalability, flexibility in production, and, a debated point, value generation for the customer [2]. However, its implementation may also pose complex challenges that need to be addressed, including data security and privacy, coordination and control, people management, and cost, as highlighted by [3–6].

Business sustainability associated with I4.0 has been widely discussed in academic and professional communities. Organizations are progressively adopting sustainable operations management as an alternative to traditional methods to enhance their sustainable performance [7–9]. According to Khan et al. [10], I4.0 has significant potential to drive sustainable industrial value creation in economic and environmental spheres by improving resource efficiency. In the social sphere, it also considers respecting workers' rights, occupational safety, and positive interaction with local communities. Khan et al. [10] acknowledge that transitioning to sustainable practices in the industry may involve complex challenges, it also offers opportunities for innovation, creating shared value, and contributing to a more sustainable future. Other works associating Industry 4.0 and Sustainability includes Al-Khatib [11] on the performance of supply chains, Erboz and Yumurtacı Hüseyinoğlu [12] on supply chain cost and flexibility, and Khodair [13] on integrating sustainability values into Industry 4.0 Egyptian supply chains. Other works worth mentioning include Ardito et al. [14], Bazan and Estevez [15], and Deng et al. [16], which collectively contributed to discuss the role of Industry 4.0 technologies in driving sustainable practices across multiple business dimensions, including supply chain optimization, resource management, and cost reduction.

Sustainable development, promoted by the United Nations' Sustainable Development Goals (SDGs) in 2015, encompasses a wide range of targets to balance economic growth, social inclusion, poverty eradication, and environmental preservation by 2030 [17–19]. SDG 9 stands out among the SDGs, aiming to drive sustainable industry, innovation, and infrastructure by strengthening energy efficiency and responsible industrialization. SDG 12 focuses on adopting responsible consumption and production practices, including proper waste management and efficient resource use. All SDGs are interconnected and aim to address global challenges, promoting sustainability across all human activities through collaboration and the implementation of sustainable policies and practices, especially for private enterprises. According to Von Geibler et al. [20], addressing the SDGs contributes to strengthening trust and promoting innovation, enabling more effective handling of the complexity and ambiguity of development challenges. Hatayama [21] emphasizes that it has become increasingly essential for organizations to identify and transparently communicate the social and environmental consequences of their corporate activities, adhering to the Principles for Responsible Investment (PRI) established by the UN in 2006.

This research aims to fill a gap in the literature by exploring the relationship between constructs faced in the implementation of Industry 4.0 and sustainable development from the perspective of professionals in the industrial sector, particularly from an emerging economy such as Brazil, where there are technology challenges and limitations [22,23]. While the topic is widely discussed, there is a scarcity of studies specifically focusing on the impacts of these challenges on sustainability [24]. Therefore, conducting this work is relevant to understanding the topic comprehensively. By collecting data directly from industry professionals, valuable insights into the barriers and challenges faced in the context

of I4.0 regarding sustainability can be obtained. Collaboration with industry professionals is necessary to find sustainable solutions, strengthen available knowledge, and promote continuous dialogue between theory and application [25].

In this context, this work poses the following question: “What are the key constructs of Industry 4.0 challenges to be considered in promoting sustainability in the industry, from the perspective of industry professionals?” This study aims to identify, analyze, and validate constructs formed by challenges of Industry 4.0 that impact the promotion of sustainability in industry. The research was conducted with key industry professionals, including CEOs (Chief Executive Officers), managers, supervisors, analysts, assistants, and operators, covering a broad range of experiences and knowledge related to the theme. To achieve this, a survey-based approach was employed [26]. Through data collection, valuable insights are expected to be gained from the perspective and experiences of these professionals, expanding the debate on the addressed topic.

2. Literature Review

Industry 4.0 represents a new phase of the Industrial Revolution, characterized by the integration of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, big data, and cyber-physical systems. This transformation aims at the automation and digitalization of production processes, enabling greater efficiency, flexibility, and mass customization. The connectivity between machines, systems, and people allows real-time data exchange, promoting more accurate decision-making and resource optimization. Industry 4.0 also drives the development of intelligent and sustainable supply chains, as well as the creation of new business models. This revolution challenges industries to quickly adapt to technological innovations to remain competitive in the global market [27,28].

Szabo et al. [29] highlight the main driving forces and barriers of Industry 4.0 implementation, emphasizing the relevance of sustainability in this process, and considering the perceived limitations by manufacturing company managers. According to Müller et al. [30], despite a growing body of economic research on Industry 4.0, there is limited discussion on the opportunities and challenges relevant to its implementation, especially concerning sustainability. They also point out the need to balance the three dimensions of sustainability (economic, environmental, and social) when analyzing the adoption and diffusion of technology. In this regard, this study highlights the constructs formed by challenges faced by companies in the adoption of I4.0 as follows.

2.1. Financial Challenges

In this context, it is worth analyzing barriers to the adoption of Industry 4.0 concepts, technologies, and pillars that can also impact the achievement of sustainable goals. Analyzing barriers related to financial issues and challenges such as high initial costs and uncertainty about the return on investment in infrastructure are relevant in the implementation of Industry 4.0. According to Bakhtari et al. [31], these issues require strategic analysis and evaluation, as they can impact the effective adoption of Industry 4.0, necessitating consideration of the individual aspects of each organization. Additionally, Demirkesen and Tezel [32] emphasize that younger companies have a greater capacity for adaptation and are willing to take risks in adopting new technologies. Ghadge et al. [33] state that the lack of research and development practices in Industry 4.0 can be an obstacle for organizations, hindering the effective implementation of these technologies. According to Kumar et al. [34], financial challenges in the manufacturing industry include high investment costs and uncertainty about the return on investment in digital technologies, with the severity varying based on the type of the company. Organizations face financial challenges when investing in Industry 4.0 technologies due to the uncertainty of economic benefits and associated costs, as stated by Kumar et al. [35]. According to Legg et al. [36], the lack of clarity about the financial benefits of investing in new technologies is one of the main challenges faced in the adoption of these innovations. Overcoming this uncertainty

requires specialized training for professionals and managers, emphasizing the need to increase awareness of the financial aspects of technologies and their impact on production processes [36].

2.2. Technology Challenges

Orzes et al. [37] highlight technology challenges in the implementation of Industry 4.0, such as low IT infrastructure and difficulties in interoperability and compatibility, but these challenges can be overcome through a well-structured roadmap. Cordeiro et al. [38] claim that the implementation of Industry 4.0 faces challenges related to information security and the lack of technology standardization. These obstacles can impact the effective adoption of Industry 4.0 in companies, necessitating the development of strategies to mitigate them. The lack of a solid infrastructure can hinder the efficient adoption of innovations associated with I4.0. Issues such as poor connectivity, limited communication systems, and the need for substantial investments in updating and modernizing existing facilities may arise. In this sense, a lack of IT infrastructure can represent an obstacle to the successful implementation of Industry 4.0 [33]. Data protection and cybersecurity have been recognized as significant challenges in the adoption of Industry 4.0. According to Demirkesen and Tezel [32], companies face issues such as low security and privacy of digital data, as well as cyber threats, making these challenges relevant in the secure and successful implementation of I4.0, regardless of the type of company.

2.3. Organizational Challenges

According to Herceg et al. [39], the implementation of Industry 4.0 in companies faces a significant challenge related to the lack of competencies and skills. Companies undergoing digital transformation perceive this organizational challenge as an obstacle when lacking the necessary competencies to adopt new technologies. For Orzes et al. [37], the implementation of Industry 4.0 in small and medium-sized enterprises (SMEs) may face challenges related to organizational culture, emphasizing that the lack of higher management support can be a significant barrier, resulting in a shortage of resources and necessary strategic direction for the I4.0 implementation process. According to Müller et al. [30], lack of experience is one of the challenges in implementing I4.0, emphasizing that this can be a significant barrier to the success of adopting these innovations. Satyro et al. [40] highlight organizational challenges in the implementation of I4.0, such as the difficulty of changing culture and the subordination of sustainability.

2.4. Human Resources Challenges

Satyro et al. [40] emphasize that the adoption of I4.0 presents relevant challenges regarding human resources, such as the social impact and the possibility of unemployment resulting from the automation and informatization of processes, as well as difficulties in hiring and training professionals with digital technology skills. According to Szabo et al. [29], the implementation of Industry 4.0 faces notable challenges related to human resources, including a shortage of suitable internal skills, competencies, and capacities, highlighted as the main obstacle, along with prolonged learning times and a shortage of qualified workforce. Virmani et al. [41] state that lack of employee empowerment, absence of a recognition and reward system, and a shortage of interpersonal skills are challenges of Industry 4.0, related not only to human resources but also to organizational culture. During the implementation of Industry 4.0, the barrier of an increase in diseases and mental health-related problems was highlighted by Kumar et al. [34], stating that Small and Medium-sized Enterprises (SMEs) also face these challenges regarding the mental health of employees during this transition of technologies. Müller [42] emphasizes that employees' adoption of I4.0 can be hindered by fears related to the possibility of losing their jobs and uncertainties associated with the use of new technologies. Furthermore, employees have concerns about surveillance and the use of their data in a harmful way, affecting workplace safety, as well as the difficulty in clearly recognizing the benefits of I4.0.

2.5. Legislation Challenges

Virmani et al. [41] point out that legal and contractual uncertainty is a barrier to the implementation of I4.0, as issues related to legal compliance and contracts can create resistance to technology transformation by companies. According to Ghadimi et al. [43], legal issues represent a barrier to the adoption of Industry 4.0. Implementation can generate complex issues related to the treatment of personal data, protection of corporate data, traceability of responsibilities in networks, and international trade restrictions. The lack of digital legislation is a barrier to I4.0, as mentioned by Bakhtari et al. [31], as companies need to deal with issues related to data security, privacy, and compliance with regulations. The lack of clear laws can generate uncertainties and hinder adoption. According to Cordeiro et al. [38], the lack of specific laws regarding I4.0 is a challenging factor for the adoption of technology, and therefore there is a need to create specific laws to deal with the technology innovations in question. These laws should especially address issues related to the protection of corporate data and the liability arising from these technologies.

2.6. Challenges Related to Geopolitical and Economic Factors

Kumar et al. [35] address demographic division and national cultural differences as implementation barriers of I4.0. It is observed that national culture can act as an influencing factor, being a facilitator or a barrier to the adoption of technological innovations, depending on the region. According to Ghadimi et al. [43], a risk factor related to the implementation of Industry 4.0 is a change in economic climate or government policy (CEC/GP). Unforeseen events, such as economic crises or changes in government policy, can have significant impacts on the economy and the market, creating an environment of uncertainty for investments in technologies like those of I4.0.

2.7. Internal Factors Challenges

Internal factors can cause delays and fluctuations in Industry 4.0 production, including low industry maturity, production fluctuation, lack of communication between management and workers, a shortage of specialized consultants, and incompatibility of technologies with company incentive systems. Karadayi-Usta [44] states that the effectiveness of I4.0 faces delays in the transformation process as a relevant barrier. According to Müller et al. [30], the loss of flexibility is one of the barriers faced in the adoption of I4.0. Therefore, there is a need to enhance companies' adaptability to changes in the business environment. For Goswami and Daultani [45], one of the identified barriers to the adoption of I4.0 technologies is the "lack of expertise" or "lack of proficiency". This challenge refers to the absence of specialized knowledge and skills needed to effectively implement and operate I4.0 technologies, which is highlighted as a significant difficulty in the adoption process of these technologies.

2.8. External Factors Challenges

Cordeiro et al. [38] point out the lack of standards as a challenge in the implementation of I4.0. The absence of technology guidelines and standards can hinder the efficient integration of technologies, generating uncertainties for companies. Additionally, Goswami and Daultani [45] identify the lack of government support as one of the barriers to the adoption of Industry 4.0 technologies, as the government can be one of the main stakeholders in encouraging the adoption of Industry 4.0, helping to improve regional infrastructure and empower companies. Virmani et al. [41] expose the lack of standards as a relevant obstacle to the establishment of I4.0, as the absence of standardized guidelines and norms can hinder integration and compatibility between different technologies and systems used in companies. Furthermore, regarding external factors, Orzes et al. [37] highlight the lack of a methodological approach as a hindrance to the efficiency of the implementation of I4.0-related technologies. Ghadimi et al. [43] emphasize the lack of certification as a limitation, considering that this can represent a risk factor for companies, as they may invest in vulnerable and eventually prohibited technologies in the future. In this regard, certification

for IT systems, data transfer, and data security is necessary to reduce this risk. Ghadimi et al. [43] also present uncertainty in the new business model as an obstacle to the adoption of I4.0, which can impact supply chains, consequently requiring guidelines for successful implementation, with small and medium-sized enterprises being more vulnerable.

Considering the context, Table 1 presents, in a synthesized form, the challenges identified in the literature grouped into constructs (financial, technology, human resources, legislation, geopolitical and economic factors, internal and external factors).

Table 1. Challenge constructs for adopting industry 4.0.

Code	Construct	Challenge	References
C_01	Financial	Lack of clarity about the economic benefits of investment	[32,33,36,37,43,45,46]
		High investment costs	[30,32,35,39,45]
		Lack of investment in research and development	[30,32,35,39,45]
		Risky investment in technologies	[31,33]
C_02	Technological	Low security and privacy of digital data	[1,31,32,38,45,47]
		Low information technology infrastructure	[1,33,38,44,45,48]
		Difficulties in machine compatibility with digital technologies	[47,49,50]
		Unavailability of the technology ecosystem	[37,51,52]
		Lack of technology knowledge	[34,41,43]
		Dependency on machines	[30,53,54]
		Lack of development of indigenous technology	[35,55]
C_03	Organizational	Lack of vision and support from top management	[31,33,37,47–49,56]
		Lack of coordination and cooperation within the production chain	[45,57]
		Lack of perseverance	[47,49,50]
		Low quality and management of data	[33,45]
		Organizational and process change	[31,38]
		Unavailability of I4.0 standards	[31,38]
		Resistance from top management system	[31,38]
		Lack of knowledge of the latest technologies	[35,50]
		Lack of involvement and engagement of stakeholders	[35,50]
		Lack of necessary competencies within the company	[58,59]
		Inadequate organizational structure	[29,39]
		Inadequate process organization	[29]
		Resistance from middle management	[29,39]
		Lack of research and development activities	[29,39]
		Lack of knowledge management system	[60,61]
		Difficulty in changing organizational culture	[40]
		Sustainability is considered secondary	[40]
		Lack of experience	[30]
C_04	Human Resources	Lack of strategy and implementation objective	[42,62]
		Lack of conscious planning: defining goals	[39]
		Lack of specialized education in Industry 4.0 for employees	[31,47]
		Lack of qualified workforce	[31,33,38,45]
		Employee resistance	[1,37,41,47,61]
		Investment in employee training	[51]
		Lack of formal training for managers	[51]
		Lack of communication between management and workers	[51]
		Lack of consultants and instructors in the field	[51]
		Insufficient talent and technical knowledge (IT)	[43]
		Longer learning times (employee training)	[39]
		Lack of managers with appropriate skills, competencies, and experience	[39]
		Unclear benefits for workers	[30]
		Difficulty in hiring/training people in digital technology	[40]
		Possibility of unemployment	[41]
		Enhanced skill requirements	[43]
		High cost of hiring qualified workforce	[39]
C_05	Legislation	Increase in mental illness	[30]
		Lack of empowerment	[41]
		Lack of recognition and reward system	[41]
		Use of employee data and surveillance	[30]
		Lack of interpersonal skills	[41]
		Lack of regulatory laws	[31,32,38,45]
		Legal issues	[43]
		Legal and contractual uncertainty	[41,63]

Table 1. *Cont.*

Code	Construct	Challenge	References
C_06	Geopolitical and economic factors	Demographic division	[35]
		National culture and regional differences	[35]
		Changes in economic or government political climate (CEC/GP)	[43]
C_07	Internal factors	Potential manufacturing delays during installation	[43]
		Transformation process delays	[38]
		Fluctuation in production size	[37]
		Lack of expertise	[37,38]
		Loss of flexibility	[30]
C_08	External factors	Lack of standards for Industry 4.0 implementation	[31,32,38,41]
		Lack of government support	[33,34,45]
		Lack of methodological approach for implementation	[37]
		Lack of a clear strategic roadmap for Industry 4.0	[34]
		Uncertainty in the new business model	[43]
		Lack of certification	[43]
		Lack of an integrated communication protocol	[29]

Source: Prepared by the authors based on the literature.

The challenges listed in Table 1 highlight the need for well-structured strategies for integrating sustainability through Industry 4.0 technologies, which requires concentrated efforts from stakeholders across sectors to establish standards, provide government support, and foster a conducive environment for the successful implementation of Industry 4.0 technologies, thereby helping to contribute to sustainable development.

3. Methodological Procedures

This study was conducted in four distinct stages: (a) literature review, focusing on constructs formed by challenges in the adoption of Industry 4.0 and their relationship with sustainability; (b) development of a data collection tool (questionnaire) for the research, based on the constructs identified in the literature review; (c) gathering of information through a questionnaire administered to industry professionals, using the Lawshe method for validation of constructs formed by challenges in the implementation of Industry 4.0, considering the perspective of industry professionals and their relationship with sustainability; (d) discussions and conclusion.

Initially, it is highlighted that the details of the literature review carried out and presented below were developed based on [64]. The three scientific databases taken into consideration during this stage of the literature review aimed to identify the constructs of sustainability in the presence of I4.0 technology; we used Science Direct, Web of Science, and Scopus. Specific terms and their relevant combinations were selected as keywords. For instance, the following terms were searched: “analyzing industry 4.0 implementation barriers”, “industry 4.0 adoption companies”, “industry 4.0 and implementation and challenges”, “industry 4.0 and sustainable development”, “industry 4.0 benefits”, “industry 4.0 definitions”, “industry 4.0 implementation barrier”, “industry 4.0 implementation sustainability and challenges”, “industry 4.0 implementation companies sustainable digital transformation”, “industry 4.0 implementations risks in manufacturing”, “industry 4.0 sustainability correlations”, “industry 4.0 implementation barrier”, “sdg guide”, “sdg un assessment industry”, “sustainability and industry professionals”, and “sustainability and industry”.

The results of this search resulted in a total of 78 articles; of these, only 58 articles were used in the review. Ten articles that were about Industry 4.0 but did not make a connection to sustainability and ten duplicate articles among the databases used in this stage were excluded. This approach allowed for cataloging and analyzing existing literature on the barriers faced in implementing Industry 4.0.

Subsequently, a questionnaire was developed based on the identified constructs, where industry professionals were asked to respond according to their perceptions using a 3-point scale: 1—It is essential to overcome these challenges to achieve sustainable development

goals in industry, 2—It is important but not essential to overcome these challenges to achieve sustainable development goals in industry, and 3—Overcoming these challenges is not important to achieve sustainable development goals in industry.

Professionals were invited to respond via emails and social media, with the questionnaire accessible through an online link generated on the Google Forms platform. A total of 230 invitations were sent, yielding a response rate of 14.35%. In terms of respondents' locations, 60.6% were from the North region, 15.2% from the South region, 3% from the Midwest region, and 21.2% from the Southeast region of Brazil. Among the respondents, 66.7% had 5 years or less of industry experience, 6.1% had 6 to 10 years, and 27.3% had 11 years or more of experience in the industry.

Upon collecting data through the survey administered to professionals, the Lawshe method was applied following the guidelines provided by Moreira et al. [65]. This method is based on administering questionnaires to professionals who evaluate each criterion in three distinct categories: “essential”, “important but not essential”, and “not important”. The methodological approach involves calculating the Content Validity Ratio (CVR) for each criterion of the questionnaire using the formula described in the literature, as per Equation (1).

$$\frac{ne - \frac{N}{2}}{\frac{N}{2}} = CRV \quad (1)$$

In the given context, the CVR values, ranging from -1 to $+1$, signify the extent of agreement among professionals regarding the essentiality of a criterion. The variable “ ne ” represents the number of professionals deeming the criterion as “Essential”, while “ N ” stands for the total number of professionals responding to the questionnaire [66]. A CVR of -1 implies perfect disagreement, and CVR of $+1$ indicates perfect agreement. To interpret the results, if over 50% of respondents view a criterion as “essential”, the CVR is positive. Conversely, if less than 50% consider the criterion as “not essential”, the CVR is negative. A CVR of zero implies a balanced perception, where half of the professionals find the criterion essential and the other half does not [67]. The critical $CVR_{critical}$ is a crucial parameter used to evaluate items potentially excluded in the final development due to CVR values falling below the critical limit. The calculation of $CVR_{critical}$ involves parameters such as mean, variance, and standard deviation, as per Equations (2)–(4).

$$\mu = nxp \quad (2)$$

$$\sigma^2 = nxpx(1 - p) \quad (3)$$

$$\sigma = \sqrt{nxpx(1 - p)} \quad (4)$$

The $CVR_{critical}$ is obtained through “ n ”, which represents the number of respondents, and “ p ”, which is the probability of considering the item as essential. Through these calculations, it is possible to determine the value of the critical $CVR_{critical}$ as per Equation (5).

$$CVR_{critical} = \frac{necritical - \frac{N}{2}}{\frac{N}{2}}, \text{ where } necritical = \mu + zx\sigma \quad (5)$$

Based on relevant literature and considering a significance level of 5% in the standard normal distribution, the value of z was adopted as 1.96. After the calculations, debates and analyses of the obtained results were conducted, leading to conclusions, as well as contributions to theory and practice along with suggestions for future research.

4. Results and Associated Debates

4.1. Construct Validation

Following the procedures outlined in the methods section, the calculation of the critical $CVR_{critical}$ was performed after determining the CVR values for each challenge examined in this study. It is important to note that the total sample for these calculations consisted of 34 professionals with expertise in the industrial context, all of whom were working in Brazil. The resulting critical $CVR_{critical}$ value was found to be 0.341. This coefficient was utilized in the validation analysis of the challenges. Consequently, challenges with a CVR coefficient exceeding 0.336 were deemed valid for the analyzed context. Conversely, challenges with a lower CVR coefficient were considered invalid for the industrial context of an emerging economy, taking into account the specificities of Industry 4.0. The outcomes of this study are summarized in Table 2.

Table 2. Validation of challenges via Lawshe’s method.

Code	“Essential” Number of Reviews	Content Validity Ratio (CVR)	CVRcritical Validation Reference: 0.341
C_01	26	0.575	✓
C_02	24	0.454	✓
C_03	28	0.696	✓
C_04	26	0.575	✓
C_05	17	0.030	X
C_06	9	−0.454	X
C_07	23	0.393	✓
C_08	19	0.151	X

4.2. Associated Debates

Analysis of Table 2 allows for the identification of validated constructs based on the opinions of experts in the industrial field operating in the Brazilian context. Therefore, to strengthen the implementation of Industry 4.0, considering the sustainability needs in an emerging economy, it is essential to focus efforts on overcoming the constructs of “Financial”, “technology”, “Organizational”, “Human Resources”, and “Internal Organization Factors”. This approach aims to direct efforts to critical areas and ensure that the transition to Industry 4.0 is effective and successful in the country’s industrial context.

Financial obstacles play a crucial role in the complex equation of adopting Industry 4.0 for the promotion of sustainability in the industry. The financial construct, formed by challenges identified by Bakhtari et al. [31], establishes notable connections between the author’s conclusions and the perceptions of professionals in the industrial sector extracted through this research. The significant entry barrier, manifested through substantial initial costs, emerges as a central concern. The uncertainty surrounding the return on investment in infrastructure adds a layer of complexity to this challenge, as recognized by Demirkesen and Tezel [32], emphasizing the urgent need for a detailed strategic analysis. Consistently, Ghadge et al. [33] underscore the imperative to address the lack of research and development practices in the context of Industry 4.0, a hurdle that must be overcome. To achieve successful implementation, there is a pressing need to dispel the lack of clarity surrounding financial benefits, an aspect that, as emphasized by Legg et al. [36], plays a central role in the adoption process. In this context, both literature and professional perspectives converge, highlighting the need for specialized training and deep awareness of the financial nuances of technologies, recognizing their impact on production processes.

The integration of Industry 4.0 consistently faces a series of technology challenges, a reality echoed in the contributions of Orzes et al. [37], Cordeiro et al. [38], Ghadge et al. [33], and Demirkesen and Tezel [32]. Underdeveloped information technology infrastructure, interoperability complexities, and lack of technology uniformity emerge as considerable weight barriers. As emphasized by Orzes et al. [37], tackling these challenges requires the development of a structured plan, an approach echoing the need for a meticulously

outlined strategy. Cordeiro et al. [38] emphasize the importance of information security and technology standardization, highlighting the need to focus on these critical areas. Ghadge et al. [33] highlight that the lack of a solid technology foundation can hinder the effective incorporation of innovations associated with Industry 4.0. This deficiency often materializes in the form of inadequate connectivity, limited communication systems, and substantial investment requirements for the modernization of existing infrastructures. Demirkesen and Tezel [32] stress the importance of data security and cybersecurity in the transition to Industry 4.0, as companies face threats related to the confidentiality and integrity of digital data. This, in turn, makes it imperative to adopt robust cybersecurity strategies and comply with constantly evolving regulations regardless of the company's profile or size, and the research results, based on industry professionals' perspectives, highlight convergence with the literature.

The implementation of Industry 4.0 brings a series of organizational challenges, as highlighted by various authors. Herceg et al. [39] underline a critical challenge, the lack of skills, which becomes even more evident in companies in the process of digital transformation. To overcome this obstacle, it is crucial not only to identify skill gaps but also to implement training plans to ensure that employees acquire the necessary competencies. Müller et al. [30] highlight two interconnected obstacles: cultural resistance and lack of experience. Resistance to change in organizations is a common barrier to adopting Industry 4.0, and this resistance is often fueled by a lack of previous experience with the involved technologies and processes. This experience gap makes specific skills a priority, as emphasized by Virmani et al. [41]. To overcome these challenges, organizations need to invest in training and personnel development.

The transition to Industry 4.0 implies a series of human resources challenges, and perspectives from specialized literature are enlightening in this regard. Szabo et al. [29] highlight the shortage of appropriate internal skills, competencies, and capabilities as a significant obstacle. The lack of professionals with the necessary skills to operate and manage Industry 4.0 technologies is a recurring theme. Learning and adapting to new technology paradigms are processes that take time and investment. The shortage of qualified human resources becomes a hindrance, complicating the effective implementation of innovations associated with Industry 4.0. Additionally, Virmani et al. [41] emphasize the importance of interpersonal skills and employee empowerment in the successful adoption of Industry 4.0. Interaction among team members and the ability to collaborate effectively are essential in this context. However, these skills are not easily acquired and can pose significant challenges. Another critical aspect is the concern for the mental health of employees during the transition to Industry 4.0, as pointed out by Kumar et al. [34]. Uncertainty, changes in the work environment, and demands arising from digital technology can contribute to an increase in mental health-related illnesses and issues. This concern is particularly relevant for Small and Medium Enterprises (SMEs), which may lack resources and robust employee well-being support structures. Müller [42] emphasizes that employees' adoption of Industry 4.0 can be hindered by fears related to potential job loss and uncertainties associated with the use of new technologies. Resistance to change, often rooted in organizational culture, is a factor worthy of consideration. Therefore, through this research, the concern with this construct is evident, both regarding the literature and the perspectives of professionals in the industrial sector.

The implementation of Industry 4.0 is permeated by internal challenges that can impact production efficiency and the transition to this paradigm. Among these challenges, low industry maturity, production fluctuations, lack of effective communication between management and workers, shortage of specialized consultants, and technology incompatibilities with companies' incentive systems are highlighted. In this context, Karadayi-Usta [44] agrees that the effectiveness of Industry 4.0 can be delayed due to delays in the transformation process, which emerge as a relevant barrier. Resistance to change and the need for adaptation by employees and managers can result in significant obstacles to implementing these innovations. Müller et al. [30] also emphasize the importance of flexibility

in organizations. The loss of flexibility is identified as a barrier to adopting Industry 4.0. Therefore, the need to improve companies' ability to adapt to changes in the business environment becomes evident. The shortage of expertise, as noted by Ghadge et al. [33], is another critical barrier to adopting Industry 4.0. The lack of specialized knowledge and skills needed to effectively implement and operate Industry 4.0 technologies is a significant difficulty that affects the adoption of these technologies. As a differential of this study, Figure 1 summarizes the axes of the main areas of challenges of Industry 4.0 to be overcome to promote sustainable development.

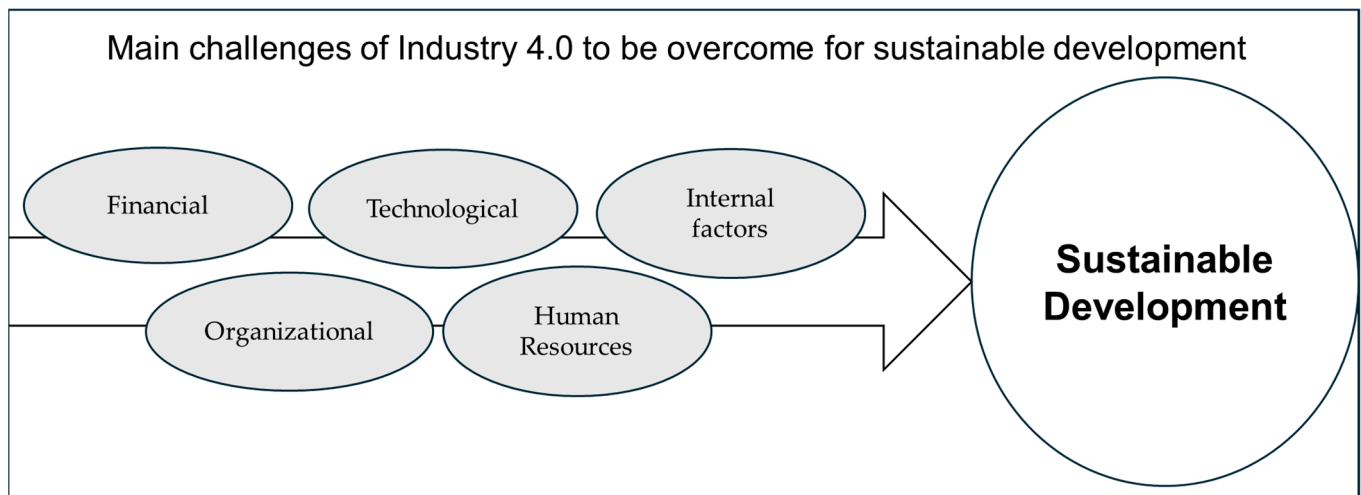


Figure 1. Main areas of challenges of Industry 4.0 for sustainable development. Source: Authors.

4.3. Managerial Implications

This research provides valuable information on the challenges companies encounter when adopting Industry 4.0 in the context of their sustainability goals, offering practical insights. The findings enable the identification of pragmatic solutions and strategies that industry managers can implement. These insights help managers understand specific challenges, ranging from necessary infrastructure to sustainability and ethical issues, allowing for the development of tailored solutions. Additionally, the study contributes to enhancing industry efficiency and competitiveness by guiding the overcoming of obstacles that hinder process optimization, cost reduction, and the development of more sustainable products and services. In the future, these findings can serve as foundations for implementing more sustainable practices in Industry 4.0, benefiting both the industry and the environment.

To address the challenges of adopting Industry 4.0 with a focus on sustainability goals, managers should prioritize several practical actions, such as assessing and investing in technological infrastructure, ensuring system interoperability, and enabling real-time data collection. Continuous employee training in new technologies is essential, fostering a culture of innovation. Simultaneously, more efficient and sustainable processes should be implemented, such as automation for energy savings and adopting circular economy practices. Monitoring sustainability-focused performance indicators through big data and advanced analytics is crucial for identifying operational improvements. Furthermore, innovation in products and services with lower environmental impact is necessary, alongside establishing a sustainable supply chain and partnerships with suppliers aligned with these principles. Risk management, including cybersecurity and ethical compliance, must be stringent, ensuring that the technologies used adhere to ethical and sustainable standards, thus promoting an efficient and environmentally beneficial transition for the industry.

5. Conclusions

This study identified constructs derived from the challenges of Industry 4.0 that impact the promotion of sustainability in the industry using the Lawshe method and experts'

opinions. The main objective was achieved by validating five out of eight constructs and a set of challenges faced by the industry in promoting sustainability in the context of Industry 4.0. To achieve this objective, constructs were formed based on the opinions of industry professionals, and these constructs were subjected to validation. The findings of this study contribute to a deeper understanding of the challenges encountered by industry professionals in their efforts to promote sustainability. Furthermore, the results provide valuable insights that can be utilized in developing strategies to effectively address these challenges, thereby fostering sustainability in the context of Industry 4.0.

Based on industry experts' opinions and the literature, the constructs validated were the following: Financial, Technology, Organizational, Human Resources, and Internal Factors. These constructs are pivotal in the context of Industry 4.0, particularly in the pursuit of promoting sustainability within an industry. The obtained results can assist organizations in understanding the challenges associated with sustainability and facilitate the formulation of future policies that encourage sustainable practices and support the adoption of Industry 4.0 in the industrial landscape. Furthermore, these results can aid in the development of internal policies that promote skill development, workforce training, and access to financial resources for companies seeking to adapt their production systems to Industry 4.0, enabling them to overcome challenges and incorporate sustainability-focused practices.

Regarding limitations, the exploratory nature of the research prevents the generalization of the results to other contexts. However, valuable industry insights were extracted from the survey. Nevertheless, future studies should conduct multiple case studies to understand the extent of these challenges in companies in the industrial sector in the Brazilian scenario. Additionally, a comparative analysis is proposed to comprehend how the challenges of Industry 4.0 impact sustainability, considering variations across different countries. This would allow for a more comprehensive understanding of the challenges faced by companies in adopting Industry 4.0 technologies and their implications for sustainability.

Author Contributions: Conceptualization, L.d.S.M. and R.M.F.; methodology, L.d.S.M.; software, D.R.d.L.N.; validation, R.M.F.; formal analysis, L.d.S.M.; resources, J.M.N.d.S.; data curation, R.M.e.s.d.O.; writing—original draft preparation, R.M.F.; writing—review and editing, R.M.e.s.d.O. and J.M.N.d.S.; visualization, D.R.d.L.N.; supervision, L.V.A. and V.W.B.M.; project administration, V.W.B.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study is exempt from Ethics Committee approval, in accordance with the Brazilian National Health Council's Resolution No. 510/2016. The research did not involve the collection of sensitive, clinical or identifiable data from the participants. Participation was voluntary, anonymous and consented.

Informed Consent Statement: Informed consent for participation was obtained from all subjects involved in the study.

Data Availability Statement: The database can be requested directly from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Culot, G.; Nassimbeni, G.; Orzes, G.; Sartor, M. Behind the definition of Industry 4.0: Analysis and open questions. *Int. J. Prod. Econ.* **2020**, *226*, 107617. [[CrossRef](#)]
2. Hernandez-de-Menendez, M.; Escobar Díaz, C.A.; Morales-Menendez, R. Engineering education for smart 4.0 technology: A review. *Int. J. Interact. Des. Manuf.* **2020**, *14*, 789–803. [[CrossRef](#)]
3. Bosman, L.; Hartman, N.; Sutherland, J. How manufacturing firm characteristics can influence decision making for investing in Industry 4.0 technologies. *J. Manuf. Technol. Manag.* **2019**, *31*, 1117–1141. [[CrossRef](#)]
4. Inkermann, D.; Schneider, D.; Martin, N.L.; Lembeck, H.; Zhang, J.; Thiede, S. A framework to classify Industry 4.0 technologies across production and product development. In Proceedings of the 29th CIRP Design Conference 2019, Póvoa de Varzim, Portugal, 8–10 May 2019; Putnik, G.D., Ed.; Elsevier: Amsterdam, The Netherlands, 2019; Volume 84, pp. 973–978. [[CrossRef](#)]

5. Noggerini, L.N.; Martins, V.W.B.; Rampasso, I.S.; Quelhas, O.L.G.; Leal Filho, W.; Anholon, R. Difficulties observed in hydroelectric turbine projects management: Evidence from case studies. *Kybernetes* **2022**, *51*, 3470–3486. [\[CrossRef\]](#)
6. Saxena, R.; Kishore, S.; Srivastava, V. Framing and control for sustainability of industries. *Technol. Sustain.* **2022**, *1*, 64–81. [\[CrossRef\]](#)
7. Kibe, L.; Kwanya, T.; Nyagowa, H. Harnessing fourth industrial revolution (4IR) technologies for sustainable development in Africa: A meta-analysis. *Technol. Sustain.* **2023**, *2*, 244–258. [\[CrossRef\]](#)
8. Pansare, R.; Yadav, G.; Garza-Reyes, J.A.; Raosaheb Nagare, M. Assessment of Sustainable Development Goals through Industry 4.0 and reconfigurable manufacturing system practices. *J. Manuf. Technol. Manag.* **2023**, *34*, 383–413. [\[CrossRef\]](#)
9. Yavuz, O.; Uner, M.M.; Okumus, F.; Karatepe, O.M. Industry 4.0 technologies, sustainable operations practices and their impacts on sustainable performance. *J. Clean. Prod.* **2023**, *387*, 135951. [\[CrossRef\]](#)
10. Khan, I.S.; Ahmad, M.O.; Majava, J. Industry 4.0 and sustainable development: A systematic mapping of triple bottom line, Circular Economy and Sustainable Business Models perspectives. *J. Clean. Prod.* **2021**, *297*, 126655. [\[CrossRef\]](#)
11. Al-Khatib, A.W. The impact of industrial Internet of things on sustainable performance: The indirect effect of supply chain visibility. *Bus. Process Manag. J.* **2023**, *29*, 1607–1629. [\[CrossRef\]](#)
12. Erboz, G.; Yumurtacı Hüseyinoğlu, I.Ö. The role of Industry 4.0 on supply chain cost and supply chain flexibility. *Bus. Process Manag. J.* **2023**, *29*, 1330–1351. [\[CrossRef\]](#)
13. Khodair, A. Key embrace factors for designing sustainable supply chains in Egyptian Industry 4.0. *Bus. Process Manag. J.* **2024**, *30*, 1111–1130. [\[CrossRef\]](#)
14. Ardito, L.; Petruzzelli, A.M.; Panniello, U.; Garavelli, A.C. Towards Industry 4.0. *Bus. Process Manag. J.* **2019**, *25*, 323–346. [\[CrossRef\]](#)
15. Bazan, P.; Estevez, E. Industry 4.0 and business process management: State of the art and new challenges. *Bus. Process Manag. J.* **2022**, *28*, 62–80. [\[CrossRef\]](#)
16. Deng, Y.; Zhang, S.; Xu, Y.; Zhang, X.; Zhou, W. Event-triggered optimal trajectory tracking control of underactuated ships based on goal representation heuristic dynamic programming. *Ocean Eng.* **2024**, *308*, 118251. [\[CrossRef\]](#)
17. Aravindaraj, K.; Rajan Chinna, P. A systematic literature review of integration of industry 4.0 and warehouse management to achieve Sustainable Development Goals (SDGs). *Clean. Logist. Supply Chain* **2022**, *5*, 100072. [\[CrossRef\]](#)
18. Rampasso, I.S.; Martins, V.W.B.; Pavan Serafim, M.; Cavaliero, C.K.N.; Gonçalves Quelhas, O.L.; Leal Filho, W.; Anholon, R. Brazilian contributions to the Sustainable Development Goal 7 and policy implications. *Kybernetes* **2022**, *51*, 3025–3040. [\[CrossRef\]](#)
19. Rasheed, M.; Liu, J.; Ali, E. Incorporating sustainability in organizational strategy: A framework for enhancing sustainable knowledge management and green innovation. *Kybernetes* **2024**. [\[CrossRef\]](#)
20. Von Geibler, J.; Piwowar, J.; Greven, A. The SDG-Check: Guiding Open Innovation towards Sustainable Development Goals. *Technol. Innov. Manag. Rev.* **2019**, *9*, 20–37. [\[CrossRef\]](#)
21. Hatayama, H. The metals industry and the Sustainable Development Goals: The relationship explored based on SDG reporting. *Resour. Conserv. Recycl.* **2022**, *178*, 106081. [\[CrossRef\]](#)
22. Villalba, F.Z.; Peinado, J.; Vianna, F.; Meneghetti, F. Industry 4.0: Technical qualifications for the fourth industrial revolution in Brazil. *Rev. Gest. Prod. Oper. Sist.* **2022**, *17*, 32. [\[CrossRef\]](#)
23. Zhou, B.; Zheng, L. Technology-pushed, market-pulled, or government-driven? The adoption of industry 4.0 technologies in a developing economy. *J. Manuf. Technol. Manag.* **2023**, *34*, 115–138. [\[CrossRef\]](#)
24. Nara, E.O.B.; da Costa, M.B.; Baierle, I.C.; Schaefer, J.L.; Benitez, G.B.; do Santos, L.M.A.L.; Benitez, L.B. Expected impact of industry 4.0 technologies on sustainable development: A study in the context of Brazil's plastic industry. *Sustain. Prod. Consum.* **2021**, *25*, 102–122. [\[CrossRef\]](#)
25. Bhanot, N.; Rao, P.V.; Deshmukh, S.G. Enablers and Barriers of Sustainable Manufacturing: Results from a Survey of Researchers and Industry Professionals. *Procedia CIRP* **2015**, *29*, 562–567. [\[CrossRef\]](#)
26. Mineiro, M. Pesquisa De Survey E Amostragem: Aportes Teóricos Elementares Survey and Sampling Research: Elementary Theoretical Contributions Investigación De Survey Y Muestreo: Aportes Teóricos Elementales. *Rev. Estud. Educ. E Divers. REED* **2020**, *1*, 284–306.
27. De Souza, V.H.; Satyro, W.; Contador, J.C.; Pinto, L.F.; Mitidiero, M.C. The Technology Analysis model—TAM 4.0 for implementation of Industry 4.0. *Int. J. Ind. Eng. Manag.* **2023**, *14*, 271–281. [\[CrossRef\]](#)
28. Rabelo, R.J.; Zambiasi, S.P.; Romero, D. Softbots 4.0: Supporting Cyber-Physical Social Systems in Smart Production Management. *Int. J. Ind. Eng. Manag.* **2023**, *14*, 63–94. [\[CrossRef\]](#)
29. Szabo, R.Z.; Vuksanović Herceg, I.; Hanák, R.; Hortovanyi, L.; Romanová, A.; Mocan, M.; Djuričin, D. Industry 4.0 Implementation in B2B Companies: Cross-Country Empirical Evidence on Digital Transformation in the CEE Region. *Sustainability* **2020**, *12*, 9538. [\[CrossRef\]](#)
30. Müller, J.M.; Kiel, D.; Voigt, K.-I. What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability. *Sustainability* **2018**, *10*, 247. [\[CrossRef\]](#)
31. Bakhtari, A.R.; Waris, M.M.; Sanin, C.; Szczerbicki, E. Evaluating Industry 4.0 Implementation Challenges Using Interpretive Structural Modeling and Fuzzy Analytic Hierarchy Process. *Cybern. Syst.* **2021**, *52*, 350–378. [\[CrossRef\]](#)
32. Demirkesen, S.; Tezel, A. Investigating major challenges for industry 4.0 adoption among construction companies. *Eng. Constr. Archit. Manag.* **2022**, *29*, 1470–1503. [\[CrossRef\]](#)

33. Ghadge, A.; Er Kara, M.; Moradlou, H.; Goswami, M. The impact of Industry 4.0 implementation on supply chains. *J. Manuf. Technol. Manag.* **2020**, *31*, 669–686. [\[CrossRef\]](#)
34. Kumar, G.; Bakshi, A.; Khandelwal, A.; Panchal, A.; Soni, U. Analyzing Industry 4.0 Implementation Barriers in Indian SMEs. *J. Ind. Integr. Manag.* **2022**, *7*, 153–169. [\[CrossRef\]](#)
35. Kumar, V.; Vrat, P.; Shankar, R. Prioritization of strategies to overcome the barriers in Industry 4.0: A hybrid MCDM approach. *Opsearch* **2021**, *58*, 711–750. [\[CrossRef\]](#)
36. Legg, B.; Dorfner, B.; Leavengood, S.; Hansen, E. Industry 4.0 Implementation in US Primary Wood Products Industry. *Drv. Ind.* **2021**, *72*, 143–153. [\[CrossRef\]](#)
37. Orzes, G.; Rauch, E.; Bednar, S.; Poklemba, R. Industry 4.0 Implementation Barriers in Small and Medium Sized Enterprises: A Focus Group Study. In Proceedings of the 2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Bangkok, Thailand, 16–19 December 2018; pp. 1348–1352.
38. Cordeiro, G.A.; Ordóñez, R.E.C.; Ferro, R. Theoretical proposal of steps for the implementation of the Industry 4.0 concept. *Brazilian J. Oper. Prod. Manag.* **2019**, *16*, 166–179. [\[CrossRef\]](#)
39. Herceg, I.V.; Kuč, V.; Mijušković, V.M.; Herceg, T. Challenges and Driving Forces for Industry 4.0 Implementation. *Sustainability* **2020**, *12*, 4208. [\[CrossRef\]](#)
40. Satyro, W.C.; de Almeida, C.M.V.B.; Pinto, M.J.A., Jr.; Contador, J.C.; Giannetti, B.F.; de Lima, A.F.; Fragomeni, M.A. Industry 4.0 implementation: The relevance of sustainability and the potential social impact in a developing country. *J. Clean. Prod.* **2022**, *337*, 130456. [\[CrossRef\]](#)
41. Virmani, N.; Salve, U.R.; Kumar, A.; Luthra, S. Analyzing Roadblocks of Industry 4.0 Adoption Using Graph Theory and Matrix Approach. *IEEE Trans. Eng. Manag.* **2023**, *70*, 454–463. [\[CrossRef\]](#)
42. Müller, J.M. Assessing the barriers to Industry 4.0 implementation from a workers’ perspective. *IFAC-PapersOnLine* **2019**, *52*, 2189–2194. [\[CrossRef\]](#)
43. Ghadimi, P.; Donnelly, O.; Sar, K.; Wang, C.; Azadnia, A.H. The successful implementation of industry 4.0 in manufacturing: An analysis and prioritization of risks in Irish industry. *Technol. Forecast. Soc. Chang.* **2022**, *175*, 121394. [\[CrossRef\]](#)
44. Karadayi-Usta, S. An Interpretive Structural Analysis for Industry 4.0 Adoption Challenges. *IEEE Trans. Eng. Manag.* **2020**, *67*, 973–978. [\[CrossRef\]](#)
45. Goswami, M.; Daultani, Y. Make-in-India and Industry 4.0: Technology readiness of select firms, barriers and socio-technical implications. *TQM J.* **2022**, *34*, 1485–1505. [\[CrossRef\]](#)
46. Kumar, V.; Vrat, P.; Shankar, R. A Graph-Theoretic Approach to Evaluate the Intensity of Barriers in the Implementation of Industry 4.0. *Int. J. Innov. Technol. Manag.* **2021**, *18*, 2150039. [\[CrossRef\]](#)
47. Jamwal, A.; Agrawal, R.; Sharma, M.; Kumar, V.; Kumar, S. Developing A sustainability framework for Industry 4.0. *Procedia CIRP* **2021**, *98*, 430–435. [\[CrossRef\]](#)
48. Beltrami, M.; Orzes, G.; Sarkis, J.; Sartor, M. Industry 4.0 and sustainability: Towards conceptualization and theory. *J. Clean. Prod.* **2021**, *312*, 127733. [\[CrossRef\]](#)
49. Dieste, M.; Sauer, P.C.; Orzes, G. Organizational tensions in industry 4.0 implementation: A paradox theory approach. *Int. J. Prod. Econ.* **2022**, *251*, 108532. [\[CrossRef\]](#)
50. Kumar, V.; Vrat, P.; Shankar, R. Factors Influencing the Implementation of Industry 4.0 for Sustainability in Manufacturing. *Glob. J. Flex. Syst. Manag.* **2022**, *23*, 453–478. [\[CrossRef\]](#)
51. Hajoary, P.K.; MA, A.; Garza-Reyes, J.A. Industry 4.0 maturity assessment: A multi-dimensional indicator approach. *Int. J. Product. Perform. Manag.* **2023**. [\[CrossRef\]](#)
52. Jain, V.; Ajmera, P. Modelling the enablers of industry 4.0 in the Indian manufacturing industry. *Int. J. Product. Perform. Manag.* **2021**, *70*, 1233–1262. [\[CrossRef\]](#)
53. Yunus, E.N. The mark of industry 4.0: How managers respond to key revolutionary changes. *Int. J. Product. Perform. Manag.* **2021**, *70*, 1213–1231. [\[CrossRef\]](#)
54. Krishnan, S.; Gupta, S.; Kaliyan, M.; Kumar, V.; Garza-Reyes, J.A. Assessing the key enablers for Industry 4.0 adoption using MICMAC analysis: A case study. *Int. J. Product. Perform. Manag.* **2021**, *70*, 1049–1071. [\[CrossRef\]](#)
55. Bettiol, M.; Capestro, M.; Di Maria, E.; Micelli, S. Disentangling the link between ICT and Industry 4.0: Impacts on knowledge-related performance. *Int. J. Product. Perform. Manag.* **2022**, *71*, 1076–1098. [\[CrossRef\]](#)
56. Jena, A.; Patel, S.K. A hybrid fuzzy based approach for industry 4.0 framework implementation strategy and its sustainability in Indian automotive industry. *J. Clean. Prod.* **2023**, *420*, 138369. [\[CrossRef\]](#)
57. Agarwal, S.; Tyagi, M.; Garg, R.K. Conception of circular economy obstacles in context of supply chain: A case of rubber industry. *Int. J. Product. Perform. Manag.* **2023**, *72*, 1111–1153. [\[CrossRef\]](#)
58. Horváth, D.; Szabó, R.Z. Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities? *Technol. Forecast. Soc. Chang.* **2019**, *146*, 119–132. [\[CrossRef\]](#)
59. Nagy, S.J.; Szabo, R.; Vajda, M.L.; Voros, A. Demonstrator for dependable edge-based cyber-physical systems. In Proceedings of the 2021 10th Latin-American Symposium on Dependable Computing (LADC 2021), Virtual, 22–26 November 2021.
60. Yadav, G.; Kumar, A.; Luthra, S.; Garza-Reyes, J.A.; Kumar, V.; Batista, L. A framework to achieve sustainability in manufacturing organisations of developing economies using industry 4.0 technologies’ enablers. *Comput. Ind.* **2020**, *122*, 103280. [\[CrossRef\]](#)

61. Agrawal, R.; Wankhede, V.A.; Kumar, A.; Luthra, S.; Huisingh, D. Progress and trends in integrating Industry 4.0 within Circular Economy: A comprehensive literature review and future research propositions. *Bus. Strateg. Environ.* **2022**, *31*, 559–579. [[CrossRef](#)]
62. Veile, J.W.; Kiel, D.; Müller, J.M.; Voigt, K.-I. Lessons learned from Industry 4.0 implementation in the German manufacturing industry. *J. Manuf. Technol. Manag.* **2019**. *ahead-of-print*. [[CrossRef](#)]
63. Narula, S.; Puppala, H.; Kumar, A.; Frederico, G.F.; Dwivedy, M.; Prakash, S.; Talwar, V. Applicability of industry 4.0 technologies in the adoption of global reporting initiative standards for achieving sustainability. *J. Clean. Prod.* **2021**, *305*, 127141. [[CrossRef](#)]
64. Rakic, S.; Medic, N.; Leoste, J.; Vuckovic, T.; Marjanovic, U. Development and Future Trends of Digital Product-Service Systems: A Bibliometric Analysis Approach. *Appl. Syst. Innov.* **2023**, *6*, 89. [[CrossRef](#)]
65. Moreira, P.A.; Fernandes, R.M.; Avila, L.V.; Bastos, L.d.S.L.; Martins, V.W.B. Artificial Intelligence and Industry 4.0? Validation of Challenges Considering the Context of an Emerging Economy Country Using Cronbach's Alpha and the Lawshe Method. *Eng* **2023**, *4*, 2336–2351. [[CrossRef](#)]
66. Ayre, C.; Scally, A.J. Critical values for Lawshe's content validity ratio: Revisiting the original methods of calculation. *Meas. Eval. Couns. Dev.* **2014**, *47*, 79–86. [[CrossRef](#)]
67. Lawshe, C.H. A quantitative approach to content validity. *Pers. Psychol.* **1975**, *28*, 563–575. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.