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Prioritizing barriers for the adoption of Industry 4.0 technologies

Pedro P. Senna [a,b,*], Luís Miguel D.F. Ferreira [c], Ana C. Barros [b], Jaime Bonnín Roca [d], Vanessa Magalhães [c]

[a] Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[b] INESC TEC, Centre for Enterprise Systems Engineering, Campus, FEUP, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[c] University of Coimbra, CEMMPRE, Department of Mechanical Engineering, Portugal
[d] Eindhoven University of Technology, Department of Industrial Engineering & Innovation Sciences, Eindhoven, the Netherlands

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ABSTRACT

While Industry 4.0 promises large technological improvements, firms face multiple challenges in its adoption. Current literature has made significant efforts to identify the barriers which are common to most companies but fails to identify their interrelationships and their implications for practitioners. We use interpretive structural modelling (ISM) methodology to identify these barriers and their interrelationships, combined with matrix impact of cross multiplication applied to classification (MICMAC) analysis to identify the root barriers, in the context of the Portuguese manufacturing industry. We categorize these barriers using the Technology-Organization-Environment framework. We conclude that barriers related to standardization and lack of off-the-shelf solutions are considered root barriers. Our results differ from other studies that regard barriers related to legal and contractual uncertainty with the highest driving power and lowest dependence power. Also, we find that organizational barriers have the highest dependency and lowest driving power, contradicting studies on the topic. We provide recommendations for managers and policymakers in three areas: Standardization Dissemination, Infrastructure Development, and Digital Strategy.

1. Introduction

Industry 4.0 requires a shift of the companies' decision-making focus from the development of technologies to the adoption and implementation decision of integrated, interoperable technologies (Kagermann, Wahlster, & Helbig, 2013). Industry 4.0 (I4.0) is based on the widespread implementation of cyber-physical systems (CPS), which are heterogeneous computational systems and bear communication capabilities achieved by means of the Internet of Things (IoT; Kamble, Gunasekaran and Sharma 2018) combined with an array of digital technologies, such as big data and analytics (Frank, Dalenogare, & Ayala, 2019), augmented reality (Rejeb, Keogh, Keong Leong, & Treiblmaier, 2021), simulation (Wang, Gunasekaran, Ngai, & Papadopoulos, 2016), and artificial intelligence (Sahu, Young, & Rai, 2020).

The adoption and implementation of I4.0 technologies have been difficult, due to barriers of adoption faced by manufacturing companies, such as low maturity level of digital technologies in the industry, as well as the existing multiplicity of equipment within the factory, acquired from a variety of suppliers, with various communication capabilities (Wang et al., 2016). In fact, the integration of various equipment into a single ecosystem has been in the centre of discussion regarding barriers to adopt I4.0 technologies (Kiraz, Canpolat, Özkurt, & Taşkın, 2020), where standardization requirements are deemed core concern (Kamble, Gunasekaran, & Sharma, 2018; Raj, Dwivedi, Sharma, de Sousa Jabbour, & Rajak, 2020). The overwhelming number of communications established between IoT devices requires high levels of cybersecurity measures (Kiel, Arnold, & Voigt, 2017; Stentoft, Wickstrøm, Philipsen, & Haug, 2020), as well as organizational efforts for enhancing focused training (Sony & Subhash, 2019) and positive adoption by the workforce (Karadayi-Usta, 2019).

Several empirical studies have identified barriers to the adoption of I4.0 technologies through an empirical approach (Calabrese, Ghiron, & Tiburzi, 2020; Kamble et al., 2018; Raj et al., 2020). However, these studies do not connect their empirical findings to a theoretical lens which could explain the structure, the categorization and prioritization of barriers. In addition, studies aimed at prioritizing barriers to adoption

* Corresponding author at: INESC TEC – Campus da FEUP, Rua Dr. Roberto Frias, S/N, 4200-465 Porto, Portugal.
E-mail addresses: pedro.senna@inesctec.pt, up201708818@fe.up.pt (P.P. Senna), luis.ferreira@dem.uc.pt (L.M.D.F. Ferreira), abarros2222@gmail.com (A.C. Barros), j.bonnin.roca@tue.nl (J. Bonnín Roca), vanessa.magalhaes@dem.uc.pt (V. Magalhães).

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have typically focused on specific technologies, such as the IoT (Kamble, Gunasekaran, Parekh, & Joshi, 2019; Singh & Bhanot, 2019) or blockchain technology (Mathivathanan, Mathiyazhagan, Rana, Khorana, & Dwivedi, 2021) and do not consider the interdependencies with other I4.0 technologies. Furthermore, previous studies emphasize the technological (Kamble et al., 2018; Wang et al., 2016; Flatt, Schriegel, Jasperneite, Trsek, & Adamczyk, 2016) and organizational contexts (Ghadge, Kara, Moradlou, & Goswami, 2020; Raj et al., 2020), with little emphasis on barriers related to the environmental context where technologies are adopted. We use the literature review as a starting stage for identifying and categorizing barriers to the adoption of I4.0 technologies, structured according to the Technology-Organization-Environment (TOE) framework (Tornatzky, Fleischer, & Chakrabarti, 1990).

To fill existing gaps in the literature, this paper sets out to define the interrelationships between the barriers to adopt Industry 4.0 technologies and their prioritization for the Portuguese manufacturing industry. The country is an early adopter of Industry 4.0, currently going through the second phase of its National I4.0 Initiative "Indústria 4.0" (República Portuguesa, 2021). We use Interpretive Structural Modelling (ISM) and Matrix Impact of Cross Multiplication Applied to Classification (MICMAC) to study the interrelationship between the barriers. We provide implications for managers and policy makers to overcome them. The contribution to the literature is three-fold: first, it provides a theoretical classification of barriers based on the Technology-Organization-Environment framework; second, it provides the interrelationships between the barriers to adopt I4.0 technologies and identification of root causes; and third, it provides concrete implications for managers and policy makers that aid in the adoption of I4.0 technologies. Our results suggest that barriers from the environmental context, neglected by previous studies (Kamble et al., 2018; Ghadge et al., 2020; Raj et al., 2020), may constitute the most important barriers to adoption of I4.0 technologies.

2. Theoretical background

2.1. Industry 4.0 concept

The digital transformation of enterprises, currently developing through Industry 4.0 (I4.0) initiatives, promises to revolutionize their systems regarding cost reductions and expansion of business opportunities. I4.0 started as a German strategic initiative with intent to create smart factories that boast a wide range of digital technologies, such as big data analytics, IoT, additive manufacturing, virtual reality, and robotic systems (Dalenogare, Benitez, Ayala, & Frank, 2018). Following the German I4.0 strategic initiative announcement, other governments and industries worldwide have launched strategic programs to develop manufacturing capabilities in order to support the market growth and take advantage of the new industrial revolution wave. A few prominent examples of current national initiatives according to the European Commission Digital Transformation Monitor are (Commission, 2019): (i) the French "Industrie du futur"; (ii) the Italian "Industria 4.0"; (iii) the Portuguese "Indústria 4.0"; and (iv) the British "HVM Catapult".

I4.0 aims to create a smart, interconnected value chain (Schumacher, Erol, & Sihn, 2016) through digital technologies that allow for the integration of physical objects, virtual models and services (Xu, Xu, & Li, 2018). Interconnectivity is at the very centre of I4.0, with a shift in the production paradigm due to the increasing digitalization of the value chain and real-time data exchange among connected actors, objects, and systems (Schumacher et al., 2016). The production process is expected to be controlled, monitored, and improved in real-time through constant analysis of information gathered from IoT devices into embedded and connected systems (Ghobakhloo, 2020).

As such, the I4.0 concept goes beyond simple changes in the manufacturing process, requiring a socio-technical evolution from workforce towards an intelligent approach to manufacturing (Frank et al., 2019; Ghobakhloo, 2020; Stock, Obenaus, Kunz, & Kohl, 2018). This approach is supported by nine digital technologies: autonomous robots (Wisskirchen et al., 2017); simulation (Wang et al., 2016); systems integration (Gartner, 2019); IoT (Ben-Daya, Hassini, & Bahroun, 2019; Haddud, DeSouza, Khare, & Lee, 2017); cybersecurity (Kiel et al., 2017); cloud computing (Lu, 2017); additive manufacturing (Rengier et al., 2010), augmented reality (Rejeb et al., 2021); big data and analytics (Frank et al., 2019).

I4.0 technologies are also a critical pillar in the digitalization of supply chains (Büyüközkan & Göçer, 2018). Digital transformation has been transforming firms' organizational and strategic models. It requires reconfiguration of business processes, operational routines and organizational capabilities and it is affecting directly supply chains and its management (Horváth & Szabó, 2019). In fact, I4.0 technologies contribute to improved integration, analytics, automation, and reconfiguration of supply chain processes (Büyüközkan & Göçer, 2018; Ghadge et al., 2020). Communication downstream and upstream is enhanced through increased transparency and visibility (Ghobakhloo, 2018). Cost might be drastically reduced due to improved production and delivery times (Frederico, Garza-Reyes, Anosike, & Kumar, 2019), and product and service added value from customers and suppliers through continuous improvement and near real time feedback loops (Büyüközkan & Göçer, 2018; Frederico et al., 2019.) However, digitalization of supply chains may face high financial costs, lack of management support, and lack of skills, legal issues, lack of policies and lack of support from the government (Büyüközkan & Göçer, 2018; Ghadge et al., 2020; Ghobakhloo, 2018).

The implementation of technologies from the I4.0 concept involves strategic processes of different hierarchical levels, which relate to a company's technological development capabilities regarding planning, management, control, and coordination activities (Dalmarco & Barros, 2018). For a successful implementation of digital technologies, companies must undergo three major stages of implementation (Rogers, 2003): (i) the decision-making process to adopt a new technology by a restricted group of practitioners and experts; (ii) the implementation stage that focuses on starting the inclusion process of technology into the routine operations, while also considering the symbiosis required between the adopter and the technology in terms of operations fit and expected outcomes; and, (iii) the assimilation stage, which requires the routinization and incorporation of technology on its full working conditions, thus losing the external characteristics since it is being absorbed as an ongoing element on operation processes by the adopter (Rogers, 2003).

A well-established theoretical lens may help when proposing suggestions of implications to managers and policy makers for overcoming the barriers. This study uses the Technology-Organization-Environment (TOE) framework (Tornatzky et al., 1990) to identify and characterize the barriers to the adoption of I4.0.

2.2. Technology-Organization-Environment framework

Proposed by Tornatzky et al. (1990), the Technology-Organization-Environment framework (TOE) is aimed at studying technological innovation in the context of organizations. TOE incorporates environment constructs to provide a holistic view of the organization's adoption challenges and factors (Hossain & Quaddus, 2011; Oliveira & Martins, 2011). While traditional adoption theory frameworks (i.e., Technology Acceptance Model – TAM and Theory of Reasoned Action - TRA) have a technological focus when considering the determinants of organizations' structure and behaviour (Venkatesh, Davis, & Morris, 2007), TOE emphasises both the social aspects and the role of environmental factors to understand the organization's condition and technological characteristics (Awa, Ukoha, & Emecheta, 2016). In the industrial context, TOE has been used to study the adoption of Enterprise Resource Planning systems (Awa et al., 2016), business analytics (Ramanathan, Philpott, Duan, & Cao, 2017), blockchain (Saberi, Kouhizadeh, Sarkis, & Shen, 2019), and Big Data (Sun, Cegielski, Jia, & Hall, 2018).

Hence, according to TOE, a decision to adopt an innovation is made based on technological context, organizational context, and environmental context (Tornatzky et al., 1990). The technological context regards technologies within the organization that address vertical and horizontal integration, as well as those that regard the communication and exchange of information with external actors to the company (Awa et al., 2016). This context is comprised of many factors, such as technological complexity and the compatibility with existing equipment (Tornatzky et al., 1990). The organizational context comprises the descriptive measures of the organization, for instance the company's size, complexity of managerial structure, financial availability, and quality of workforce (Tornatzky et al., 1990; Awa et al., 2016). The environmental context considers the context in which an organization is established and conducts its business. It regards factors such as the business complexity, relationships between clients and suppliers, and technological trends (Tornatzky et al., 1990).

The environmental context is notoriously neglected within literature given the difficulty to assess all direct and indirect factors (Simões et al., 2019). Yet, these external factors are related to impactful barriers to adopt I4.0 (Bueno, Godinho Filho, & Frank, 2020). Among these are the presence of technology service providers and the regulatory environment (Baker, 2012). Regulations and government support are key factors in the adoption process of some digital technologies, such as Radio Frequency Identification (Shi & Yan, 2016), IoT (Haddud et al., 2017) and Enterprise Resource Planning systems (Raj et al., 2020). Other environmental factors that have significant impact on the decision-making process of technology adoption are customer readiness (Hwang, Huang, & Wu, 2016), trading partner collaboration (Low, Chen, & Wu, 2011), and trust (Shi & Yan, 2016).

2.3. Barriers to the adoption of I4.0 technologies

The production paradigm brought by I4.0 requires organizational changes under high levels of uncertainty (Kamble et al., 2018). This scenario is driving researchers to identify and understand the barriers faced by companies that attempt to adopt I4.0. Nevertheless, the current research on the topic has been widespread and focused on particular technologies or contexts, without attempting a broader, more holistic approach. Previous studies have focused on identifying barriers of specific I4.0 technologies, such as blockchain (Kamble, Gunasekaran, & Arha, 2019; Saberi et al., 2019) or IoT (Haddud et al., 2017; Kamble et al., 2019); of a specific context within manufacturing industry, such as automotive (Kannan et al., 2017); or of a specific set of companies, e.g., Small and Medium Enterprises (SMEs; Horváth & Szabó, 2019). We identified 14 barriers to the adoption of industry 4.0 within the reviewed literature, which were classified according to the TOE dimensions and portrayed in Table 1.

The organization's internal processes, as well as its strategy, culture, and workforce, should be considered when undergoing the adoption process of I4.0 technologies (Horváth & Szabó, 2019; Kiel et al., 2017). Adopting new technological procedures and/or methods requires a shift in the human resources' mindset. Studies have observed that a lack of skilled workforce and a natural resistance to changes in the work environment can be detrimental to the adoption of the I4.0 technologies (Kiel et al., 2017; Kamble et al., 2018; Karadayi-Usta, 2019; Sony & Subhash, 2019). There is an increasing need to continuously promote the retraining of staff to adapt to ever changing circumstances and work ethics (Moeuf et al., 2020).

All these interventions require organizational and process changes (Kiel et al., 2017; Kamble et al., 2018; Karadayi-Usta, 2019). These incurs additional investments by companies, which are seen as critical barriers to adoption by a few authors (Kiel et al., 2017; Erol et al., 2016). Nevertheless, given that some technological improvements can be achieved with minimal financial investments due to being developed in-house, other authors argue that such component is secondary to more technologically grounded barriers, e.g. technological integration (Kiel

Table 1
Summary of barriers to adoption - I4.0. The right-most column specifies that the identified barriers is related to one of the (T) Technology – (O) Organization – (E) Environment dimensions.

#	Barrier	Definition	TOE
1	**Need for High Level of Investments** (Ghadge et al., 2020; Kamble et al., 2018; Karadayi-Usta, 2019; Lee & Lee, 2015; Stentoft & Rajkumar, 2020)	Organizations need to incur in high capital expenditures to develop I4.0 infrastructure. SMEs are particularly affected by investment. Emerging technologies have increased risk due to potential financial losses and unrealized return on investments.	O
2	**Need for Adaptive Modifications at Organizational and Process Levels** (Barros et al. 2017; Fantini, Pinzone, & Taisch, 2020; Haddud et al., 2017; Karadayi-Usta, 2019; Müller et al., 2018)	The implementation of digital technologies requires process and organizational changes within companies. The rise of decentralized organizations, the use of autonomous robotics leading to organizational changes, and IoT solutions that present internal and external integration challenges, are examples of the required adaptive modifications.	O
3	**Lack of Qualified Workforce** (Dalmarco, Ramalho, Barros, & Soares, 2019; Fantini et al., 2020; Karadayi-Usta, 2019; Stentoft & Rajkumar, 2020)	Workforce skills, higher education requirements and special qualifications are paramount to deal with I4.0 technologies, both during and after the implementation stage. The full integration of I4.0 technologies relies on a multidisciplinary workforce with highly developed soft and hard skills.	O
4	**Lack of knowledge management systems and data knowledge** (Barros et al. 2017; Kamble et al., 2018; Karadayi-Usta, 2019; Stentoft & Rajkumar, 2020)	Existing systems are not capable of handling real-time data, thus requiring more robust knowledge management systems to be implemented. These embedded systems store and retrieve knowledge, can locate knowledge sources through repository mining, enhance knowledge management processes and are capable of integrating with embedded IoT components.	T
5	**Lack of clear comprehension about IoT benefits** (Kamble et al., 2018; Lee & Lee, 2015; Stentoft & Rajkumar, 2020)	When fully implemented, IoT devices should, theoretically, incur in potential financial gains for enterprises. Nevertheless, the lack of understanding about the IoT capabilities, benefits, value creation, delivery, and data gathering & analysis, lead to poor implementation of IoT devices and to financial losses.	O
6	**Lack of Standardization Efforts** (Kamble et al., 2018; Karadayi-Usta, 2019; Schroeder et al., 2019; Stentoft & Rajkumar, 2020; Stentoft et al. 2020; Xu et al., 2018)	There is a need for standards that are both comprehensive and widespread among equipment manufacturers to foster the production and implementation of I4.0-enabled componentry. SMEs are particularly affected by this gap, given that promoting retrofitting and integration of smart machinery is costly without standardized approaches.	E
7	**Need for Adaptive Retrofitting Implementation** (Arnold, Kiel, & Voigt, 2016; Müller et al., 2018; Stock & Seliger, 2016)	Widespread implementation of I4.0, coupled with interoperability concerns, bring forth the need for transforming existing equipment into CPS-	T

(continued on next page)

Table 1 (*continued*)

#	Barrier	Definition	TOE
		enabled machinery, known as the retrofitting process. The integration of I4.0-related technologies with current organizational hierarchies, architectures, structures, production, and logistics systems bears high levels of complexity and investment that hinder companies from achieving the full digital transformation.	
8	**Lack of Communication and IT Infrastructures** (Karadayi-Usta, 2019; Kiraz et al., 2020; Xu et al., 2018)	Implementation of I4.0 technologies requires robust IT and Communication infrastructures, since it relies on real-time data gathering, analysis and dissemination, all of which are enabled by IoT.	E
9	**Need to consider Security, Safety and Privacy Issues** (Dalmarco & Barros, 2018; Dalmarco et al., 2019; Kamble et al., 2018; Stentoft & Rajkumar, 2020; Xu et al., 2018)	Cyber-attacks are expected to be a rising issue given the data generated and distributed among companies by CPS and IoT devices, especially those related to communications: identification verification, authorization procedures and protocols, privacy, and system access.	T
10	**Lack of Seamless integration and Interoperability Capabilities** (Barros et al. 2017; Flatt et al., 2016; Pedone & Mezgár, 2018)	Establishment of integration and interoperability between existing equipment and new machinery, with focus on the different technologies and network systems. Retrieval of available data from the IoT devices and seamless integration are cumbersome, due to identification requirements surrounding memory segmentation and logical knowledge of lifecycle procedures.	T
11	**Lack of Regulatory Framework** (Ghadge et al., 2020; Kamble et al., 2018; Stentoft et al. 2020)	IT security, cybersecurity, human–machine interaction and integration, and human-resources laws become increasingly more important for organizations, which must provide stricter internal regiments, codes of conduct and overall procedural rules.	E
12	**Lack of Legal and Contractual Assurances** (Ghadge et al., 2020; Kamble et al., 2018; Stentoft et al. 2020)	The presence of a virtual environment and a virtual organization impose the need for legal and contractual assurances that considers the virtual part of organizations as legally viable and identifiable, thus comprising a legally independent entity.	E
13	**Lack of off-the-shelf solutions** (Barros et al. 2017)	Current digital technologies still lack additional development for full deployment in terms of off-the-shelf solutions. This is aggravated by the need to fully integrate the solutions with the legacy systems, to achieve real-time information management and to allow for full interoperability with systems and data analytics services.	T
14	**Lack of Digital Strategy** (Ghadge et al., 2020; Müller et al., 2018; Stentoft & Rajkumar, 2020)	There is an increasing need for development and deployment of digital strategies that consider the vertical and horizontal aspects of the value chain. This means that the digital strategy must consider the integration with various IT systems, where compatibility and interoperability are the key aspects.	O

et al., 2017) and adaptive retrofitting (Zhou et al., 2017).

Additional barriers that have received attention from researchers are: lack of clear comprehension about IoT benefits (Haddud et al., 2017; Lee & Lee, 2015; Kamble et al., 2018); lack of communication and Information Technology (IT) infrastructures (Kamble et al., 2018; Karadayi-Usta, 2019) and lack of a digital strategy (Müller, Kiel, & Voigt, 2018). Moreover, adoption of I4.0 involves integration and interoperability requirements that amplify the level of complexity and risk management required for its successful implementation (Jbair, Ahmad, Ahmad, & Harrison, 2018; Horváth & Szabó, 2019; Kiraz et al., 2020). There are growing concerns regarding data security (Kiraz et al., 2020; Schroeder, Bigdeli, Zarco, & Baines, 2019; Stentoft & Rajkumar, 2020), poor knowledge of systems architecture (Flatt et al., 2016; Barros, Simões, Toscano, Marques, Rodrigues, & Azevedo, 2017), and lack of knowledge management systems (Barros et al. 2017; Müller et al., 2018; Kamble et al., 2018; Karadayi-Usta, 2019).

Existing literature misses an identification of root barriers and analysis of the interrelationships among the barriers to adopt I4.0. To fill this gap, we present an approach based on Interpretive Structural Modelling combined with Matrix Impact of Cross Multiplication Applied to Classification methodologies to depict the interrelationships between the identified barriers.

3. Research method

The research question guiding this study is: *What are the interrelationships between the barriers to adopt digital technologies in the manufacturing industry?* To answer this question, we have defined the research process and subsequent steps necessary, as described in Fig. 1. Firstly, we performed a literature review to identify the barriers to adopt I4.0 technologies in manufacturing industry, listed in Table 1. Afterwards, we conducted a focus group consisting of Portuguese experts to review the set of barriers and determine their relevance considering the Portuguese manufacturing industry. To this end, we applied the Interpretive Structural Modelling (ISM) methodology to establish the interrelationship between the barriers, followed by the Matrix Impact of Cross Multiplication Applied to Classification (MICMAC) analysis consisting of the definition of root barriers, as well as the driving and dependency powers.

3.1. Focus group

Focus groups provide an exploratory approach and are used to gather information from a group of experts in a specific subject area (Nassar-McMillan & Borders, 2002). Differently from classical interview methods, focus groups are employed when there is a need to understand a common conception built through sharing of multidisciplinary views on a particular topic (Eriksson & Kovalainen, 2015). Interactions between experts are facilitated by the researchers and are used to either enhance available information or to investigate a topic from a particular perspective (Nassar-McMillan & Borders, 2002).

The focus group of our research had the collaboration of 15 I4.0 researchers and consultants from universities and research institutions in Portugal. The country has seen an improvement on its innovation scoring (Dutta, Lanvin and Wunsch-Vincent 2020; European Commission 2020) due to a significant contribution from Portugal's National government I4.0 Initiative "Indústria 4.0" (República Portuguesa, 2020;

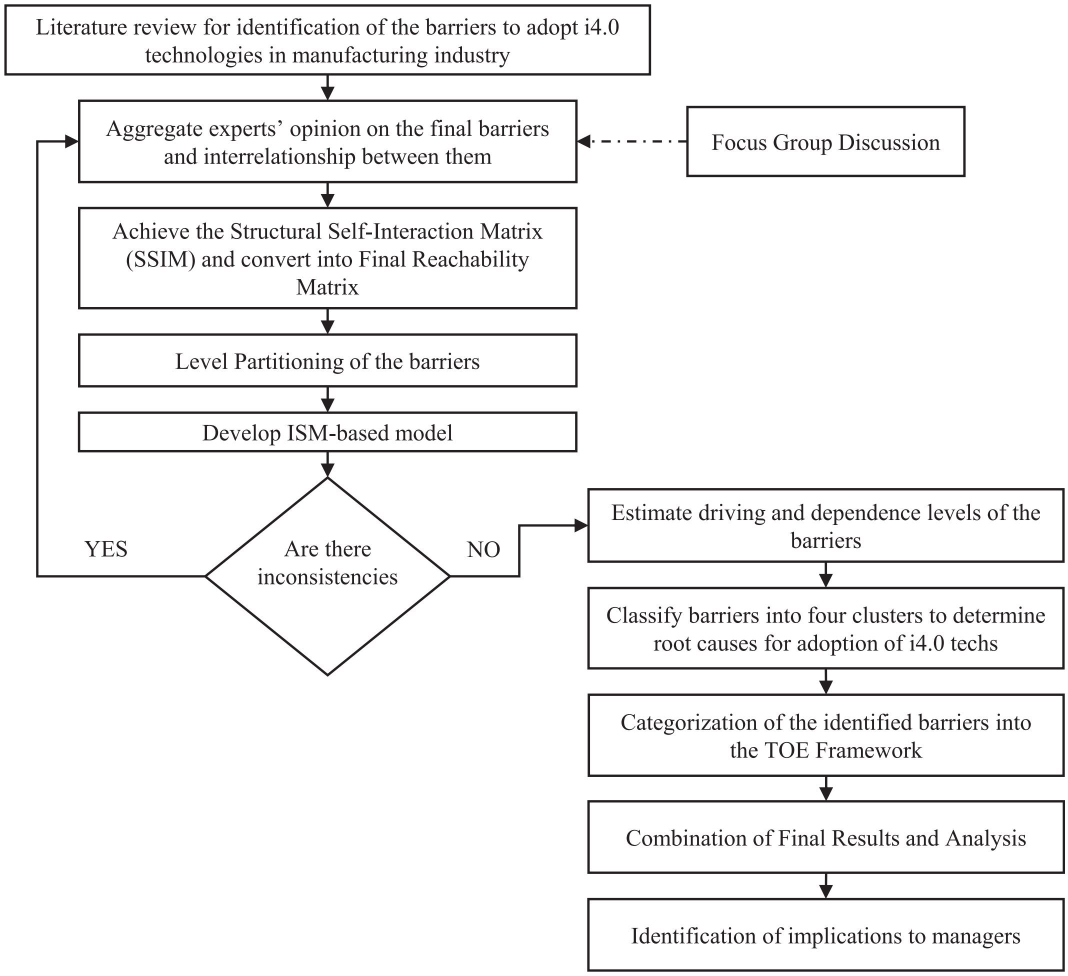

Fig. 1. Research Process.

KPMG Portugal, 2019). Being an early adopter of I4.0 technologies and with institutional support (República Portuguesa, 2021), Portugal represents a flourishing environment to understand the difficulties faced by manufacturing companies to adopt I4.0 technologies.

The criteria used for the selection of the focus group participants were: (i) extensive knowledge on the manufacturing sector; and (ii) extensive knowledge on one or various I4.0 technologies. The I4.0 technologies considered for this study were: autonomous and collaborative robots, simulation, systems integration, IoT, big data and analytics, cloud computing, additive manufacturing and augmented reality, and cybersecurity requirements for manufacturing industry machinery, applications, and solutions. The definition of participant profiles, criteria of selection, focus group guidelines and methods followed the methodology depicted by Billups (2020) and is supported by other studies that have employed similar methods, such as Ali, Hossen, Mahtab, Kabir, and Paul (2020), Magalhães, Ferreira, and Silva (2020), Shukla and Shankar (2022) and Biswas and Gupta (2019). The profile of the 15 experts that participated in this study is depicted in Table 2 below.

The focus group discussions took place in two sessions, with average duration of approximately 60 min each, which is within the timeframe proposed by Billups (2020) and Krueger and Casey (2014). The overall objective was to validate the identified set of 14 barriers with regards to the Portuguese manufacturing sector and establish the interrelationship between these barriers. The moderation method was single-purpose focus group for the identification of barriers and interviews (Billups, 2020). Moderators followed a standard question sequence composed of icebreaking questions, introductory and transitioning questions and content questions, with a closing statement at the end (Krueger & Casey, 2014). Questions were tailored to enhance discussion regarding pairwise relationships between the barriers (Billups, 2020). This approach ensured that the barriers were discussed in detail and a consensus was reached within the limited timeframe for the sessions. Eight experts participated in the first session, while the remaining seven participated in the second session. In both sessions, a research team member moderated the discussion to reduce bias and increase research reliability by helping to reach consensual agreements amidst the groups of experts.

Prior to the focus groups sessions, the research team sent the list of identified barriers to the participants of both sessions. At the beginning of the sessions, the research team re-introduced the list of 14 identified barriers to the participants and asked them to discuss the role of these barriers within the Portuguese manufacturing industry. Afterwards, the research team asked the participants of each session to judge the relationships between the barriers, according to the ISM methodology (presented in section 3.2). The identified relationships were noted, and afterwards served to guide the evaluation of all results from the combination of the different groups. By applying the MICMAC analysis to the results, we could classify the barriers considering their dependency and driving powers and identify the root barriers for the adoption of I4.0 technologies. We merged all evaluations of pairwise relationships into a single matrix to perform the remaining methodological stages. The outcome of the ISM-MICMAC analysis was later presented to, and validated by, the experts.

Table 2
Profile of the experts for the focus group.

Expert ID	Technology	Manufacturing Sector(s)	Experience (Years)
EX01	Big Data and Analytics	Automotive	12
EX02	Simulation	Equipment manufacturer (forestry)	8
EX03	Simulation; Big Data and Analytics	Aircraft manufacturing	15
EX04	Big Data and Analytics	Aerospace	7
EX05	Cybersecurity; Simulation; Additive Manufacturing	Equipment manufacturer (forestry)	16
EX06	Simulation; Big Data and Analytics	Equipment manufacturer (health)	7
EX07	Big Data and Analytics	Construction Agriculture Engineering	5
EX08	Systems Integration; IoT; Simulation; Cloud Computing	Equipment manufacturer (energy systems) Footwear	8
EX09	Systems Integration; Simulation	Equipment manufacturer (agriculture)	7
EX10	Big Data and Analytics	Equipment manufacturer (multiple)	7
EX11	Systems Integration; Autonomous Robots; IoT	Automotive Equipment manufacturer (CNCs and composite Materials) Footwear	10
EX12	IoT; Simulation; Cloud Computing	Equipment manufacturer (Industrial machine tools) Footwear	16
EX13	Simulation; Big Data and Analytics	Aerospace Agriculture Engineering	8
EX14	Big Data and Analytics	Automotive	5
EX15	IoT; Simulation	Aerospace Equipment manufacturer (multiple)	10

3.2. Interpretive structural modelling and matrix impact of cross multiplication applied to classification

Interpretive Structural Modelling (ISM) can be used to identify the structure of the relationships among elements related to a particular complex problem (Kwak, Rodrigues, Mason, Pettit, & Beresford, 2018; Mathivathanan et al., 2021). It transforms unclear and poorly articulated mental models of systems into visible and well-defined models (Venkatesh, Rathi, & Patwa, 2015) and helps in understanding a complex system by considering the hierarchy and relationships among the variables of the system (Kwak et al., 2018). ISM was chosen for this study given the assumption that the barriers are not independent from each other. The driving and dependency relationships are further assessed through the MICMAC methodology. This approach contrasts with Analytical Hierarchical Process (AHP; Raj et al., 2020), which assumes independency between criteria and constructs, and with the Grey Decision-Making Trial and Evaluation Laboratory (DEMATEL/Grey-DEMATEL) approach, which is driven towards small samples of data (Lee, Tzeng, Yeih, Wang, & Yang, 2013). ISM can capture dynamic complexities, while other structural modelling and decision-making methodologies, such as AHP or Analytic Network Process, are focused on specific behaviours under defined circumstances (Shahabadkar, 2012).

was used in this research to identify and evaluate interactions among the barriers to adoption of I4.0. The findings present a graphical structural map of the barriers, highlighting the connections between them. The hierarchical model developed by the ISM methodology will feed the MICMAC analysis to further determine the driving and dependence powers of each variable, to assess which are the most influential barriers (Kwak et al., 2018).

ISM comprises a set of well-defined steps for its successful implementation and in this research the works of Venkatesh et al. (2015), Kwak et al. (2018) and Ali et al. (2020) were used to guide its implementation. Implementing ISM begins by identifying the key variables of the system, which are the list of barriers in our case. It follows by identifying the contextual relationships between each pair of barriers. These contextual relationships are registered in the Structural Self-Interaction Matrix (SSIM), and can be of four different types:

- V: variable i leads to achieve or influences variable j;
- A: variable j leads to achieve or influences variable i;
- X: variable i leads to achieve or influences variable j and vice versa;
- O: there is no relationship between the variables i and j.

Next, the SSIM is converted into a binary matrix – Initial Reachability Matrix (IRM) – substituting V, A, X and O with 1′s and 0′s according to the cases presented in Table 3 below.

Afterwards, the IRM is checked for transitivity. That is, if variable *i* is related to variable *j* and if variable *j* is related to variable *k*, then variable *i* is indirectly related to variable *k*. Also, if entry $(i,k) = 0$ in the IRM, then $(i,k) = 0$ becomes $(i,k) = 1^*$ in the Final Reachability Matrix (FRM). The FRM is converted into the conical matrix to enable the level partitioning where, for each variable, the reachability set (RS), the antecedent set (AS), and the intersection set (IS = RS ∩ AS) are identified. The RS is comprised of the variable itself and others which it leads to achieve or influences. The AS is comprised of the variable itself and others that help in achieving it or influencing it. When ($IS = RS$), then the variable is attributed to the level of that iteration, which are then removed from the remaining RS and IS for the next iteration and the same process is applied until all the variables are partitioned into levels. Finally, the connecting variables in each level are drawn into an ISM-based model considering their relationships.

The MICMAC analysis examines the driving and the dependence power of the variables (Charan et al. 2008). In the FRM, the sum of the row from barrier *i* determines its driving power. The same reasoning is applied to calculate the dependence power, that is, the sum of the column from barrier *j* determines its dependence power. Subsequently, the driving-dependence power diagram is constructed, and the barriers are classified into four clusters according to their driving and dependence powers. The first cluster, known as the Autonomous Cluster, portrays barriers that have **low** dependence power and **low** driving powers, therefore being set apart from the other barriers and not having direct relationships with them. The second cluster, known as the Dependent Cluster, depicts barriers that have **high** dependence power and **low** driving power, thus depicting barriers which are driven by other barriers, or, in other words, that are influenced by other barriers, despite themselves not having high influence in the pairwise relationships. The

Table 3
SSIM to initial reachability matrix conversion.

Case	Action
(i,j) = V	• (i,j) = 1; • (j,i) = 0
(i,j) = A	• (i,j) = 0; • (j,i) = 1
(i,j) = X	• (i,j) = 1; • (j,i) = 1
(i,j) = O	• (i,j) = 0; • (j,i) = 0

third cluster, known as the Linkage Cluster, displays barriers with **high** dependence power and **high** driving power, which demonstrates that these barriers significantly influence other related barriers while they themselves are influenced by related barriers. Finally, the fourth cluster, known as the Independent Cluster, is composed of barriers that have **low** dependence power and **high** driving power, therefore being able to significantly influence other barriers but not being influenced by related barriers. Barriers from the independent cluster are considered root barriers and, therefore, should be prioritized in the adoption of I4.0 technologies, which is the aim of the MICMAC analysis.

4. Application and analysis of the ISM–MICMAC approach

4.1. Structural self-interaction, final reachability matrices and level partitioning

The 14 barriers generate 91 (14x13/2) pair wise relationships. Through the focus group, the interrelationships between the 91 pair wise relationships were identified into the SSIM matrix, as shown in Table 4. This matrix was then converted into the IRM, and transitivity was checked through a MATLAB routine to avoid human error. After identification of the indirect relationships, the FRM matrix was achieved (Table 5). After developing the FRM, level partitioning was conducted. Table 6 illustrates the level partitioning results of the 14 barriers under study, obtained after five iterations. Driving and dependence powers were also calculated in this step to assist the MICMAC analysis.

4.2. ISM-based model

A direct graph, or digraph, is built by arranging the variables vertically and horizontally according to the level partitioning and, if variable *i* influences variable *j* in the IRM, then an arrow is used, pointing from *i* to *j*, to show the direct influence between these two variables. The ISM-based model, shown in Fig. 2, demonstrates the hierarchical structure of the barriers and highlights their interrelationships. The digraph was generated by arranging the 14 barriers according to the level partitioning (Table 6) and by connecting these according to the FRM (Table 5).

The levels of the different barriers in the ISM-based model (Fig. 2) provide an understanding of their impact in the adoption of I4.0. A MICMAC analysis was used to further assess which barriers are the root of the issue and need to be tackled first when adopting I4.0 technologies. Moreover, the barriers depicted in the Fig. 2 are framed within the TOE framework according to Table 1, in order to present a combinatory result of all analysis carried out in this study.

4.3. MICMAC analysis

Following the methodology described above, Fig. 3 was achieved and presents the four clusters depicting the driving and dependence powers of the barriers in relationship to themselves. From Fig. 3, we can see that no barrier is included in the autonomous cluster (first cluster), having weak driving and dependence powers. Therefore, all the barriers are considered to have large influence over the others investigated and no particular one is more isolated from the system.

The second cluster, comprising the dependent barriers, has weak driving and strong dependence power. Barriers 1, 2, 3 and 7 are included in this cluster. Strong dependence indicates that these barriers rely on almost all the others to successfully adopt I4.0, i.e., these barriers are strongly influenced by the others considered, but do not have a big capacity to influence those barriers.

The third cluster, regarding the linkage barriers, has strong driving and dependence powers and includes the barriers 4, 5, 8, 9, 10, 11, 12 and 14. These barriers are considered volatile: they heavily influence, and are influenced by, other barriers. This hinders assessment of beneficial changes to these barriers on the whole system.

Fourth cluster includes the independent barriers having strong driving, but weak dependence power. Barriers within this cluster influence most of the other barriers but are almost not influenced by them, which makes them root barriers to the adoption of I4.0. Barriers 6 and 13 are the two root barriers, given the MICMAC analysis shown in Fig. 3.

5. Discussion

5.1. Interrelationship between the barriers to adopt I4.0 technologies

The results of this study show that the barriers related to standardization efforts (barrier 6) and off-the-shelf solutions (barrier 13) have the highest driving power and lowest dependence power. Similar studies have concluded that the lack of standardization is the most important barrier to the adoption of I4.0 technologies which is corroborated by our findings (Kagermann et al. 2013; Stentoft et al. 2020; Raj et al., 2020). On the other hand, the lack of off-the-shelf solutions was not considered a root cause amidst established literature on the topic, either from a country's perspective (Kamble et al., 2018; Raj et al., 2020) or from a technological perspective (Kamble et al., 2019; Singh & Bhanot, 2019; Mathivathanan et al., 2021). Therefore, it is a root barrier more prominent within the Portuguese manufacturing industry.

Table 4
Structural Self-Interaction Matrix (SSIM).

C[i/j]	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	–	O	O	A	O	O	A	O	O	A	O	O	A	O
2		–	O	A	O	O	O	O	O	O	A	A	O	A
3			–	O	O	O	A	O	O	A	O	O	A	O
4				–	O	A	V	O	A	X	A	A	O	X
5					–	O	V	A	O	X	O	O	O	V
6						–	V	O	V	V	V	V	V	O
7							–	A	A	X	A	A	A	O
8								–	O	V	O	O	O	A
9									–	V	X	X	O	A
10										–	A	O	A	A
11											–	V	O	O
12												–	A	O
13													–	O
14														–

Note:
- C[*i/j*] represents the barrier in line *i* or in column *j*.
- V: barrier *i* leads to achieve or influences barrier *j*;
- A: barrier *j* leads to achieve or influences barrier *i*;
- X: barrier *i* leads to achieve or influences barrier *j* and vice versa;
- O: there is no relationship between the barriers *i* and *j*.

Table 5
Final Reachability Matrix (FRM).

C[i/j]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	DVP
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
4	1	1	1*	1	1*	0	1	1*	1*	1	0	0	0	1	10
5	1*	1*	1*	1*	1	0	1	1*	1*	1	0	0	0	1	10
6	1*	1*	1*	1	1*	1	1	1*	1	1	1	1	1	1*	14
7	1	0	1	1*	1*	0	1	0	0	1	0	0	0	0	6
8	1*	1*	1*	1*	1	0	1	1	1*	1	1*	1*	0	1*	12
9	1*	1*	1*	1	1*	0	1	1*	1	1	1	1	0	1*	12
10	1	1*	1	1	1	0	1	1*	1*	1	1*	1*	0	1*	12
11	1*	1	1*	1	1*	0	1	1*	1	1	1	1	0	1*	12
12	1*	1	1*	1	1*	0	1	1*	1	1*	1*	1	0	1*	12
13	1	1*	1	1*	1*	0	1	1*	1*	1	1*	1	1	1*	13
14	1*	1	1*	1	1*	0	1*	1	1	1	1*	1*	0	1	12
DPP	12	11	12	11	11	1	11	10	10	11	8	8	2	10	

Note:
- C[*i/j*] represents the barrier in line *i* or in column *j*; DPP – Dependence Power; DVP – Driving Power.
- From SSIM (Table 4) to FRM (Table 5):
  - o Case (i,j) = V | (i,j) = 1 and (j,i) = 0
  - o Case (i,j) = A | (i,j) = 0 and (j,i) = 1
  - o Case (i,j) = X | (i,j) = 1 and (j,i) = 1
  - o Case (i,j) = O | (i,j) = 0 and (j,i) = 0
- Transitivity check: when *i* is indirectly related to *k*, and (*i,k*) = 0 in the IRM, then (*i,k*) = 0 becomes (*i,k*) = 1* in the FRM

Table 6
Level partitioning results.

Barrier	Reachability Set	Antecedent Set	Intersection Set	Level
1	1	1,4,5,6,7,8,9,10,11,12,13,14	1	I
2	2	2,4,5,6,8,9,10,11,12,13,14	2	I
3	3	3,4,5,6,7,8,9,10,11,12,13,14	3	I
4	4,5,7,8,9,10,14	4,5,6,7,8,9,10,11,12,13,14	4,5,7,8,9,10,14	II
5	4,5,7,8,9,10,14	4,5,6,7,8,9,10,11,12,13,14	4,5,7,8,9,10,14	II
6	6	6	6	V
7	4,5,7,10	4,5,6,7,8,9,10,11,12,13,14	4,5,7,10	II
8	8,9,11,12,14	4,5,6,8,9,10,11,12,13,14	8,9,11,12,14	III
9	8,9,11,12,14	4,5,6,8,9,10,11,12,13,14	8,9,11,12,14	III
10	4,5,7,8,9,10,11,12,14	4,5,6,7,8,9,10,11,12,13,14	4,5,7,8,9,10,11,12,14	II
11	8,9,11,12,14	6,8,9,10,11,12,13,14	8,9,11,12,14	III
12	8,9,11,12,14	6,8,9,10,11,12,13,14	8,9,11,12,14	III
13	13	6,13	13	IV
14	8,9,11,12,14	4,5,6,8,9,10,11,12,13,14	8,9,11,12,14	III

Our result differs from other studies that regard barriers related to legal and contractual uncertainty with the highest driving power and lowest dependence power. In our case, legal and contractual assurance was found to have medium relevance in terms of driving and dependence power, despite the high importance of standardization efforts, therefore putting more weight on decisions taken by standardization bodies. This is a point of debate within the literature. The lack of contractual and legal assurance was considered highly influencing cause with the highest relevance (Kamble et al., 2018; Shukla & Shankar, 2022; Raj et al., 2020) and had crucial role in the digital transformation (Christians & Lipien, 2017). Others have found that the driving barriers were the need for advancing the educational system for training purposes (Moeuf et al., 2020; Karadayi-Usta, 2019).

The barrier regarding requirement for high levels of investments (barrier 1) was found to have low driving power and high dependence power. This result is in accordance with the findings from Kamble et al. (2018), who portrayed the role of investments as a contributor to the industry digitalization. Data and cybersecurity (barrier 9), integration and interoperability capabilities (barrier 10) and compliance efforts (barrier 11) were identified with medium driving power and dependence power, clearly indicating the need for companies to tackle them in a combinatorial effort, and in close resemblance to what is presented in the literature (Kamble et al., 2018).

Organizational barriers have the highest dependency and lowest driving power, in general, with the only exception of "Lack of Digital Strategy" (barrier 14). This is an unusual result, given that some authors have considered barriers from this dimension to have higher importance and relevance to the adoption of I4.0 technologies (Karadayi-Usta, 2019; Raj et al., 2020; Kiel et al., 2017). This might be a consequence from the Portuguese governmental push towards I4.0 adoption through its national initiative on a very early stage, given its initial focus on the mobilization and demonstration activities. One outcome of this first phase was an informative perspective for companies on the need to establish, early on, a digital strategy to guide their digital transformation (KPMG Portugal, 2019, República Portuguesa, 2020).

In our study, environmental barriers depicted in Table 1 have the highest importance (low dependency, high driving power). This is a novelty on the discussion of barriers to the adoption of I4.0 technologies, given that: (i) barriers related to this dimension are rarely studied (Simões et al., 2019); and, (ii) when discussed, they have lower relevance and importance when compared to technological barriers (Pedone & Mezgár, 2018; Kamble et al., 2018) and to organizational barriers (Horváth & Szabó, 2019). Nevertheless, less developed countries have greater need for actions on standardization, legal and regulatory framework establishment, and infrastructure development (Raj et al., 2020; Horváth & Szabó, 2019), which is corroborated by our findings.

No barriers were found to be considered autonomous, this is, barriers that have weak driving and dependence power. This shows that the

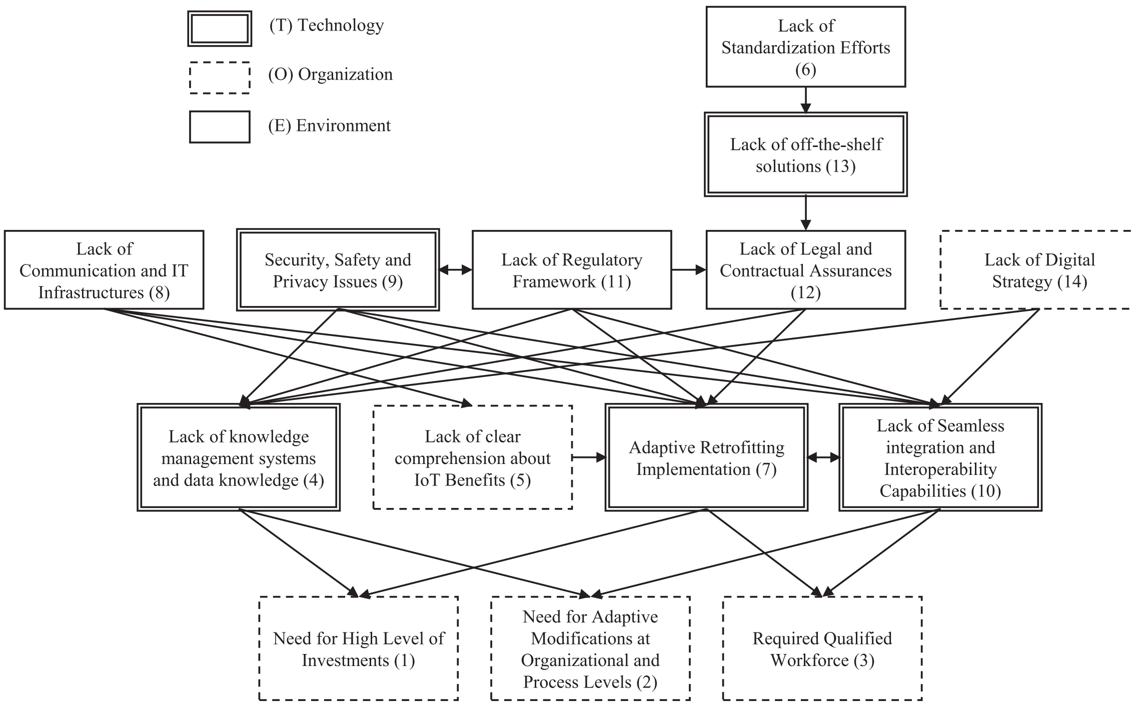

Fig. 2. ISM-based model of the barriers to adoption of I4.0. Each barrier is framed under the TOE framework.

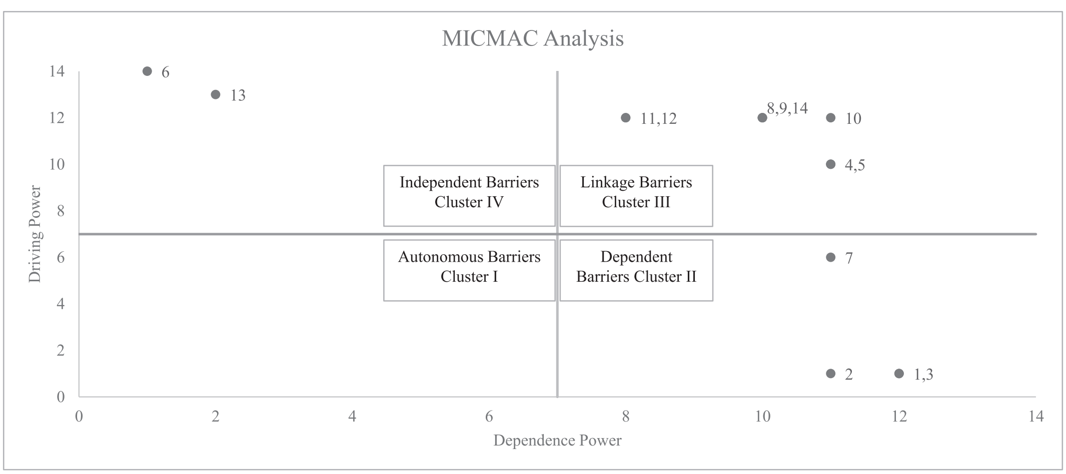

Fig. 3. MICMAC analysis of the barriers to adoption of I4.0.

identified barriers have a prevalent role in the I4.0 adoption process, given that the identified barriers were coherent with the principles of integration, interoperability, and flexibility of industry 4.0 (Bley et al. 2016; Hórvath and Szabó 2019).

When comparing to the literature on the topic, it is clear that much attention has been given to the technologically driven barriers, whereas the environmentally-driven were seconded to the organizational barriers (Awa et al., 2016; Oliveira & Martins, 2011; Venkatesh et al., 2007). The lack of consensus on the variables that pertain the environment surrounding the adoption process, as well as the incapability of quantifying rigorously their effects, are clear flaws of the literature and have, at this moment, greater impact on the decision-making process of companies regarding adoption of I4.0 technologies.

Considering the theoretical implications of this research, we can highlight three major contributions. Firstly, the root barriers identified for the adoption of I4.0 technologies were from the environmental context, which contradicts most of the literature on the topic that has pointed out technological and/or organizational barriers as root barriers. In fact, apart from studies that focused on specific sets of technologies (Simões, Soares, & Barros, 2020; Bonnín Roca & O'Sullivan, 2020), there is a lack of studies that suggested environmental barriers as root barriers to the adoption of I4.0 technologies. Secondly, to our knowledge our study is the first to combine ISM-MICMAC with the TOE framework to identify and categorize barriers to the adoption of I4.0 technologies. Finally, we were able to identify a new barrier to the adoption of I4.0 technologies – "Lack of off-the-shelf solutions" – which enhances the theoretical literature on the topic. This barrier was identified within the Portuguese manufacturing context, and subsequent studies can assess its validity by investigating this barrier in other European and non-European countries. Moreover, the Portuguese manufacturing industry is mostly composed SMEs (República Portuguesa, 2021), which could benefit from off-the-shelf solutions that would decrease solution development costs and aid in increasing technology adoption. Economies with similar manufacturing industry profiles could also benefit from investigating this particular barrier to the adoption of I4.0.

5.2. Implications for managers and policy makers

The identified barriers for the Portuguese manufacturing industry pertain both the internal aspects of companies, namely those within the technological and organizational dimension, as well as the external aspects of companies, which are those pertaining the environmental dimension and a few selected barriers from the organizational dimension. Consequently, managers and policymakers need to coordinate actions to overcome barriers to adopt I4.0. We propose three primary actions, focused on tackling the most relevant barriers identified in our study.

- **Standardization Dissemination:** to overcome barriers related to standardization activities and regulatory and contractual assurance, companies may look to join technical bodies and technical committees. This would promptly increase their ability to adopt most used standards, which, in the case of I4.0 technologies, pertain the family of standards ISO 88/95 (Instrument Society of America (ISA), 1995, 1999). This action would aid in overcoming, at least partially, barriers 6, 11 and 12.
- **Infrastructure Development:** I4.0 communications infrastructure enables the combination of production and business processes by means of a flexible configuration of production facilities, whose benefits have internal and external implications for companies (Zielinski, Schulz-Zander, Zimmermann, Schellenberger, Ramirez, Zeiger, Mormul, Hetzelt, Beierle, Klaus, Ruckstuhl, & Artemenko, 2019). Externally, the 5G paradigm is expected to ensure high speed and increased security. Investment projects that target infrastructure upscaling and implementation are of note here, with focus on 5G mobilizers. Companies need to set up technicians' teams that are dedicated towards integrating the proprietary IT systems with the global infrastructure, securing interoperability capabilities and data transferring/sharing (Jbair et al. 2018). This would also help implement cybersecurity measures, thus enhancing the safety, security, and reliability of the overall network (Sony & Subhash, 2019). This action would aid in overcoming, totally or partially, barriers 1, 7, 8, 9 and 11.
- **Digital Strategy:** Digital transformation in manufacturing companies usually start with the design and implementation of a digital strategy (Rogers, 2003). The first phase of the Portuguese I4.0 national initiative has indeed had noteworthy results on imposing the need for companies to design and establish their digital strategies at early adoption stages (KPMG Portugal, 2019). However, following similar patterns on less developed countries (Raj et al., 2020; Horváth & Szabó, 2019), there is a significant difference among SMEs and large companies when it comes to having already designed their digital strategy. The digital strategy encompasses both managerial and technological actions. For example, on the technological side, to be useful with real-time capabilities, data must be processed as close as possible to the generating source, which implies a digital strategy that considers a segmented production process towards the implementation of Edge/Fog computing (Caiza, Saeteros, Oñate, & Garcia, 2020). To achieve this, it is necessary to consider both the operational strategy as well as the human resources strategy, which must account for formal training to prepare for this digital transformation. The digital strategy should begin by assessing the current level of technological maturity and capabilities to integrate new machinery and to perform retrofitting on existing machinery (Rogers, 2003). This assessment should be based on a trade-off analysis between the cost for purchasing and buying new machinery (and the need to have focused training for the workforce that will be handling this machinery) compared to the cost of retrofitting the existing machinery (considering the down-time of the machinery in the production process, and any workforce-related requirements to operate the new machinery, as well as the cost of the retrofitting process in itself) (Simões et al., 2020). On a second stage, the digital strategy should take into account the educational requirements for secondary workforce (the portion of the workforce that does not directly work with the smart machinery, and yet, must use the data/information from the smart machinery to perform their duties, such as operational managers), and outline the necessary training courses/exercises to achieve the skill level required by all elements of the workforce (Sony & Subhash, 2019). This may also consider the adaptive modifications at organization and process level, which can be focused on integrating off-the-shelf solutions without needing to invest in costly customized solutions. Finally, the digital strategy should consider the final product/service and the role that the digital transformation process will have on it, in terms of adding value for the final customer, transforming the product/service, or even the business model. This action would aid in overcoming, or mitigating, barriers 2–5, 13 and 14.

6. Conclusions

This study identified 14 barriers to the adoption of I4.0 technologies based on a literature review and categorized them following the criteria from the TOE framework. After conducting a focus group with I4.0 experts, we applied the ISM-MICMAC methodology, rendering five levels of interrelationships between the barriers. The lack of standardization and the lack of off-the-shelf solutions were identified as root barriers, thus suggesting that these should have higher priority for managers to tackle when considering the adoption of I4.0 technologies. On the other hand, the organizational process, the enhanced skills required for digitalized workforce, and high levels of investments have the lowest influence interdependence in decision-making with respect to adoption of I4.0 technologies.

Our results show that focusing on environment dimension barriers could prove to be a good prioritization strategy, given that these barriers had lower degrees of dependency and higher degrees of driving power when compared to all the organizational barriers, as well as to all but one of the technological barriers. Considering the recent developments on Portuguese manufacturing industry and the current governmental programs for fostering I4.0, it was expected that most, if not all, of the environmental components to the adoption of I4.0 technologies were still in development stages. Therefore, companies should strive to better evaluate the effect of the externalities and to better assess their impacts within the decision-making process of adopting I4.0 technologies. Following the environment dimension, the technological barriers are to be considered with significant relevance on the adoption process, while the organizational barriers should receive minor attention on this evaluation process.

The contribution of this paper to the literature is three-fold. Firstly, it identifies the set of barriers and categorizes them into the TOE framework. Secondly, it provides an analysis of the interrelationships between the barriers to adopt I4.0 technologies and identification of root barriers considering the Portuguese manufacturing industry. We can highlight two different novelties for the theoretical literature on the topic: the identification of a new barrier – "Lack of off-the-shelf solutions" – and the fact that the root barriers were categorized within TOE's Environment dimension. Finally, it provides implications for Portuguese managers and policy makers to accelerate the digital transformation in three areas: standardization dissemination, infrastructure development, and digital strategy.

This study has the limitation of presenting barriers only related to the manufacturing sector. Other sectors relevant to I4.0 are the service sectors. Furthermore, this research used a methodology aimed at identifying the dependence relationships between the barriers, but not the causal relationships. Additionally, the definition of interrelationships and driving-dependence powers were conducted targeting the

Portuguese manufacturing industry and, therefore, should be extended to other similar contexts to further compare results and provide possible common actions on a multinational level. Finally, this research was conducted just before the COVID-19 global pandemic, thus a future study should be done to evaluate the impacts of this disruptive events on the adoption of digital technologies by the manufacturing industry. Future related works may focus on structural modelling techniques to account for causal relationships complementary to the presented dependence relationships. Given the constant development of I4.0 technologies, future studies should apply this methodology periodically to understand the changes to the interrelationships between barriers. Finally, future studies should also focus on assessing the relationships between the barriers identified on this research by means of structural equation modelling analysis.

CRediT authorship contribution statement

Pedro P. Senna: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Luís Miguel D.F. Ferreira:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Ana C. Barros:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Jaime Bonnín Roca:** Writing – review & editing, Supervision. **Vanessa Magalhães:** Methodology, Formal analysis, Data curation, Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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