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POLICIES FOR THE DIGITAL ERA

DIGITAL TECHNOLOGY ADOPTION, IMPLEMENTATION AND THE ROLE OF GOVERNMENTS

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Policies for the Digital Era: Digital Technology Adoption, Implementation and the Role of Governments

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Abstract

Researchers and policymakers in Europe have recognized the role that a competitive manufacturing sector plays in establishing a leading economy, which requires continuous development of the industrial environment. Yet, designing, developing and adopting new technologies is a capital-intensive venture that often leads to multiple setbacks and prototypes before stabilizing into value-adding solutions. This is especially true with digital technologies, most notably those pertaining the Industry 4.0 paradigm, since they not only require high levels of investments, but also organizational modifications and environmental impulses for their adoption. Companies face multiple obstacles in the development and adoption stages, and require both internal assessments and external incentives during the digitalization journey. After exposing the general motivation, research questions and objectives, this dissertation focuses on exploring the barriers to the adoption of these technologies, a set of models that can aid organizations in understanding their current and future digitalization perspectives, and the policies at the European context that are supporting the digital transformation of the manufacturing sector.

The first study regards the identification and prioritization of the barriers to adopt digital technologies in the scope of Industry 4.0. Afterwards, these barriers are evaluated in order to assess the level of interrelationship, as well as their dependence and driving powers. To this end, this study makes use of interpretive structural modelling combined with matrix impact of cross multiplication applied to classification, through focus groups with 15 experts, focusing on the Portuguese manufacturing industry. Despite this limited focus, the identified barriers are supported by literature on other empirical studies from other European countries and internationally, and were categorized following the technology-organization-environment framework. With the results, this research proposes a focus on an understudied area of companies: the environment, that is, the external factors that can hinder, or help, organizations in their digital transformation journey. Additionally, it proposes a set of policies to tackle the identified barriers.

The second study focuses in understanding digital maturity models as a tool for organizations to determine their current digital technology maturity and define their future expectations after the adoption of digital technologies. We performed a systematic literature review of 45 digital maturity models published only on top journals

and which were designed for manufacturing organizations. During the analysis of the digital maturity models, a similar gap was observed regarding the lack of focus on technological maturity assessment of external factors of the organizations. The results were applied into an established methodology for maturity model building to develop a novel digital maturity model that combines the characteristics of the reviewed digital maturity models with the least researched area of organizations, the environment, in a bid to overcome this setback of the literature and provide organizations with a more accurate representation of their digital maturity level. The developed digital maturity model was tested in a multiple case study with 24 manufacturing companies with the intent of validating and fine tuning the model. The final digital maturity model consists of three dimensions, 12 axes and 50 items.

The third study builds on the findings of the first and second study by focusing on the European national digital strategies published by the EU nations. The objective is to evaluate the different initiatives depicted on the national strategies considering the main gap observed previously, that is, the lack of actions to overcome obstacles on the external factors of organizations. Moreover, the national strategies were also evaluated considering the newly established DIGITAL programme of the European Commission, which builds on its predecessors and outlines a more focused approach to enable a set of target technologies: cloud computing, artificial intelligence and cybersecurity. The programme also promotes incentives for the development of formal education programs, as well as digital skills development and training. To perform these analysis, we conducted a content analysis of the European national digital strategies considering both the pillars of the DIGITAL programme and the set of barriers identified in the first study. Results demonstrated a lack of initiatives for four barriers: lack of off-the-shelf solutions, lack of knowledge management systems, need for adaptive retrofitting implementation solutions, and the need to promote a clear comprehension of digitalization benefits. This research proposes nine different policies to overcome these barriers, which could be incorporated into the national digital strategies.

In summary, this thesis makes original contributions to research, practice, and public policy. First, it contributes to the field of research dedicated to technology management by (1) identifying the interrelationships between barriers to adoption of Industry 4.0 technologies within the Technology-Organization-Environment framework, (2) and proposing a comprehensive and empirically validated digital maturity model for

manufacturing companies. Second, it contributes to practice, since (1) it provides recommendations for practice and policy makers to overcome barriers to adopt digital technologies, and (2) proposes a tool for manufacturing companies to assess their current and future digital maturity level in order to define and monitor their digital transformation. And finally, the thesis contributes to public policy by proposing initiatives for the European national digital strategies to overcome the barriers to adopt digital technologies.

Keywords: Digital Technologies, Industry 4.0, Barriers, Maturity Model, Public Policy, European Digital Strategies, Manufacturing.

Resumo

Investigadores e decisores de políticas públicas europeus reconheceram o papel que um setor de manufatura competitivo tem na formação de uma economia de liderança, que requer desenvolvimento contínuo do tecido industrial. Porém, desenhar, desenvolver e adotar novas tecnologias são atividades intensivas em capital que frequentemente levam a múltiplos obstáculos e protótipos antes de se estabilizar em soluções de valor acrescentado. Isto é ainda mais verdadeiro relativamente às tecnologias digitais, principalmente às do âmbito da Indústria 4.0, dado que estas não só requerem altos volumes de investimento, bem como modificações organizacionais e impulsos contextuais para a sua adoção. As empresas enfrentam múltiplos obstáculos nas fases de desenvolvimento e adoção de tecnologias, e procuram tanto avaliações internas quanto mecanismos externos durante a jornada para a digitalização. Após a exposição da motivação geral e das questões e objetivos de investigação, esta dissertação foca-se em explorar as barreiras à adoção das tecnologias digitais, os modelos que podem auxiliar as organizações em compreender suas perspectivas atuais e futuras de digitalização, e as políticas europeias que dão suporte à transformação digital do setor da manufatura.

O primeiro estudo compreende a identificação e prioritização de barreiras à adoção de tecnologias digitais no âmbito da Indústria 4.0. Estas barreiras são avaliadas consoante as suas interrelações, bem como os seus níveis de interdependência e poder decisório. Com este objetivo em mente, este estudo utiliza modelação estrutural interpretativa combinada com matriz de impacto para multiplicação cruzada aplicada à classificação, bem como grupos focais (*focus groups*) com 15 peritos, tendo como foco a indústria portuguesa de manufatura. Embora tenham um foco limitado, as barreiras identificadas são suportadas pela literatura de estudos empíricos internacionais, e foram categorizadas de acordo com o enquadramento tecnologia-organização-contexto. Com estes resultados, esta investigação propõe um foco detalhado numa área pouco investigada: o contexto, i.e. os fatores externos que dificultam ou auxiliam as organizações na sua tranformação digital. Além disso, o estudo propõe várias ações para enfrentar as barreiras identificadas.

O segundo estudo foca-se em compreender os modelos de maturidade digital como ferramentas para as organizações determinarem a sua maturidade digital tecnológica atual e definirem as expectativas futuras após a adoção de tecnologias digitais. Realizamos uma revisão sistemática de literatura de 45 modelos de maturidade digital

publicados em revistas de topo e que foram concebidos para empresas de manufatura. Durante a análise dos modelos de maturidade digital, foi observado uma lacuna de investigação relativamente à falta de foco em avaliações de maturidade tecnológica que consideram os fatores externos das organizações. Os resultados foram usados numa metodologia de construção de modelos de maturidade digital bem definida, de modo a desenvolver um modelo de maturidade digital que combinasse as características dos modelos revistos com a área de menor foco identificado nas organizações, o contexto, numa tentativa de superar as limitações da literatura e prover as organizações com uma representação mais realista do seu nível de maturidade digital. O modelo de maturidade digital desenvolvido foi testado em estudos de caso com 24 empresas de manufatura, tendo como objetivo a validação e aperfeiçoamento do modelo. A versão final do modelo de maturidade digital consiste em três dimensões, 12 eixos e 50 ítems.

O terceiro estudo utiliza os resultados do primeiro e do segundo estudo ao focar nas estratégias europeias nacionais para a digitalização. O objetivo é avaliar as diferentes iniciativas presentes nas estratégias nacionais considerando as lacunas de investigação previamente observadas, isto é, a falta de ações para superar obstáculos relativos aos fatores externos das organizações. Ainda, as estratégias nacionais foram também avaliadas relativamente ao novo programa da comissão europeia – DIGITAL – que complementa os programas antecessores ao definir um modelo de ação mais focado de modo a incentivar tecnologias específicas: computação em nuvem, inteligência artificial e cibersegurança. O programa ainda promove inventivos para o desenvolvimento de programas de educação formal, bem como o desenvolvimento e formação de competências digitais. Para realizar este estudo, efetuamos uma análise de conteúdo das estratégias europeias nacionais para a digitalização, tendo em consideração tanto os pilares do programa DIGITAL quanto o conjunto de barreiras identificados durante o primeiro estudo. Os resultados demonstram uma falta de iniciativas para quatro barreiras: falta de soluções chave-na-mão, falta de sistemas de gestão do conhecimento, necessidade para soluções de implementação de reconfiguração adaptativa, e a necessidade de promover uma compreensão clara dos benefícios da digitalização. Esta investigação propõe nove recomendações para as políticas públicas de forma a superar estas barreiras, que podem ser incorporadas às estratégias nacionais para a digitalização.

Em suma, esta dissertação propõe contributos originais para a investigação, para a prática, e para o desenvolvimento de políticas públicas. Primeiro, contribui para a área

de investigação da gestão de tecnologia ao (1) identificar as interrelações entre barreiras à adoção de tecnologias da Indústria 4.0 considerando o enquadramento tecnologia-organização-contexto e (2) propor um modelo de maturidade digital completo e validado empiricamente para empresas de manufatura. Em segundo lugar, contribui para a prática, dado que (1) indica recomendações para a prática e para decisores de políticas relativamente à superação das barreiras para a adoção de tecnologias digitais, e (2) propõe uma ferramenta para que empresas de manufatura possam avaliar o seu nível maturidade digital atual e futuro, de modo a definir e monitorizar a sua transformação digital. Finalmente, esta dissertação contribui para as políticas públicas ao propor iniciativas para as estratégias europeias nacionais para a digitalização de maneira a superar as barreiras à adoção de tecnologias digitais.

Palavras-chave: Tecnologias Digitais, Indústria 4.0, Barreiras, Modelo de Maturidade, Políticas Públicas, Estratégias Digitais Europeias, Manufatura.

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1.

Introduction

1. Introduction

Nowadays, it is recognized that manufacturing companies are under a strong competitive pressure (Kira, Sinha and Srinivasan, 2021). They should be flexible when adapting to changes, responsive to the satisfaction of variable and diversified demand profiles, and efficient both in terms of energy and material consumption, as well as in the use of productive resources (EFFRA, 2019). To cope with this context, it is recognized that an effective use of digital technologies becomes crucial for competitiveness (ManuFUTURE, 2018). Indeed, the mastering of digital technologies and platforms offers very significant opportunities to create value for the customer and to strengthen the competitiveness of manufacturing companies (Hsu and Yeh, 2017). Moreover, under certain circumstances, companies that had intention to grow their exports share by means of implementing innovative technologies have increased efficiency due to learning effects (Madaleno et al., 2018).

1.1. Motivation and Relevance

The digital transformation of organizations promises to revolutionize their systems, namely concerning cost reductions and expansion of business opportunities. After more than 200 years of industrial revolutions - from the steam engines of the 1800's, to the assembly lines of the early 1900's and the automation paradigm of the 1970's – the fourth industrial revolution accelerated the development of the Digital Era, which began during the third industrial revolution, by combining previous analog and digital technologies with real-time communications, advanced robotics, cyber-physical systems, and centralized data sharing services (Ghobakhloo, 2018). Industry 4.0 (i4.0) started as a German strategic initiative with the 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 (Schmidt et al., 2015, Simas and Rodrigues, 2017). 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 (Geissbauer et al., 2016; Liao et al., 2017).

1.

Introduction

Industry 4.0 invokes the contemporary technological advances that integrate physical objects, virtual models and services, as well as coordination efforts (Drath and Horch, 2014). Thus, it extends beyond organizational boundaries in order to create a smart, interconnected and agile value chain (Dalmarco and Barros, 2018; Schumacher et al., 2016). On the manufacturing industry, i4.0 has received increased attention from researchers and practitioners alike. Most experts consider that i4.0 presents high potential when concerning value creation, while its implementation presumably renders three benefits: the reduction of operational costs; the increase of efficiency; and additional revenues (Geissbauer et al., 2016; Schumacher et al., 2016).

While i4.0 is part of the Governments' strategic plans and many research projects, organizations still face challenges related to understanding their current situation with regards to this new industrial revolution wave (Erol et al., 2016). Moreover, these challenges encompass the identification of manners in which i4.0 technologies can support their processes (Ganzarain and Errasti, 2016) and the knowledge gathering regarding its implementation details, as well as possible benefits (Liao et al., 2017).

The implementation of technologies from the i4.0 concept involves strategic processes pertaining different hierarchical levels, which relates to a company's technological development capabilities regarding planning, management, control and coordination activities (Simas and Rodrigues, 2017, Dalmarco and Barros, 2018). According to Rogers (2003), the implementation of technologies is part of the Innovation-Decision Process. For a successful implementation of digital technologies, companies must undergo three major stages of implementation (Greenhalgh et al., 2004; Rogers, 2003): (i) the adoption stage, which regards the decision-making process to adopt a new technology by a restricted group of practitioners and experts (Gallivan, 2001), and which considers the first three stages of the Innovation-Decision Process combined (Rogers, 2003) - knowledge, persuasion and decision; (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, finally, (iii) the assimilation stage, which deals with the routinization and incorporation of technology on its full working conditions, being absorbed as an ongoing element on operation processes by the adopter (Gallivan, 2001; Greenhalgh et al., 2004, Rogers, 2003). Our research focuses on the first two stages, the adoption stage and the implementation stage. First, our conclusions in chapter 2 contribute for the adoption process through the identification, categorization and prioritization of barriers to adopt Industry 4.0 technologies, among which is a novel barriers not yet mentioned in literature – “lack of off-the-shelf solutions” – and a set of recommendations for practitioners and policy makers to overcome them. Second, this thesis strongly contributes to the implementation stage by providing a digital maturity model for Industry 4.0 technologies supported by a systematic literature review and empirically validated through multiple case studies, which enhances the organization’s understanding of their current technological level and the requirements for future implementations, as well as their current organizational and environmental levels – depicted in chapter 3. This digital maturity model serves to assess the maturity level improvements both before and after the implementation of technologies in companies. Thirdly, this study contributes to both the adoption and implementation stages on a higher level through the analysis of national digital strategies and their policies, and through the proposal of additional policies from the literature to foster the technology adoption and implementation processes – as portrayed in chapters 4 and 5.

Within this context, it is also important to note the role of governments, which has shifted throughout history. Previously considered as a provider of public goods, that is, goods and services that can obtained or used by any citizen, the governments functions have increased to encompass a more active set of roles: self-preservation of citizens and the nations, conflicts supervision and resolution, economy regulation, political and social rights protection, provider of goods and services (Britannica, 2022, Lin & Benjamin, 2018). In the current digital era and the increasing considerations of environmental, social and governance regulations (ESG), as well as of the United Nations Sustainable Development Goals (SDGs; United Nations, 2015), previous literature has discussed if the role of governments should expand to accommodate new and more sustainable functions into the traditional set (Naysha & Odhiambo, 2019).

Considering this context, a few research gaps have been identified:

1. There is a weak understanding of the barriers and challenges regarding the adoption and implementation of digital technologies (Wang et al. 2016). Thus far, the literature on the topic has provided mere definitions of barriers (Kamble et al. 2018), without

attempting to categorize them according to a priority index or to propose a feasible and optimal route for overcoming each identified barrier (Raj et al. 2020) (see Chapter 2);

2. There is a lack of empirical studies aimed at assessing the maturity level of i4.0 on manufacturing companies that encompass not only the technological and organizational aspects, but also the environmental and contextual aspects of companies (Gökalp et al., 2021; Zoubek et al., 2021). Moreover, empirical studies concerning the impact of regulatory frameworks and legislations on the implementation level of i4.0 technologies are also lacking (Santos and Martinho, 2020) (see Chapter 3);

3. Policies regarding the technology adoption and implementation of digital technologies are unclear on many aspects (Rocha et al., 2022). There are very few studies that attempt to suggest formulations of policies or the results of policy implementation in a national-wide level (Nazarov & Klarin, 2020). Additionally, there is a lack of research on the similarities and differences between European national digital strategies on initiatives to overcome the barriers do adopt digital technologies (Teixeira & Tavares-Lehmann, 2022) (see Chapter 4).

These research gaps have provided the motivation for this research project. The following section depicts the devised research questions and objectives towards addressing the aforementioned research gaps.

1.2. Research Questions and Objectives

Considering the identified research gaps and the overall context of digital technologies, as well as technology-oriented policy, the following research questions have been formulated, alongside the definition of objectives to be accomplished along the proposed research.

- *RQ1: What are the interrelationships between the barriers to adopt digital technologies in the manufacturing industry?*

This research question refers specifically to the gap identified within barriers to adopt digital technologies and related challenges. More importantly, the objective of this stage of the research is to identify the most relevant barriers, categorize them according to priority, and propose a meaningful discussion that leads towards more productive and effective decision-making when overcoming these barriers.

- *RQ2: How to assess digital maturity level within companies of the manufacturing industry?*

The sole identification of the barriers to adopt digital technologies and their categorization is the first stage towards providing support for companies to succeed in overcoming these obstacles. Nevertheless, to fully promote a technology adoption path, it is necessary to develop a roadmap of adoption and implementation that considers companies' technological maturity and that is based upon well-established roadmaps on technological innovation. Therefore, the objective related to this research question is to provide an adoption framework with action plan based on roadmapping methodology for aiding companies in the decision-making process of digital technology adoption and implementation.

- *RQ3: How can European National Initiatives be improved for the adoption of i4.0 technologies?*

Policies targeting the adoption and implementation of digital technologies are unclear and, often, controversial. Despite setting the objectives for National strategies, European digital programmes seldom provide detailed guidelines that the national governments can use to draft their digital strategies. Additionally, the national digital strategies do not make use of academic outcomes when drafting the policy documents, often incurring in incomplete sets of initiatives that do not tackle most of the challenges faced by manufacturing companies. Hence, the objective of this final study is to analyse current European digital programmes and European national digital strategies to identify initiatives designed to overcome the barriers to adopt digital technologies. Additionally, the study sets to propose policies from literature that can be implemented into the national digital strategies.

In summary, this research is motivated by the adoption process of digitalization in manufacturing companies with particular focus on the adoption of digital technologies pertained to the Industry 4.0 paradigm. The first stage (chapter 2) is to determine the difficulties faced by companies when considering the adoption of digital technologies, taking into account the interrelationships between these difficulties, namely the barriers to adopt digital technologies. From this broader view, in chapter 3, we move to understand the more detailed characteristics of companies required for the adoption and implementation of digital technologies in the manufacturing sector, achieved through the assessment of the technological maturity through a robust maturity assessment tool. Having both the broader and the more detailed aspects of the adoption decision-making at hand, we can finally consider in chapter 4 the different policy initiatives depicted in the European National Digital Strategies for digitalization. The aim is to identify policies to overcome the difficulties and support the different areas of companies when considering the adoption decision-making process of digital technologies, and to contribute to them by providing examples of policies from the literature, as well as from other National digital strategies.

1.3. Thesis synopsis

The overview of this dissertation if depicted in Table 1 below.

TABLE 1 DISSERTATION OVERVIEW

Ch.	Research Gaps	Research Questions	Methods	Contribution
Ch. 2	• Weak understanding of the barriers and challenges regarding the adoption and implementation of digital technologies. • Lack of study of interrelationships between barriers to the adoption of digital technologies. • Lack of supporting framework for categorization of barriers to adopt digital technologies.	*What are the interrelationships between the barriers to adopt digital technologies in the manufacturing industry?*	• Technology-Organization-Environment framework (TOE). • Interpretive Structural Modelling theory (ISM) with Matrix Impact of Cross Multiplication Applied to Classification (MICMAC). • Focus groups with 15 experts of the manufacturing sector.	• Set of 14 barriers to adoption of Industry 4.0 technologies, categorized through the Technology-Organization-Environment framework. • Interrelationship assessment of barriers considering their driving and dependence power. • Barriers of the environment dimension have higher driving power and lower dependence power. • Environment barriers should higher importance when devising a plan of actions to overcome adoption barriers. • Recommendations to managers and policy makers.
Ch. 3	• Lack of empirical studies to assess the I4.0 digital maturity level of manufacturing companies considering internal and external factors. • Lack of empirical validation of digital maturity models of manufacturing companies.	*How to assess digital maturity level within companies of the manufacturing industry?*	• Systematic Literature Review (SLR) and coding methodology of 45 digital maturity models published on top journals. • Categorization according to the Technology-Organization-Environment (TOE) framework. • Case research on 24 manufacturing organizations.	• I4.0 Digital maturity model that encompassed the common characteristics of reviewed models and enhanced the evaluation items by considering more important elements of the Environment dimension. • Identification of topics to improve in order to achieve higher levels of digital maturity on the assessed companies.
Ch. 4	• Lack of clarity regarding policies for digital technology adoption and implementation on national strategies. • Lack of research on the similarities and differences between European national digital strategies on initiatives to overcome barriers to adopt digital technologies.	*How can European National Initiatives be improved for the adoption of i4.0 technologies?*	• Analysis of the European DIGITAL programme and incorporated programmes. • Content analysis of 31 documents comprising all 27 EU national digital strategies. • Content analysis of EU national digital strategies supported by the set of 14 barriers to adoption identified in the first study.	• Set of 17 sub-barriers and 94 initiatives. • Proposal of nine policy recommendations for four barriers not addressed either by literature or by national digital strategies.

2. Prioritizing barriers for the adoption of Industry 4.0 technologies[1]

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.

Keywords: industry 4.0; barriers; technology adoption; interpretive structural modelling.

2.1 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 et al. 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 et al. 2019),

[1] This chapter has been published as:
Senna, P. P., Ferreira, L. M. D., Barros, A. C., Roca, J. B., & Magalhaes, V. (2022). Prioritizing barriers for the adoption of Industry 4.0 technologies. Computers & Industrial Engineering, 171, 108428.

augmented reality (Rejeb et al. 2021), simulation (Wang et al. 2016), and artificial intelligence (Sahu, Young and 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 et al. 2020), where standardization requirements are deemed core concern (Kamble, Gunasekaran and Sharma 2018; Raj et al. 2020). The overwhelming number of communications established between IoT devices requires high levels of cybersecurity measures (Kiel et al. 2017; Stentoft et al. 2020), as well as organizational efforts for enhancing focused training (Sony and 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 et al. 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 have typically focused on specific technologies, such as the IoT (Kamble et al. 2019; Singh and Bhanot 2019) or blockchain technology (Mathivathanan et al. 2021) and do not consider the interdependencies with other I4.0 technologies. Furthermore, previous studies emphasize the technological (Kamble, Gunasekaran and Sharma 2018; Wang et al 2016; Flatt et al. 2016) and organizational contexts (Ghadge et al. 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 and 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.

2.2 Theoretical Background

2.2.1 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 et al. 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 (European 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 et al. 2016) through digital technologies that allow for the integration of physical objects, virtual models and services (Xu, Xu and 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 et al. 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 and Bahroun 2019; Haddud et al. 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 and 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 and Szabó 2019). In fact, I4.0 technologies contribute to improved integration, analytics, automation, and reconfiguration of supply chain processes (Büyüközkan and 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 et al. 2019), and product and service added value from customers and suppliers through continuous improvement and near real time feedback loops (Büyüközkan and 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 and 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 and 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, Fleischer and Chakrabarti 1990) to identify and characterize the barriers to the adoption of I4.0.

2.2.2 Technology-Organization-Environment framework

Proposed by Tornatzky, Fleischer and Chakrabarti (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 and Quaddus 2011; Oliveira and 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 et al. 2007), TOE emphasises both the social aspects and the role of environmental factors to understand the organization's condition and technological characteristics (Awa et al. 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 et al. 2017), blockchain (Saberi et al. 2019), and Big Data (Sun et al. 2018).

Hence, according to TOE, a decision to adopt an innovation is made based on technological context, organizational context, and environmental context (Tornatzky, Fleischer and Chakrabarti 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, Fleischer and Chakrabarti 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, Fleischer and Chakrabarti 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, Fleischer and Chakrabarti 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 et al. 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 and 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 et al. 2016), trading partner collaboration (Low et al. 2011), and trust (Shi and Yan 2016).

2.2.3 Barriers to the adoption of I4.0 technologies

The production paradigm brought by I4.0 requires organizational changes under high levels of uncertainty (Kamble, Gunasekaran and Sharma 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 and 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 and Szabó 2019; Schröder 2016). 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 2.

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 and 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, Gunasekaran and Sharma 2018; Karadayi-Usta 2019; Sony and 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; Smit et al. 2016).

All these interventions require organizational and process changes (Kiel et al. 2017; Kamble, Gunasekaran and Sharma 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 et al. 2017) and adaptive retrofitting (Zhou et al. 2015).

Additional barriers that have received attention from researchers are: lack of clear comprehension about IoT benefits (Haddud et al. 2017; Lee and Lee 2015; Kamble, Gunasekaran and Sharma 2018); lack of communication and Information Technology (IT) infrastructures (Kamble, Gunasekaran and Sharma 2018; Karadayi-Usta 2019) and lack of a digital strategy (Müller et al. 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 et al. 2018; Horváth and Szabó 2019; Kiraz et al. 2020). There are growing concerns regarding data security (Kiraz et al. 2020; Schroeder et al. 2019; Stentoft and Rajkumar 2020), poor knowledge of systems architecture (Flatt et al. 2016; Barros et al. 2017), and lack of knowledge management systems (Barros et al. 2017; Müller et al. 2018; Kamble, Gunasekaran and Sharma 2018; Karadayi-Usta 2019).

TABLE 2 SUMMARY OF BARRIERS TO ADOPTION - I4.0. THE RIGHT-MOST COLUMN SPECIFIES THAT THE IDENTIFIED BARRIER 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, Gunasekaran and Sharma 2018; Karadayi-Usta 2019; Lee and Lee 2015; Stentoft and 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 et al. 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 et al. 2019; Fantini et al. 2020; Karadayi-Usta 2019; Stentoft and 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, Gunasekaran and Sharma 2018; Karadayi-Usta 2019; Stentoft and 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 can integrate with embedded IoT components.	T
5	**Lack of clear comprehension about IoT benefits** (Kamble, Gunasekaran and Sharma 2018; Lee and Lee 2015; Stentoft and 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, Gunasekaran and Sharma 2018; Karadayi-Usta 2019; Schroeder et al. 2019; Stentoft and Rajkumar 2020; Stentoft et al. 2020; Xu, Xu and Li 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 et al. 2016; Müller et al. 2018; Stock and Seliger 2016)	Widespread implementation of I4.0, coupled with interoperability concerns, bring forth the need for transforming existing equipment into CPS-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.	T
8	**Lack of Communication and IT Infrastructures** (Karadayi-Usta 2019; Kiraz et al. 2020; Xu, Xu and Li 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**	Cyber-attacks are expected to be a rising issue given the data generated and distributed among companies by CPS	T

	(Dalmarco and Barros 2018; Dalmarco et al. 2019; Kamble, Gunasekaran and Sharma 2018; Stentoft and Rajkumar 2020; Xu, Xu and Li 2018)	and IoT devices, especially those related to communications: identification verification, authorization procedures and protocols, privacy, and system access.	
10	**Lack of Seamless integration and Interoperability Capabilities** (Barros et al. 2017; Flatt et al. 2016; Pedone and 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, Gunasekaran and Sharma 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, Gunasekaran and Sharma 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 and 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

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.

2.3 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 Figure 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.

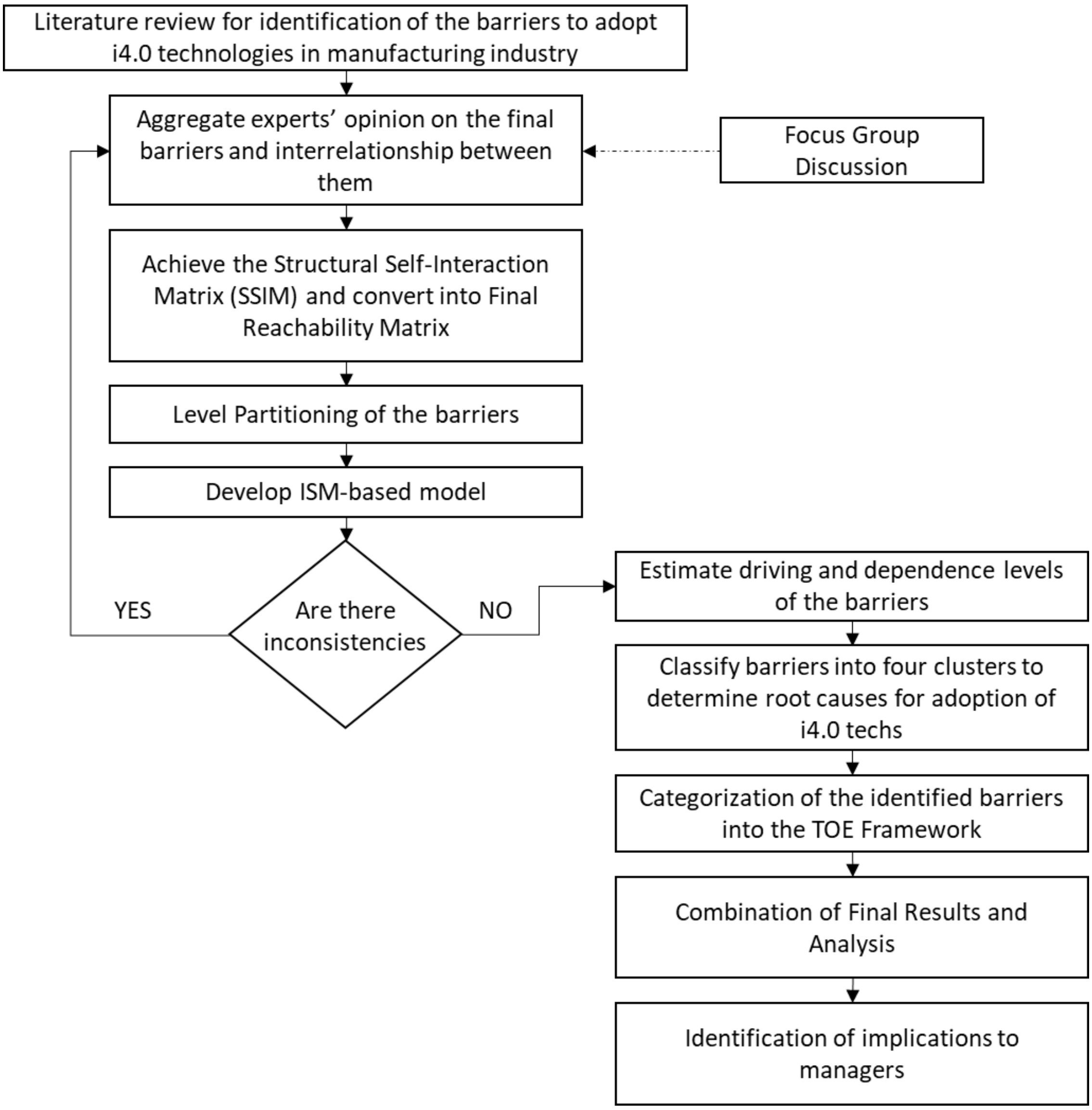

FIGURE 1 RESEARCH PROCESS

2.3.1 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 and 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 and 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 and 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; 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 et al. (2020), Magalhães, Ferreira and Silva (2021), Shukla and Shankar (2022) and Biswas and Gupta (2022). The profile of the 15 experts that participated in this study is depicted in Table 3 below.

TABLE 3 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;	Equipment manufacturer (energy systems)	8

	IoT; Simulation; Cloud Computing	Footwear	
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

The focus group discussions took place in two sessions, with average duration of approximately 60 minutes 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 and 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.

2.3.2 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 et al. 2018; Mathivathanan et al. 2021). It transforms unclear and poorly articulated mental models of systems into visible and well-defined models (Venkatesh et al. 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 et al. 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 et al. 2012).

ISM 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 4 below.

TABLE 4 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

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 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.

2.4 Application and analysis of the ISM–MICMAC approach

2.4.1 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 5. 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 6). After developing the FRM, level partitioning was conducted. Table 7 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.

TABLE 5 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 6 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):
  - Case (i,j) = V | (i,j) = 1 and (j,i) = 0
  - Case (i,j) = A | (i,j) = 0 and (j,i) = 1
  - Case (i,j) = X | (i,j) = 1 and (j,i) = 1
  - 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 7 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

2.4.2 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 Figure 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 7) and by connecting these according to the FRM (Table 6).

The levels of the different barriers in the ISM-based model (Figure 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 Figure 2 are framed within the TOE framework according to Table 2, in order to present a combinatory result of all analysis carried out in this study.

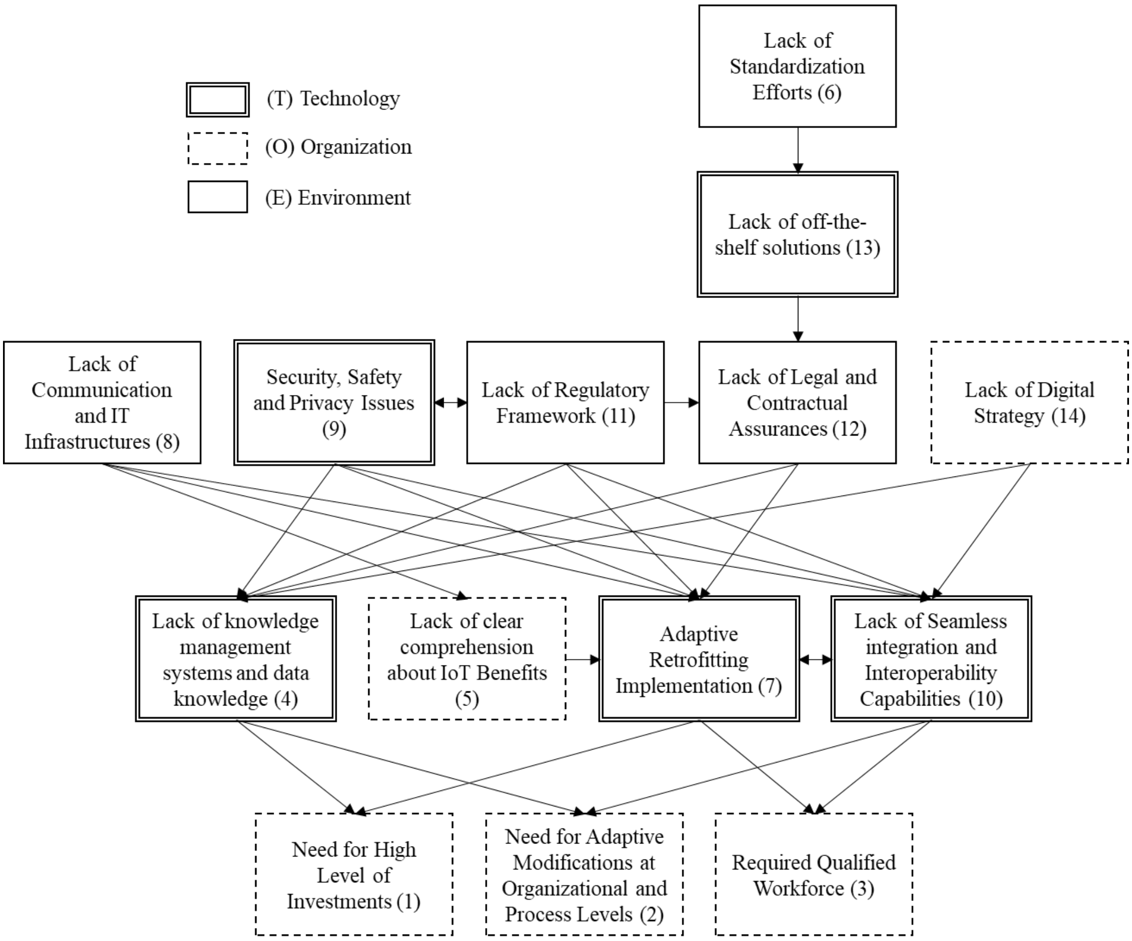

FIGURE 2 ISM-BASED MODEL OF THE BARRIERS TO ADOPTION OF I4.0. EACH BARRIER IS FRAMED UNDER THE TOE FRAMEWORK

2.4.3 MICMAC Analysis

Following the methodology described above, Figure 3 was achieved and presents the four clusters depicting the driving and dependence powers of the barriers in relationship to themselves. From Figure 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 Figure 3.

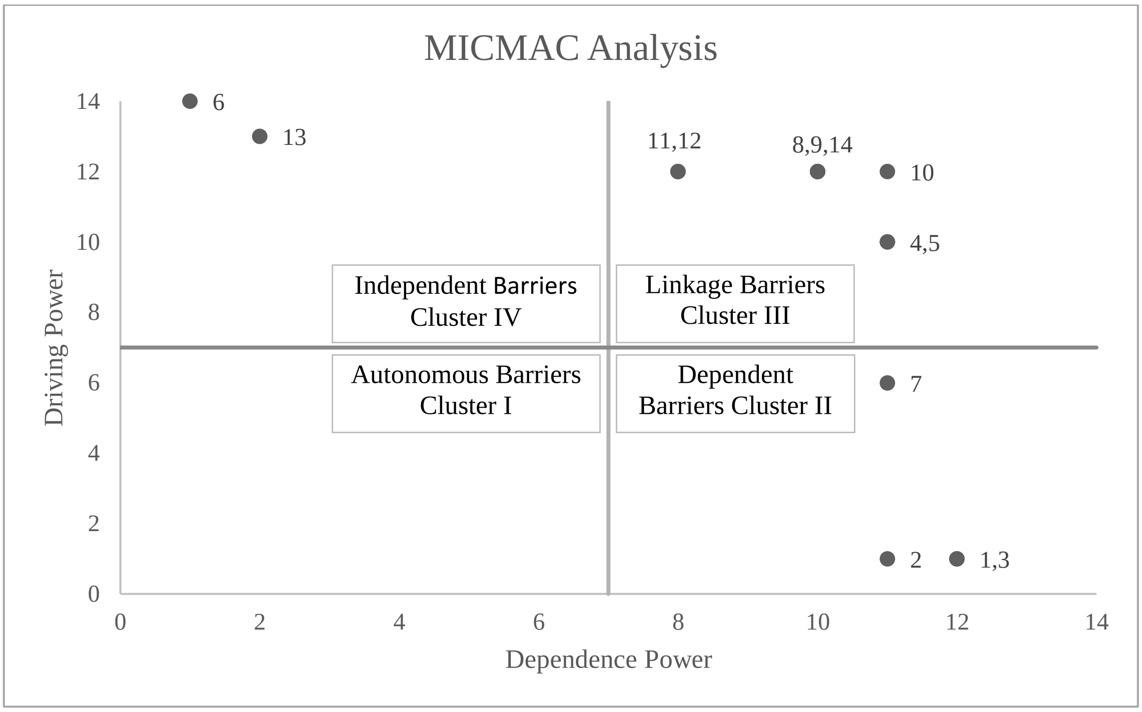

FIGURE 3 MICMAC ANALYSIS OF THE BARRIERS TO ADOPTION OF I4.0.

2.5 Discussion

2.5.1 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, Gunasekaran and Sharma 2018; Raj et al. 2020) or from a technological perspective (Kamble et al. 2019; Singh and Bhanot 2019; Mathivathanan et al. 2021). Therefore, it is a root barrier more prominent within the Portuguese manufacturing industry.

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, Gunasekaran and Sharma 2018; Shukla and Shankar 2022; Raj et al. 2020) and had crucial role in the digital transformation (Christians and 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, Gunasekaran and Sharma (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, Gunasekaran and Sharma 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 (Zhou et al. 2015; Pedone and Mezgár 2018; Kamble, Gunasekaran and Sharma 2018) and to organizational barriers (Horváth and 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 and 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 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 and 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 and Barros 2020; Bonnín Roca and 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.

2.5.2 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 (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 et al. 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 and 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 and 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 et al. 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, Soares and Barros 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 and 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.

2.6 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.

The first author was responsible for the conceptualization, definition and development of the methodology, data collection and analysis writing both the original draft and subsequent versions, as well as for providing data visualization. Apart from the supervisors, the additional authors were invited to contribute their knowledge of the methods applied, discuss the main outcomes, and provide contributions for the discussions on the innovations of the research.

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3. Development and empirical validation of a Digital Maturity Model for Industry 4.0[2]

Purpose: The successful adoption of Industry 4.0 technologies by firms requires them to formulate a digital strategy and implementation roadmap. An established approach to assess firms' needs towards digitalization is through maturity models. While there is a large number of maturity models in the literature, they present several limitations related to their generalizability and theoretical foundations. Our study aims to build and empirically validate an Industry 4.0 digital maturity model, based on the Technology-Organization-Environment framework, which considers not only technological and organizational aspects, but also environmental and contextual topics, and which can be applied to any manufacturing company regardless of their sector and size.

Methodology: We conducted a systematic literature review of 45 digital maturity models, which we synthesized to create an integrated digital maturity assessment model, using the well-devised method described by de Bruin *et al.* (2005). We tested our model through a focus group with industry experts and validated it through case research at 24 companies from various manufacturing sectors.

Findings: Our review suggests that existing digital maturity models have underestimated the relevance of the Environment dimension. Our case research highlights that companies often invest in digital technologies without considering critical organizational and environmental constraints.

Originality: Compared to other digital maturity models, we deepen into the environmental factors affecting technology adoption, and we provide theoretical substantiation to the structure of the model. Based on our findings, we provide recommendations for managers to increase the maturity level of their companies.

Keywords: Digital Maturity Model, Industry 4.0, Technology Management, Industrial Management, Systematic Literature Review, Case Research

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3.1 Introduction

The use of cyber-physical systems and data exchange in Industry 4.0 (I4.0) trespasses the traditional organizational boundaries, requiring a smart, interconnected, and agile value chain (Caiado et al., 2021; Schumacher et al., 2016). I4.0 promises three benefits: reduction of operational costs; increase of efficiency; and additional revenue (Geissbauer et al., 2016). However, organizations face challenges in identifying manners in which I4.0 technologies can support their existing processes (Ganzarain and Errasti, 2016) and the best way to reap its benefits (Liao et al., 2017). Often, organizations tend to prioritize technology implementation before developing a clear understanding of I4.0's organizational and environmental requirements (Senna et al., 2022).

To successfully adopt I4.0 technologies, an organization needs a digital strategy comprised of an action plan and a well-developed roadmap (Antony et al., 2021; Chiarini et al., 2020). The first step to develop this strategy is the assessment of how prepared organizations are to adopt I4.0 technologies (Antony et al., 2021; Krishnan et al., 2021). Maturity assessment models are one of the most common tools to understand firms' digital readiness level (Felch et al., 2019). These tools help companies understand their development and progression within the digitalization journey, providing them with an exhaustive overview of the changes required to facilitate technology implementation, across multiple departments of the organization (Antony et al., 2021; Proença and Borbinha, 2016; Schumacher et al., 2016).

Existing scholarly work on the development of digital maturity models for I4.0 is extensive, but presents three limitations. First, these maturity models are hardly generalizable, given that they are built for specific organizational contexts, specific technologies (e.g., Artificial Intelligence, Internet of Things) or industrial sectors (De Jesus and Lima, 2020; Onyeme and Liyanage, 2022). Second, they often miss key aspects of I4.0, such as the influence of the market and institutional environment in which firms operate (Chatterjee et al., 2021; Tripathi and Gupta, 2021), and how that environment interacts with organizational aspects (Pu et al., 2019). Third, they are disconnected from existing theories on technology adoption (Santos and Martinho, 2020). As a result, maturity models have been criticized for presenting an oversimplification of reality, often lacking supporting empirical evidence (Colli et al., 2018; de Bruin et al., 2005).

The purpose of this paper is to create a digital maturity model for I4.0 which is 1) generalizable across manufacturing sectors and contexts and 2) theoretically substantiated. To overcome the limitations of existing work, we conducted a systematic literature review of 45 maturity models. Our review focuses on models published in peer-reviewed journals in both Q1 and Q2 according to the SCImago Journal Ranking (SJR), between 2016 and 2021, targeted specifically towards I4.0 and manufacturing companies. To provide theoretical substantiation, we use the Technology-Organization-Environment (TOE) framework (Tornatzky et al., 1990). As part of the coding process, we mapped the dimensions and characteristics of each of the 45 models to the three dimensions of the TOE framework. Thereafter, we synthesized a maturity model using the method proposed by de Bruin et al. (2005). We tested and validated our model through focus group (Billups, 2021) and two-stage case research (Voss et al., 2002) with 24 manufacturing companies operating in multiple sectors.

Our model consists of three dimensions, 12 axis and 50 items. The model is a third-party assessment tool designed for multiple consultants and/or researchers application, and requires interviews with multiple respondents from the same company, as well as complimentary data and in loco assessments. During the testing phase we identified a set of most notable obstacles within each dimension faced by companies and provided recommendations for managers to overcome them.

3.2 Background on Industry 4.0 Maturity Models

Industry 4.0 (I4.0) was created as a strategic plan to foster innovation and competitive advantage within the German Industrial sectors (Kagermann et al., 2013). I4.0 mainly refers to processes related to the vertical and horizontal integration of workforce, assets, equipment, and additional resources towards enhancing agility, flexibility, and autonomy (Dalenogare et al., 2018; Frank et al., 2019). I4.0 invokes the contemporary technological advances that integrate physical objects with their virtual models and services, improving the overall coordination (Drath and Horch, 2014), which helps overcome organizational boundaries towards a smart, interconnected, and agile value chain (Schumacher et al., 2016). In this environment, the manufacturing system is self-controlled, supported by innovative platforms that assists intelligent products, data and services (Lasi et al., 2014), and generates integrated optimized systems (Martinez et al., 2019).

I4.0 may provide substantial benefits to manufacturing companies, ranging from increased operational efficiency and reliability, to decreased manufacturing costs and lead-times (Sousa-Zomer et al., 2020). The adoption process is a complex implementation procedure, which requires integrating technologies into the routine work of an organization (Simões et al., 2019). This requires adaptive and skilled workforce capable of extracting the best out of the new smart manufacturing environment (Ghobakhloo, 2020). However, companies often struggle changing their workforce culture and fostering knowledge transfer (Antony et al., 2021). I4.0 is an especially complex case, given that the implementation of digital technologies requires multiple technological shifts that should occur simultaneously (Rahamaddulla et al., 2021). Setbacks can be financially costly, raise uncertainty on the benefits of technological development, or hinder the shift of an organization's business model towards a more digitalized marketplace (Schumacher and Sihn, 2020). From a macroeconomic point of view, these problems may lead to a lack of competitiveness and inefficiencies in the allocation of public resources (Tripathi and Gupta, 2021).

To decrease risks during the adoption process, companies have strived to develop assessment tools which help them understand their current readiness for integrating digital technologies (Ailisto et al., 2016). This is often referred to as the company's digital maturity, which is the combination of "*an organization's people, culture, structure and tasks*" to "*compete effectively by taking advantage of opportunities enabled by technological infrastructure, both inside and outside the organization*" (Rader, 2019). While maturity models aim to portray the current maturity level of the organization, readiness models look to understand if organizations are ready to begin the adoption process (Akdil, Ustundag and Cevikcan, 2018).

To assess the digital maturity, organizations can rely on maturity models designed for evaluation of the level of adoption and implementation digital technologies (Schumacher et al., 2016), which are amongst the most common assessment tools and have received growing interest from practitioners and scholars alike (Mettler et al.2010; Asdecker and Felch, 2018). They are progressive models which help organizations achieve expected skills in specific dimensions such as culture, processes, and resources, through the evaluation of the organization's readiness towards their digital transformation goals (Mittal et al., 2018).

Generally, maturity models are designed with three objectives in mind (Saari et al., 2019): (i) assessing the current technological level; (ii) guiding the development of future vision; and (iii) providing comparability capabilities between corporations (partners or competitor). Usually, maturity models are divided into dimensions, ranging from a minimal of 3 up to 18 dimensions, depending on the defined approach and the objectives of each developing team (Schumacher et al., 2016). To assess each of the dimensions, researchers may combine both qualitative (Schumacher et al., 2016) and quantitative approaches (Büyüközkan and Güler, 2020; Ramos et al., 2020).

Existing work on maturity models presents several shortcomings. First, there is a lack of empirical studies on the development of maturity models, as well as a focus on prescriptive models in detriment of descriptive models (Dikhanbayeva et al., 2020; Elibal and Özceylan, 2020; Rafael et al., 2020). Second, existing work is disconnected from theory on technology adoption (Santos and Martinho, 2020), limiting its generalizability and explanatory power. Consequently, studies have pointed out the lack of models that targeted multiple industrial sectors (Çınar et al., 2021; Gökalp et al., 2021; Santos and Martinho, 2020; Zoubek et al., 2021).

To fill these gaps, we develop and test a theoretically backed, generalizable maturity model. Our model expands on existing work by including environmental context topics, such as the market positioning related to digital strategy, the role of governmental funding and regulatory frameworks, and the cooperation between rivals to advance technological development.

3.3 Research Methods

We followed de Bruin et al.'s (2005) maturity model building method, which is a method for building general, flexible and holistic maturity models. We began by conducting a systematic literature review of 45 digital maturity models. The driving research question of this systematic review was: How is the Industry 4.0 maturity assessed within companies of the manufacturing industry? We synthetized the 45 maturity models to create a single model which can be generalized to any manufacturing sector. Afterwards, we applied case research at 24 manufacturing companies to validate the model for multiple manufacturing sectors, ensuring that our model can serve as benchmarking tool for the development of digitalization initiatives and design of digital strategy. Figure 4 contains a summary of the steps we followed in our research.

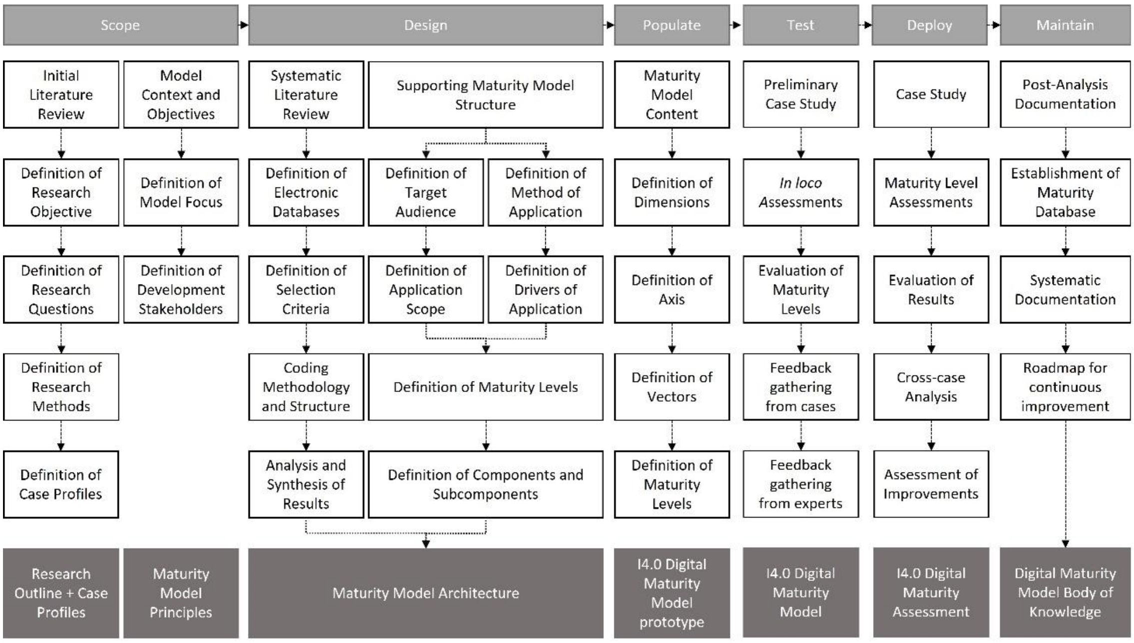

FIGURE 4 RESEARCH METHODS OUTLINE

The following subsections explain how we performed each of these steps to build our model.

3.3.1 Scope

The first phase focuses on the characterization of the desired model in terms of the aim and the development stakeholders which are part of the building stage. In our case, we propose a domain specific model, targeting I4.0 technologies and digital technologies. The aim of the model is to serve as an assessment tool of the manufacturing companies' digital maturity and readiness regarding the adoption of Industry 4.0. Hence, our model looks not only to understand the current digital maturity level of an organization, but also its readiness to begin the adoption of additional Industry 4.0 technologies. Another goal of our model is to serve as an assessment tool for companies to understand the improvement of their technological maturity level by comparing the maturity levels both before and after the implementation of technologies. Our stakeholders are a combination of scholars and industrial experts who participated in the validation process.

3.3.2 Design

The second phase consists of creating the supporting structure for the model. In this research, the target audience consists of industrial companies' executives and management levels, while the application method of the model is the third-party assisted form. Drivers of application are both internal and external requirements, and the application context is comprised of multiple entities located in Portugal. It is important to establish the relationships between the considered items on the multiple maturity model layers. We use the terminology "Dimension" for the first layer (Domain – C-Level), "Axis" for the second, mid-tier layer (Domain Component – Executive level) and "Vector" for the third, more detailed layer (Domain Sub-Component – Management and Staff level). Below is the definition of each of these terms (de Bruin et al., 2005):

(i) Dimension (Domain): a key component of an organization, representing the first distinguishable categorization of process and operations activities within the organization, e.g., Business Strategy. Dimensions (domains) reflect all areas from an organisation and comprehend sub-areas (known as "axis" or "domain components") that, when evaluated in combination with all other domains, provide the organisation's overall maturity level.

(ii) Axis (Domain Component): "a major, independent aspect of a given domain that is important to domain maturity e.g., critical success factors. Domain components are reflected in general stage definitions and enable clustering of results to model audience."

(iii) Vector (Domain Sub-component): "are specific capability areas within the domain components that provide further detail enabling targeted maturity level improvements."

3.3.3 Populate

The third phase – Populate – consists of entering the contents of the models. We performed a systematic literature review (SLR) to identify and synthesize the maturity models available that target specifically the implementation of I4.0 within manufacturing industries. We followed Denyer and Tranfield's (2009) method. We coded the maturity models following the guidelines proposed by Gioia et al. (2012).

During coding, we ensured that 1st Order Concepts (Vectors) retrieved from the reviewed maturity models could be clustered into 2nd Order Themes (Axes) and, afterwards, that these themes were under Aggregate Dimensions (Dimensions). To achieve this, we made multiple coding iterations with the help of the MAXQDA® software, to arrive to a consensual form of the dimensions, axes and vectors used for the framework of the proposed digital maturity model. We present below Figure 5 with the coding structure used on our SLR.

References	1st Order Concepts – Vectors	1st Order Concepts – Axes	1st Order Concepts – Dimensions	2nd Order Themes – Vectors	2nd Order Themes – Axes	Aggregate Dimensions – TOE Dimensions	# Questions
1, 3, 4, 6, 8, 9, 11, 12, 13, 15, 17, 18, 19, 21, 22, 23, 27, 30, 31, 32, 33, 34, 35, 36, 43, 45		20	3		Infrastructure	Technology	4
1, 2, 8, 10, 11, 13, 15, 17, 18, 21, 22, 23, 27, 30, 31, 33, 34, 35, 36, 39, 40, 42, 43, 45	4	25	6		Data Technologies	Technology	5
2, 5, 8, 16, 23, 24, 26, 32, 33, 34, 35, 39, 42, 44	17	66	9		Advanced Manufacturing Technologies	Technology	5
2, 11, 17, 18, 22, 23, 28, 29, 30, 33, 34, 36, 37, 40, 42, 43, 45	11	43	3	Smart Solutions	Technologies for smart products and services	Technology	2
2, 23, 26, 30, 35, 36, 39, 45	11	22	6	Smart Design	Technologies for smart products and services	Technology	1
1, 2, 3, 7, 9, 10, 11, 14, 17, 18, 19, 43, 21, 22, 23, 25, 26, 28, 33, 34, 35, 36, 37, 39, 41, 43, 45	45	152	27		Strategy	Organization	5
8, 11, 12, 20, 21, 22, 23, 28, 29, 41, 42, 45	18	31	8		Governance	Organization	2
1, 2, 9, 11, 12, 14, 15, 19, 21, 22, 55, 33, 35, 38, 39, 44, 45	1	21	3		Culture	Organization	3
1, 3, 11, 14, 15, 43, 22, 23, 26, 33, 34, 37, 34, 44	44	74	16	Competencies and Skills	Human Resources	Organization	2
2, 9, 10, 11, 15, 18, 22, 25, 31, 33, 36, 38, 40, 44, 45	12	36	8	Training	Human Resources	Organization	2
2, 8, 26, 27, 31, 32, 38, 44, 45		21	5	Quality and Asset Management	Processes	Organization	2
2, 3, 8, 9, 10, 11, 15, 16, 17, 23, 24, 26, 28, 33, 35, 34, 40, 44, 45	25	72	16	Engineering, Production Planning and Control	Processes	Organization	5
1, 3, 4, 6, 8, 9, 11, 15, 16, 23, 24, 26, 28, 25, 31, 32, 33, 34, 35, 36, 35, 42, 44, 45	15	64	14	Supply Chain	Processes	Organization	7
28, 31, 34, 45	14	5	3		Legal and Regulatory Aspects	Environment	2
11, 20, 21, 28, 31, 45, Kotler, Kartajaya and Setiawan (2017)	12	10	4		Market Perspective	Environment	1
1, 15, 20, 21, 22, 23, 28, 30, 33, 35, 37, 45	10	11	2		Interorganizational Aspects	Environment	2

FIGURE 5 SYSTEMATIC LITERATURE REVIEW CODING STRUCTURE FOLLOWING GIOIA ET AL. (2012) METHODOLOGY (REF. # - NUMBER ASSIGNED FOR EACH MODEL IN APPENDIX 7.1)

We considered research papers published between 2013 and 2021 that have evaluated, proposed, or reviewed I4.0/digital maturity models. We collected the papers using Web of Science and SCOPUS databases. We used the following query: (("READINESS") OR ("MATURITY") AND ("MODEL*")) AND (("INDUSTRY 4.0") OR ("I4.0") OR ("DIGITAL TECHNOLOG*")). The query resulted in 638 publications from ISI Web of Science and 522 publications from SCOPUS. Afterwards, the papers and publications were added into an electronic spreadsheet for comparisons, with abstracts and keywords included. Duplicated publications were removed from the selection, and the remaining publications were selected according to the following criteria (C1): Are the papers proposing, or reviewing, readiness or maturity models for digital technologies and/or I4.0 technologies?

A set of 349 papers emerged after the first selection. The selected papers had their full-text review and evaluated according to the following criteria (C2): Are the models relevant for manufacturing companies? This resulted in a set of 120 papers. Finally, the following quality criteria was used to filter publications and leave only the more impactful candidates (C3): Q1/Q2 Journals only using the SCImago Journal Ranking (SJR). After applying the exclusion criteria, 55 publications were part of the final set. Each of these were reviewed manually by the authors considering the objectives of this research, and a set of 45 unique digital maturity models were identified (see Appendix 7.1).

Our coding of the 45 models focused on their dimensions, subdimensions, objectives, methodologies, application techniques, application industry fields, geographical application areas, and year of publication. To provide theoretical substantiation to our model, we used the Technology-Organization-Environment framework (TOE – Tornatzky et al. 1990) as the theoretical lens to support the dimensions of our digital maturity model. The TOE framework was developed study the different complexities of organizations, building on traditional adoption theory frameworks to highlight cultural characteristics and contextual factors to the extensively studied technological and organizational concepts of companies (Shukla and Shankar, 2022). The three dimensions of our model are the ones of the TOE framework: Technology, Organization and Environment.

The technology dimension considers all relevant technologies to an organization which are already in use, available for purchase or in development/implementation stages through research, development and innovation actions (Baker, 2012; Tornatzky et al., 1990). It regards the level of complexity, the compatibility requirements with existing equipment and/or legacy systems, as well as the technologies being developed for deployment in smart products or data-driven services (Chatterjee et al., 2021). It also addresses vertical and horizontal integration, as well as communication and the exchange of information with external actors (Baker, 2012).

The organization dimension regards the organization's profile, complexity of managerial structure, financial availability, as well as the digital strategy outlined (Tornatzky et al., 1990; Wang et al., 2015). Moreover, aspects related to the workforce formal education, training, competencies, and skills, as well as the retainment of talent, are also part of the topics within this dimension. The connections established within, and between, internal subunits of a company can lead to innovation actions, which may be further enhanced through a greater decentralization of the organic structure (Baker, 2012). Finally, topics related to the business and operational processes of the organization, such as the engineering, production, planning and control, supply chain and quality management are also taken into account on the evaluation of the organization dimension (Nasrollahi and Ramezani, 2020; Sassanelli et al., 2020).

The environment dimension focuses on the organization's setting and its environment (Tornatzky et al., 1990). It regards external factors, such as the market positioning, the opportunities for technological innovation from novel technologies, as well as the regulatory framework and funding opportunities (Raj et al., 2020; Tornatzky et al., 1990). The intense and high-levelled competitive environment has been a stimulant to innovation since the 1960's (Hsu and Yeh, 2017), while the regulatory framework and funding opportunities are key factors in the adoption of digital technologies such as RFId (Shi and Yan, 2016), IoT (Haddud et al., 2017) and ERP (Raj et al., 2020).

3.3.4 Test

To test our model, we conducted a focus group with I4.0 industrial and consultancy experts in order to validate the dimensions and axis before the case research stage. We conducted the focus group following Billups (2021) guidelines. The objective of the focus group was to evaluate the clarity and fit of the proposed dimensions, axes, and vectors, and was conducted in three sessions with the same group of eight experts. The average duration of the sessions was 120 minutes. To select participants for our focus group, we considered the following criteria: (i) participants must have knowledge and practice of technology implementation in manufacturing companies; and (ii) participants must have knowledge of assessing the technological maturity of companies through established maturity models. All nine experts had at least 10 years of experience in multiple manufacturing industries, having conducted research and implementations of digital technologies, as well as assessments of technological maturity. The authors served as moderators of the session, following a standard question sequence for each of the assessed topics (Krueger and Casey, 2014). Questions were repeated on subsequent sessions after improvement modifications for each topic were done in-between sessions. After each session, the authors discussed and applied modifications to the model structure and contents and send the improved versions to the experts prior to the subsequent sessions. During the third session, experts reached a consensus on a final testing version of the developed model so that it could be further evaluated through case research.

To validate the model, we conducted a two-stage case research (Voss et al., 2002) with 24 companies. The first stage was conducted with 15 companies aimed at validating the contents and the constructs of the model. The second stage considered the initial 15 companies with the addition of 9 companies, all with different profiles, with the intent to understand the model's generalisability. We focused on the Portuguese manufacturing industry, having internal firm-specific documentation and semi-structured interviews as the data sources. The semi-structured interviews followed a well-devised interview protocol based on the axes and dimensions of the developed digital maturity model (Table 11) and were conducted with companies' multiple representatives ranging from CEOs to Operations Managers, shop-floor technicians, and back-office workforce. Our theoretical sampling criteria were three: (i) companies are from Portuguese manufacturing industry; (ii) companies are not all from the same manufacturing sector; and, (iii) companies want to achieve a higher digitalization level as an strategic objective. Table 8 shows the profile of the 24 companies

We contacted multiple informants for each of the companies to increase the validity of our findings. We used the pattern matching method between multiple case studies, leading to a cross-case analysis, and explanation building for development of improvement actions towards next levels of digitalization, to achieve internal validity. By conducting a multi-case study in different manufacturing sectors and with companies of multiple sizes, many of which are well-established in their markets, we were able to increase external validity.

TABLE 8 CASES PROFILE

CASE ID	Industry	Size	NACE Code (Eurostat, 2008)
C1	Footwear	Large	C.15.20 / C.22.23
C2	Oil	Large	B.09.10 / C.19.20
C3	Aeronautics	Large	C.25.11 / C.25.50 / C.25.99 / C.30.30 / C.30.40
C4	Industrial Automation	SME	C.28.22
C5	Manufacture of Metal Forming Machinery	SME	C.28.41
C6	Automotive and Cycling metalworking	SME	C.28.9
C7	Thermo-heating systems	SME	C.25.2.1 / C.25.3.0
C8	Industrial Equipment Manufacturing	SME	C.28.99
C9	Cork Products	Large	C.16.29
C10	Footwear	SME	C.15.20 / G.46.16 / G.46.42
C11	Industrial Equipment Manufacturing	SME	C.28.93
C12	Graphic Arts Plastic Injections	SME	N.82.9.9
C13	Factory Automation	SME	M.71.1.2
C14	Packaging	SME	N.82.9.2
C15	Agriculture Industry Equipment Manufacturing	Large	C.28.30
C16	Metalworking	SME	C.25.99
C17	Pressure-based Systems Manufacturing	SME	C.25.99
C18	Advanced Industrial Equipment Manufacturing	SME	C.28.93 / C.28.99
C19	Industrial Equipment Manufacturing	SME	C.28.93 / C.28.99
C20	Advanced Industrial Equipment Manufacturing	SME	C.28.93 / C.28.99

C21	Cork Industrial Equipment Manufacturing	SME	C.28.93 / C.28.99
C22	Automotive Equipment and Accessories Manufacturing	Large	C.29.39
C23	Automotive Metalworking	SME	C.29.39
C24	Plastic Moulding Manufacturing	SME	C.29.39

3.3.5 Deploy

The fifth phase regards the deployment of the model in its finished form. To this end we specified additional documentation of the model that encompass the organizational administration. The research group and the consultancy team are responsible for fulfilling the documentation to enable benchmarking between multiple assessments. During this phase we conducted the second stage of the case research with all 24 companies.

3.3.6 Maintain

The sixth and final phase related to the model's maintenance over a longer period. We developed full documentation of the model's constructs, usability, instruments, and contents Within this documentation we have defined a set of policies to ensure longitudinal tracking of interventions by means of safe-keeping multiple versions of the models with significant changes and a database displaying most notable changes corresponding to each version, greatly improving the understanding of previous versions of the model. Table 9 contains a summary of all stages, criterion and choices regarding the development and use of the digital maturity model.

TABLE 9 CHOICES FOR THE DIGITAL MATURITY MODEL FOLLOWING DE BRUIN ET AL.'S (2005) MODEL BUILDING METHODOLOGY

Stage	Criterion	Choice
Scope	Focus of Model	Domain specific – Industry 4.0 and digital technologies
	Development of Stakeholders	Combination – academia and industrial experts
Design	Audience	Internal – Executives and Management Staff
	Method of Application	Third Party Assisted
	Driver of Application	Internal and External Requirements
	Respondents	Management and Staff

	Application	Multiple entities / single region
Populate	Target to be measured	Industry 4.0 technological maturity and digital technological maturity in manufacturing companies
	Methods of measurement	Structured questionnaire, interviews, documentation analysis and on-site verification
	Model components and sub-components definition	Systematic Literature Review (Moher *et al.*, 2015; Denyer *et al.*, 2008) of top-tier journals for digital and I4.0 maturity models. Coding methodology (Gioia *et al.*, 2012) for assessment of the components (dimensions) and sub-components (axes and vectors).
Test	Constructs and content validity	Face validity achieved through multi-case studies (Voss *et al.*, 2002) with 15 manufacturing companies of different sectors Content validity achieved through Systematic Literature Review
	Instruments validity	Review of maturity assessment questionnaire by experts' focus group with relevant experience
	Reliability	Convergence of opinions during the multi-case study supported contents validity and suggestions of improvements
Deploy	Organizational Administration	Overall administration of the model is entitled to the research group within the affiliate institution, where this group is responsible for expanding deployment of the model towards multiple manufacturing industries and companies
	Generalisability	Expanding the initial multi-case study with 9 additional manufacturing companies of different profiles and industrial sectors
Maintain	Longitudinal tracking of interventions	Documentation with policies on storing multiple model versions, with specific intervention tracking and a database with most relevant changes was specified to ensure model maintenance and constant improvement.

3.4 Results

3.4.1 Findings from the Systematic Literature Review

Maturity models that assess I4.0 maturity level are a recent phenomenon given their most recent appearance in the specialized literature, where the oldest model dates from 2016. Additionally, we identified 41 models between 2019 and 2021, representing 91% of the identified maturity models, which demonstrates the increasing level of awareness on this research field.

We identified 24 fields of application for the digital maturity models. Of these, half of the reviewed models (50%) did not specify the manufacturing sector and were not empirically validated. For the remaining models, the spectrum is quite widespread (see Table 10). Only three models performed a cross-industry analysis of manufacturing companies (Gökalp et al., 2021; Mittal et al., 2020; Moura and Kohl, 2020). Two of these models used case research (Gökalp et al., 2021; Mittal et al., 2020), while their cross-industry analysis considered only two companies, each from a different manufacturing industry.

TABLE 10 MANUFACTURING SECTOR OF APPLICATION

Sector	# MM	Ref.
Advanced Industrial Machinery Manufacturing	1	[44]
Automotive	3	[2, 15, 27]
Auto-parts manufacturing	2	[4, 23]
Clothing	1	[43]
Consumer Goods	1	[21]
Food and Beverages	1	[43]
Furniture	1	[43]
Industrial Electric Equipment	2	[16, 28]
Industrial Equipment Manufacturing	1	[21]
Jewellery Manufacturing	1	[5]
Kitchen Manufacturing	1	[5]
Machine Tool Companies	1	[36]
Metalworking	1	[43]
Plastic Manufacturing	1	[43]
Plastic Shoe Manufacturing	1	[34]
Shipbuilding	1	[26]
Non-sector specific	31	[1, 3, 6 – 14, 17 – 20, 22, 24, 25, 29 – 33, 35, 37 – 42, 45]
Total	51	

In terms of results, the maturity models are divided into: (1) self-assessment tools, simple in terms of the aspects covered and the depth of details depicted, and are usually distributed through online platforms, and (2) service-oriented tools, focused in achieving a technical detailed overview of the organization through guided interviews and on-premises assessments. Additionally, some maturity models were designed as stand-alone outcomes, instead of being initial stages to the development of a roadmap, which is usually the overall aim found in literature (Gudanowska, 2016).

Most maturity models set themselves to assess the maturity level of manufacturing organizations, either on a specific sector (e.g. automotive, industrial electric equipment) and geographical fields (e.g. Brazil, Italy) or more broadly (Asdecker and Felch, 2018; Pirola et al., 2019; Santos and Martinho, 2020; Sjödin et al., 2018). However, some maturity models were developed with other objectives, such as to serve as a tool to reflect firm's preferences (Büyüközkan and Güler, 2020), to examine the impact of the association between adoption of Lean Production and I4.0 on the improvement levels of manufacturers' operational performance (Rossini et al., 2019), to investigate innovation in manufacturing and their challenges (Sjödin et al., 2018), or to identify regional potential of I4.0 through a specific indicator system (Czvetkó et al., 2021).

The technology dimension is present in 42 out of the 45 reviewed models, which was expected given that all reviewed models had the commonality of assessing the companies' technological maturity level. Yet, when diving deeper into the topics considered by the maturity models, we observed a focus on infrastructure and data technologies related themes. This can indicate that the development of maturity models is less concerned with specific technologies and more concerned with the factors that lead to multiple technological solutions, which can be tailor-made for the purposes of the company being assessed. The development of smart products and services were considered in few reviewed models (19 models), showing a distinct lack of assessment of technological developments and impacts on the design and manufacturing of products, as well as on the development of services. This provides further evidence of the focus on the factors to adopt technologies rather than on specific technological solutions. Considering this finding, we have focused the development of our digital maturity model having both approaches – the factors that enable the adoption of digital technologies, and the set of advanced manufacturing technologies.

The organization dimension is present in 40 out of 45 models. There was a preference for axes and vectors that related digital strategy (present in 35 models), operations (31 models), as well as culture (present in 29 models) with regards to technological and leadership aspects, business models, training and skills requirements, and openness to change. We observed that most models favour assessment of the companies' digitalization strategy since it is the most common aspect. Combined with the digitalization strategy is the focus on the operations and business processes, which was not surprised given that one topic cannot be distinguished from the other if a company is set to have a defined digital strategy. Aspects related to the competencies and skills of workers, as well as their formal training to conduct tasks and professional activities, were also noteworthy. On this topic, some models have alluded to the required digital skills for the companies' digitalization journey (Çınar et al., 2021; Colli et al., 2018; Pirola et al., 2019), whereas other models considered the added value that continuous training and soft skills development have on the overall performance of workers relating to the use of digital technologies (Bibby and Dehe, 2018; Fareri et al., 2020; Sjödin et al., 2018), as well as their openness to changes concerning the adoption of new and/or improved solutions (Amaral and Peças, 2021; Lin et al., 2020; Wagire et al., 2021). Closely related to this topic is the organization's culture, which was generally treated as the innovative and open-minded working environment (Büyüközkan and Güler, 2020; Santos and Martinho, 2020), as well as the sense of belonging (Amaral and Peças, 2021; Fareri et al., 2020), that could foster new digital initiatives.

The environment dimension is comparatively understudied. Externalities were least present maturity models (16 models), portraying aspects that relate to interorganizational relationships, the market perspective and positioning, as well as the role of government regulations & incentives on the technological maturity of an organization. From these, the interorganizational relationships, which account for cooperation actions between rival companies, and for the collaboration efforts between companies of different tiers within the same supply chain, are by far the most regarded (Amaral and Peças, 2021; Büyüközkan and Güler, 2020; Turisova et al., 2020). After those, the market perspective is also reasonably addressed in maturity models.

We looked to propose an innovative approach to this dimension by studying the use of digital technologies in market positioning strategies. To this end, we combined the conceptual analysis of market perspective from Benešová et al. (2021), Tripathi and Gupta (2021), and Nasrollahi and Ramezani (2020), with the work of Kotler et al. (2017) on Market 4.0 and the use of digital technologies for market positioning. For the legal and regulatory aspects, we considered the work of Tripathi and Gupta (2021) on attempting to define a digital maturity model for nations, as well as the works of Chonsawat and Sopadang (2020), and Nasrollahi and Ramezani (2020). We reached a proposition of an axis that covers the funding opportunities provided by national governments and regional bodies, considering the knowledge and use of these funding schemes. Our environmental dimension also considers the collaboration efforts with Research, Innovation and Development organizations when evaluating the company's maturity level.

Maturity models in our sample differ broadly in their goals. A small portion of the reviewed models targeted either a restrictive group of technologies or a particular aspect of an organization value chain in terms of its technological maturity and development. Most models attempted a broader overview of the organization's technological maturity (e.g. Amaral and Peças, 2021; Bibby and Dehe, 2018; Büyüközkan and Güler, 2020; Gürdür et al., 2019; Lin et al., 2020; Lokuge et al., 2019; Rahamaddulla et al., 2021; Sjödin et al., 2018). However, models did not portray the same set of dimensions. This common issue is greater when considering that most models served as the first stage for the development and implementation of roadmaps towards achieving full digitalization. We attempted to overcome this hindrance by clustering the reviewed models into a set of three dimensions, which consider all the aspects of an organization, to promote a standard first stage towards the design of a roadmap for I4.0 full implementation.

Each of the three dimensions of our digital maturity model was then subdivided into axes, following the structure proposed by Schumacher et al. (2016), Asdecker and Felch (2018) and de Bruin et al.'s (2005) methodology. The axes were retrieved from the reviewed maturity models and aimed at providing a summary of each aspect pertained within the dimensions, which can be observed in Table 11 below. The model was developed as a third-party tool; therefore, it is not a self-assessment tool and requires a trained researcher or consultant to apply it with multiple informants for each company.

TABLE 11 I4.0 DIGITAL MATURITY MODEL STRUCTURE

DIMENSIONS	AXES	DEFINITION
TECHNOLOGY (T)	**Infrastructure**	Refers to the systems integration considering interconnectivity and interoperability aspects (Alcácer *et al.*, 2021; Castelo-Branco *et al.*, 2019). Apart from these, it regards cybersecurity policies and concerns related to horizontal and vertical integration of Information Systems and Operation Technologies (Tripathi and Gupta, 2021). Finally, equipment infrastructure with embedded systems and I4.0 infrastructure are also taken into account (Santos and Martinho, 2020; Zoubek *et al.*, 2021).
	Data Technologies	Focuses on aspects related to data management, such as data collection and acquisition, data transformation, data policies, data analytics and data security (Gürdür *et al.*, 2019; Saad *et al.*, 2021; Santos and Martinho, 2020). Moreover, it also pertains the use of real time data for autonomous/automatic decision-making (Chonsawat and Sopadang, 2020) and the application of data-driven solutions within the production process (Saad *et al.*, 2021).
	Advanced Manufacturing Technologies	Regards the application of advanced manufacturing technologies into the production and business processes of the company, considering the level of automation of applied solutions, smart or intelligent capabilities, user experience enhancing capabilities, and supporting digital services (Amaral and Peças, 2021; Büyüközkan and Güler, 2020; Çınar *et al.*, 2021; Rossini *et al.*, 2019; Zoubek *et al.*, 2021). The scope is supported by the smart factory concept (Alcácer *et al.*, 2021; Santos and Martinho, 2020), with the

		following digital technologies (Alcácer *et al.*, 2021; Amaral and Peças, 2021; Bibby and Dehe, 2018; Chonsawat and Sopadang, 2020; Colli *et al.*, 2019; Rossini *et al.*, 2019; Sassanelli *et al.*, 2020): IIoT, CPS, Cloud Computing, Autonomous and Collaborative Robots, Sensors, Additive Manufacturing, SCADA / MES / ERP, Big Data and Analytics, AI / ML and Data-driven services, RFId and Tracking Systems, AR / VR, Simulation and Optimization.
	Technologies for Smart Products and Services	Refers to the supporting technologies and data related to smart products and data-driven services (Manavalan and Jayakrishna, 2019). It comprises the organization's capabilities to secure product and service-related information, acquire product/service data, and optimize the business model through gathered product/service usability information (Mittal *et al.*, 2018; Wagire *et al.*, 2021).
ORGANIZATION (O)	**Strategy**	Refers to the company digital strategy, implementation level, definition of KPIs, investments and innovation management (Alcácer *et al.*, 2021; Mittal *et al.*, 2018; Pirola *et al.*, 2019). It also refers to change management, business value creation through digitalization, business model transformation and digital production / manufacturing strategy (Amaral and Peças, 2021; Mittal *et al.*, 2020; Rauch *et al.*, 2020).
	Governance	Refers to infrastructure for integration of physical and computational processes, communication and connection between information systems and interoperability (Bastos *et al.*, 2021; Caiado *et al.*, 2021; Tripathi and Gupta, 2021). Also regards governance at the organizational level with regards to the infrastructure, project management, resource allocation, digital awareness and engagement on different hierarchical levels (Colli *et al.*, 2019).
	Culture	Refers to values, norms, beliefs, attitudes and assumptions which are intrinsic to a collaborative environment and are pertinent with regards to human behaviour (Antony *et al.*, 2021). It is the widespread understanding, throughout the hierarchical levels, of the company's digital vision and the employees' collaborative acknowledgement of the roadmap towards successful digitalization (Gürdür *et al.*, 2019; Lokuge *et al.*, 2019).
	Human Resources	Aspects related to the companies' employees, considering the leadership roles, talent acquisition and training activities (Alcácer *et al.*, 2021; Antony *et al.*, 2021), likewise rewarding and recognition systems in place (Alcácer *et al.*, 2021; Büyüközkan and Güler, 2020). Also considers the employees’ perspective in terms of satisfaction, acceptance to change, soft and hard skills, as well as level of education (Colli *et al.*, 2019; Lin *et al.*, 2020; Ramos *et al.*, 2020; Santos and Martinho, 2020). Competences, which are the mind-set and skills (internally or based on external partnerships) needed for addressing the digital process (Colli *et al.*, 2019). All aspects are considered both with regards to the companies' strategy towards employees' development and with regards to the employee's adaptability for I4.0 technologies and digital technologies (Antony *et al.*, 2021; Colli *et al.*, 2019).
	Processes	Refers to the operations and production processes regarding digitalization of information flows, operational performance, data management and data governance policies (Alcácer *et al.*, 2021; Amaral and Peças, 2021; Bastos *et al.*, 2021; Çınar *et al.*, 2021). It is focused on optimizing and

		promoting automation for operations and business, production and engineering processes (Caiado *et al.*, 2021; Lin *et al.*, 2020; Rauch *et al.*, 2020; Santos and Martinho, 2020). Also considers logistics management and order processing from the data flow perspective (Antony *et al.*, 2021; Asdecker and Felch, 2018; Caiado *et al.*, 2021; Rauch *et al.*, 2020). Additionally, it regards operational quality and asset management (Glogovac *et al.*, 2020; Sassanelli *et al.*, 2020).
ENVIRONMENT (E)	**Legal and Regulatory Aspects**	Regards aspects related to legal requirements, standards and regulatory frameworks applicable to the manufacturing context: region, country, industrial sector, or other contexts (Nasrollahi and Ramezani, 2020; Tripathi and Gupta, 2021). It focuses on the strength of governing bodies, existing standardization requirements and governmental funding / infrastructure incentives for adoption and implementation of digital technologies (Tripathi and Gupta, 2021).
	Market Perspective	Focuses on the market aspects related to competition and collaboration, as well as employment capabilities surrounding manufacturing organizations (Chatterjee *et al.*, 2021; Czvetkó *et al.*, 2021). Additionally, considers the customer response adoption, user experience and feedback, and overall customer satisfaction (Manavalan and Jayakrishna, 2019; Tripathi and Gupta, 2021).
	Interorganizational Aspects	Refers to cross company collaboration and the relationships between the manufacturing organization, partners and stakeholders (Amaral and Peças, 2021; Chatterjee *et al.*, 2021; Manavalan and Jayakrishna, 2019). Focuses on aspects related to the horizontal integration of logistics and visibility of information, as well as long term contract policies and improved cost performance (Manavalan and Jayakrishna, 2019; Nasrollahi and Ramezani, 2020).

3.4.2 Definition of interview questions and maturity model levels

After defining the axes for each of the dimensions, we developed the assessment tool with a set of questions. All questions are supported by the findings of the reviewed maturity models and enhanced with additional literature (Figure 5). In the proposed model, each dimension, axis and interview question is evaluated following six levels of maturity (from level 1 – the lowest maturity level, to level 6 – the highest maturity level). There is a lack of consensus amidst the reviewed maturity models concerning the scale of maturity levels, with many being supported by either five or six levels (e.g., Amaral and Peças, 2021; Asdecker and Felch, 2018; Kääriäinen et al., 2021; Saad et al., 2021; Santos and Martinho, 2020; Schumacher and Sihn, 2020). We advocate for six levels to allow for a higher resolution. Additionally, we chose to have the first two levels (level 1 and level 2) as denoting the transition from Industry 3.0 to Industry 4.0, which begins promptly from level 3 and is deemed as fully implemented when a company achieves level 6. Table 12 below presents the levels, their categorization amidst Industry 3.0 and Industry 4.0, as well as the references from the systematic literature review. This digital maturity scale, and the digital maturity model itself, were both validated through a focus group before being empirically tested.

TABLE 12 MATURITY SCALE FOR THE PROPOSED DIGITAL MATURITY MODEL (REF. # REFER TO THE NUMBER IN APPENDIX 7.1)

Industry	Level	Definition	Ref. #
Industry 3.0	**Level 1 - Digitization**	Processes are not defined, mostly done through manual labour or in digitization stage. The organization has no knowledge of the scope and impact of digital technologies or I4.0. Traditional processes and business models are common ground, and very few (if any) digital initiatives are present.	2, 4, 7, 9, 10, 16, 22, 30, 31, 32, 37, 40, 42, 43
	Level 2 - Communication	Systems are structured and IT systems are connected, reflecting the key processes, which are defined. The organization has knowledge of digital technologies and I4.0 initiatives, but has not defined a strategy or set of actions. Most processes are still done through manual labour or have recently become digitized. Communications and operations are done through traditional channels	
Industry 4.0	**Level 3 - Visibility**	There are first initiatives of digitalization and a vision of digital strategy. Decision-making supporting systems are being developed, supported on the business visibility and in gathered data. There are formal strategies and set of actions for I4.0 concepts and digital technologies, most of which are on planning stages or initial development stage	
	Level 4 - Transparency	The organization has begun to establish long-term digital strategy and digital culture. Decisions are made based on knowledge recognition and there are meaningful investments and strategies for I4.0 technologies adoption.	
	Level 5 - Predictability	There is a structured set of actions taken place for digitalization of operations and processes. Digital culture and digital strategy are widespread amidst company workforce on all levels. Autonomous decision-making is done based on future scenarios forecasting and real-time data gathering.	
	Level 6 - Flexibility/Adaptability	The company has embraced digital technologies into its business model and value creation propositions. All operations and processes are integrated, with full autonomy and self-adjusting capabilities. Workers are under continuous training and education programs for soft and hard skills enhancement. Leadership and career development are defined and fostered within the hierarchy. There are smart products and data-driven services with supporting activities and servitization capabilities.	

3.4.3 Findings from the Case Research

We tested our initial model with 15 companies (codes C1 through C15 on Table 8). During the test phase we adjusted the model following the advice from the companies' respondents. These include: (i) the removal of a topic related to the use of smart contracts given that more than 90% of the respondents either did not have knowledge of the technology or stated that it would not be applicable to their particular industrial sector; (ii) the addition of a new question related to the cooperation efforts between rival companies (C7, C11); and (iii) the addition of a question related to the market positioning and its relationship with the company's digital strategy (C9).

The final model after the alterations is comprised of three dimensions, 12 axes and 50 interview questions – 17 questions for the Technology dimension, 28 questions for the Organization dimension and 5 questions for the Environment dimension. During the deployment phase, we used the revised model to assess the maturity of the 24 manufacturing companies. Overall, the 24 Portuguese manufacturing companies have a digital maturity level (DML) of 2.9 (Level 2 – Communication), reasonably close to finally entering the first stage of I4.0. As expected, SMEs have a lower DML compared to large companies – 2.6 against 3.8, respectively. On the one hand, SMEs are still struggling to digitise day-to-day activities such as switching from manual reporting to electronic means and improved use of communications applications. Large companies have already taken measures to solidify a footing on I4.0's visibility by improving the electronic monitoring of their production process, mostly achieved through extensive use of Human-Machine Interfaces, elaborate dashboards, and centralized databases for knowledge management. The average of all maturity assessments can be observed in Figure 6 below.

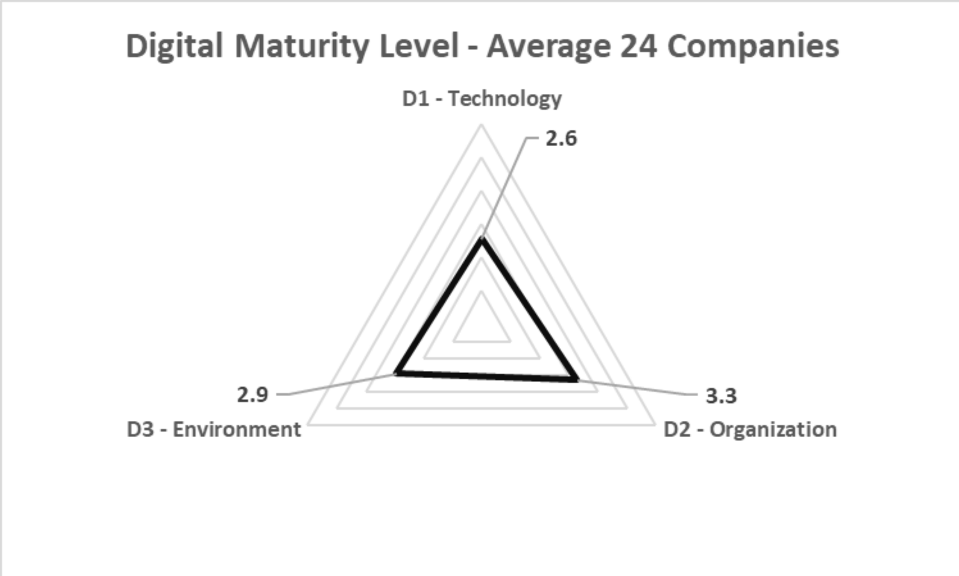

FIGURE 6 DIGITAL MATURITY LEVEL - AVERAGE OF ALL 24 COMPANIES - THREE DIMENSIONS

Companies also portrayed different characteristics considering the three dimensions of analysis. In terms of the **Technology dimension**, respondents have noted some difficulty in integrating information technologies with operation technologies (C2, C18, C22). One reason is that production equipment still needs to be improved towards enabling real-time production data collection and analysis. Hence, the current quality of data that is retrieved from the shopfloor is low and with many redundancies, leading to possible production down-times. Moreover, there is a lack of synergy between the companies' information systems and the business processes, which is more noticeable within SMEs (C4, C6). Although 17 companies assessed have an Enterprise Resource Planning (ERP) system, they still cannot integrate the ERP with the production equipment controllers, either because they do not have a Manufacturing Execution System (MES) in place, or because their MES is unidirectional. Therefore, the ERP can only provide information from the shopfloor to the management area but cannot apply any changes to the equipment controllers (C5-C12, C14-C17, C19-C21, C23). Additionally, most companies do not have adequate solutions for advanced planning and scheduling of the production, nor do they have solutions that enable the exchange of information between themselves and third parties, such as suppliers and customers (20 companies). Finally, only four companies had begun the development of technologies for smart products and services, where data collection and sharing are considered key (C3, C18, C20, C21). Overall, companies are still on the second DML regarding the Technology dimension, as portrayed in Figure 7 below.

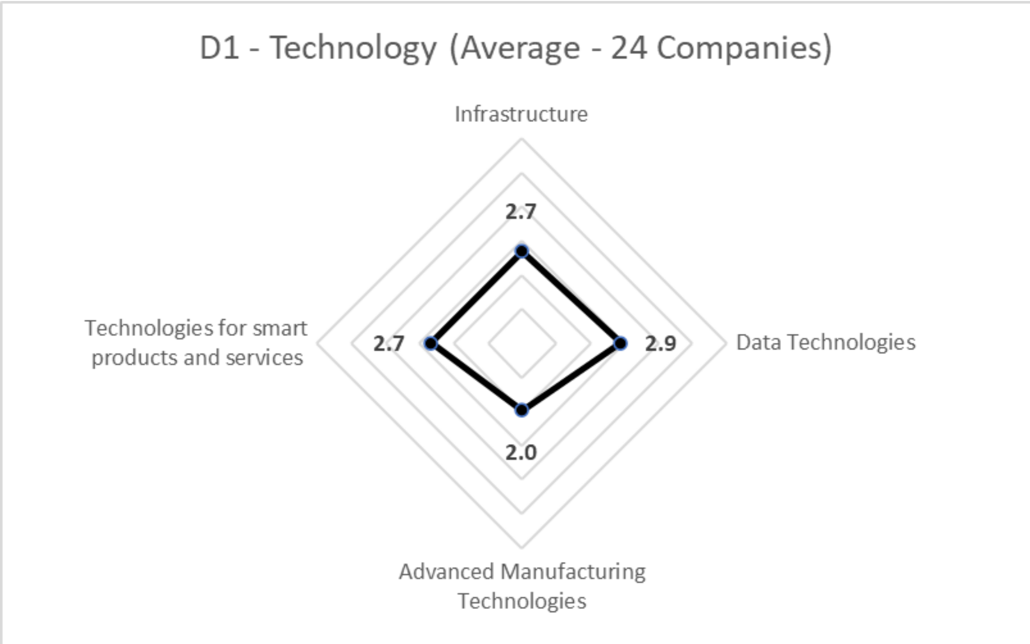

FIGURE 7 DIGITAL MATURITY LEVEL OF ALL 24 COMPANIES FOR D1 - TECHNOLOGY (AVERAGE)

Regarding the Organization dimension, and despite recent investments regarding acquisition or development of digital technologies, 19 companies still struggle to extract the full potential of the newly implemented technologies. We identified a few reasons for this issue: (i) companies, most notably SMEs, struggle to provide formal training to their employees regarding the knowledge and use of I4.0 technologies (C11, C12, C18, C20); (ii) nearly all companies have stated their difficulty in hiring qualified workforce that already has formal training on I4.0 technologies (23 companies); and, (iii) regardless of their profile, many companies have difficulties in defining their digital strategy through a clear roadmap and action plan, and with active involvement of all levels of the workforce (16 companies). Despite having the required standardization certifications for proper management, many companies have not switched their approach from the stand-alone departments to a process-based management, with client-based view and results-oriented approach. Most companies still make use of non-automated operations, where production quality inefficiencies are high due to unstable production process or logistic issues (C4, C5, C7, C8, C10-C14, C16-C19, C21, C23). Additionally, 20 companies do not have predictive maintenance procedures applied on their production processes, which further contributes for the quality and scheduling issues. On average, the evaluated companies have reached the first stage of I4.0 – DML

3.3 (visibility), mostly due to their approach on governance and in establishing a positive company culture. Nevertheless, it should be stated that most of this achievement resides on large companies (average DML 4.2) compared to SMEs (average DML 2.9). A breakdown of the DMLs for each Organization axis is depicted on Figure 8 below.

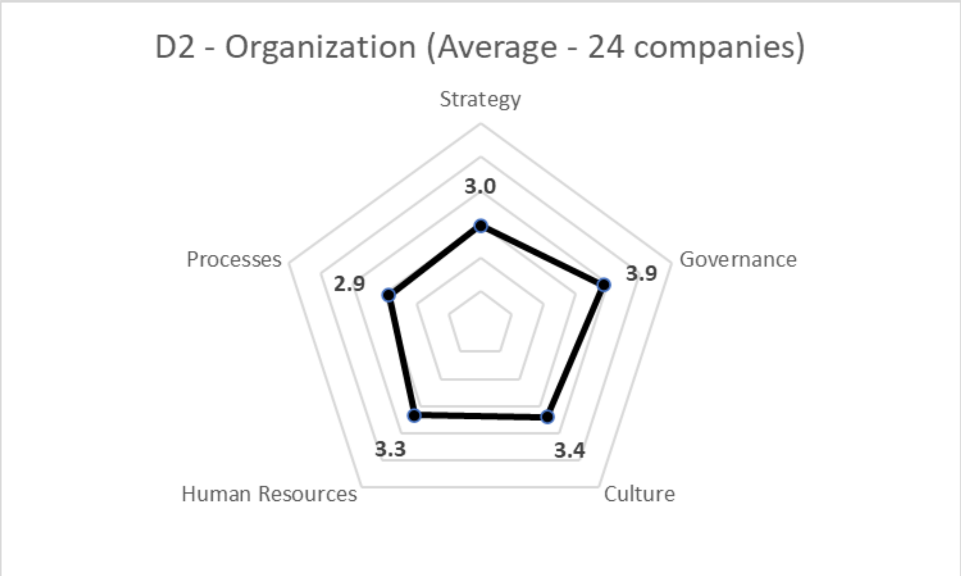

FIGURE 8 DIGITAL MATURITY LEVEL OF ALL 24 COMPANIES FOR D2 - ORGANIZATION (AVERAGE)

We found a large difference in the understanding of the **Environmental dimension** between large companies and SMEs, where the former are more attentive. All companies are somewhat balanced in terms of their DML considering the legal and regulatory aspects, the market perspective and the interorganizational aspects. SMEs have a noticeable deficiency concerning the knowledge of public funding for the development and/or adoption of I4.0 technologies and are either unaware of their existence almost entirely (C14, C17) or cannot allocate personnel to keep track of the many aspects related to the development, building and submission of a call proposal (C12, C16, C23, C24). Large companies have either a designated business development and opportunities team (C15, C22) or full departments dedicated to securing multiple financial revenues for the company (C1, C2, C3, C9). The same discrepancy can be observed with regards to the market perspective, where the digital strategy of SMEs is either missing/undefined or does not consider the market positioning and interaction with suppliers and customers, leading to poor collaboration initiatives. Moreover, many of the assessed companies do not have a solid background in securing partnerships with Technology Research, Innovation and Development institutes or technology providers, which could aid in the adoption of I4.0 technologies both from a technological perspective and from an organizational/formal education perspective. The cooperation with rivals is more present in large companies, which usually seek these cooperative initiatives either when developing solutions that can be applied to multiple companies without incurring in major disruptions, or when conducting formal training of employees on established I4.0 technologies. On average, the 24 companies are close to achieving the first level of I4.0 with a DML of 2.9 (connectivity), where large companies (DML 4.0) have clear advantage over SMEs (DML 2.6) regardless of the industrial sector. Figure 9 displays a breakdown of the Environment dimension axes.

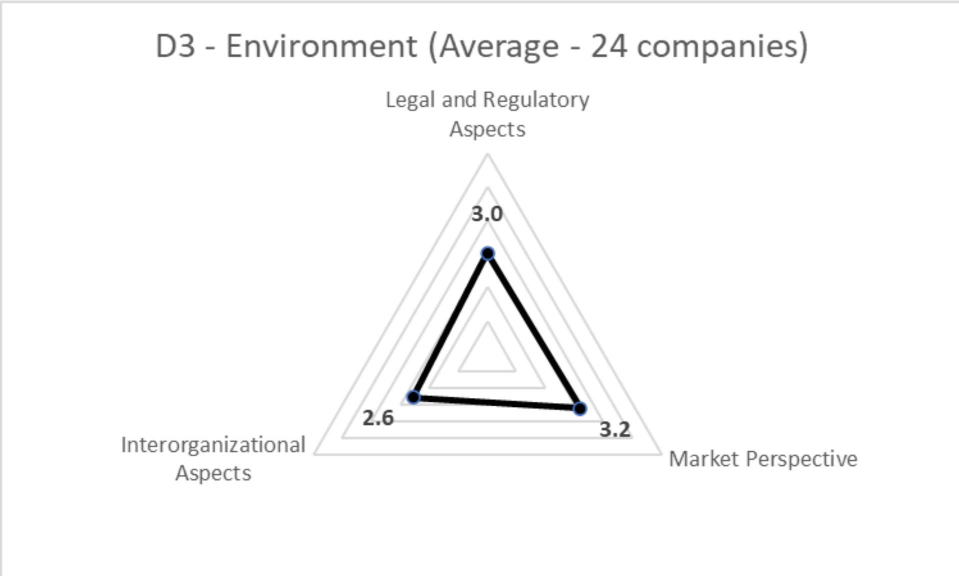

FIGURE 9 DIGITAL MATURITY LEVEL OF ALL 24 COMPANIES FOR D3 - ENVIRONMENT (AVERAGE)

3.5 Discussion

The empirical validation of our I4.0 digital maturity model led, for the technological and organization dimensions, to results similar to those found in the literature (Amaral and Peças, 2021; Lokuge et al., 2019; Rahamaddulla et al., 2021). However, our findings on the **environment dimension** differed from the established literature on technology adoption and on the empirical findings of digital maturity models. Our model enhances the literature by improving the environmental dimension themes through the inclusion of marketing positioning related to digital strategy, the role of funding initiatives and regulatory frameworks, and expanding cooperation and collaboration actions on the adoption of I4.0 technologies.

When considering the **technological dimension**, our findings suggest that companies are still struggling with the vertical and horizontal integration of information systems, which is consistent with similar studies (Bastos et al., 2021; Pirola et al., 2019). Moreover, there is a very low level of data quality and data use within companies, exacerbated by the lack of integration of shop-floor equipment to the management systems, as well as the lack of use of manufacturing execution systems, similar to the findings of Gökalp et al. (2021) and Saad et al. (2021). These obstacles also affect the maturity level of interoperability capabilities, hindering the information flow between the multiple agents of the value chain (Castelo-Branco et al., 2019). Despite only a handful of companies having smart products and services, they have a substantially higher maturity level both in terms of smart products and services and in terms of data acquisition, interoperability, integration, and infrastructure. All companies that have pursued the development of smart products and services are large organizations, which is in accordance to literature, but have achieved a higher level of maturity compared to the observed in similar studies of this subject (Moura and Kohl, 2020; Schumacher and Sihn, 2020). One possible reason for this discrepancy is the fact that this set of companies is also considered with very high digital maturity when concerning the use of digital technologies for market perspective and positioning (within the Environment dimension), which provides them with the possibility of pursuing innovation while less established companies are still looking to overcome more traditional management and technological-oriented barriers.

Concerning the **organization dimension**, companies have a low maturity level when considering talent acquisition, retainment, and formal training, which is in accordance with similar research (Colli et al., 2019; Sjödin et al., 2018). As denoted by management and economics studies on technological complexity and its impacts on technology adoption, the knowledge sharing and level of education of collaborators are paramount for successful implementation of technologies (Rogers, 2003; Simões et al., 2021). Moreover, as pointed out by Bonnín Roca and O'Sullivan (2020), the adoption of digital technologies requires high investments and produces tacit knowledge through multiple trial cycles, which can hinder knowledge sharing and can create an asymmetric information barrier to the development of multiple companies under the same industrial sector. Our findings corroborate this proposition and complement it with the observation that the current level of knowledge of the use of I4.0 technologies is very low within manufacturing companies. In most cases, companies already have invested in the technological development of their systems, but their collaborators lack the knowledge to use the multitude of available tools, functions, and applications of these systems, hence making suboptimal use of already available technology.

The results of our review confirm that the **environment dimension** is the least studied. In particular, SMEs tend to neglect their context and surroundings, mostly due to the need to focus on product development and organizational requirements to establish themselves in the market firstly. This obstacle is most felt by the lack of collaboration initiatives between SMEs and technology research centres, as well as with digital innovation hubs or other bridging entities that can aid in the development of innovation actions and technology adoption (Büyüközkan and Güler, 2020). In contrast, large organizations have innovation and continuous improvement departments aimed at securing these collaborations. This discrepancy is exacerbated when considering the cooperation efforts between large companies, which tend to reduce costs and lead to reduced development cycles (Simões et al., 2021). In similar fashion, our findings regarding the low use of funding schemes and public policy incentives by SMEs, either due to lack of knowledge, or due to lack of workforce to perform the necessary activities and proposed innovation actions, can also be witnessed in the works of Amaral and Peças (2021) and Tripathi and Gupta (2021). Here, SMEs could attempt to promote initiatives through their sector association, somewhat similar to a crowdfunding scheme, which would reduce the workload for each organization, the technology and/or solution development cycle, and possibly increase the profitability (Kotler et al., 2017). This action would also aid in securing a more sustainable position in their market, and provide enough resources to be allocated in defining the company’s digital strategy and a feasible roadmapping of multiple technological and organizational improvements.

3.6 Conclusion

This research focused on developing and validating an I4.0 digital maturity model for manufacturing companies. It was conceived to aggregate the dimensions and characteristics of available digital maturity models in order to be applied to multiple manufacturing sectors, thus serving as a benchmarking tool for comparison and development of a digital strategy. To achieve this goal, we have conducted a systematic literature review of 45 digital maturity models published on top international, peer-reviewed journals between 2016 and 2021. We used focus groups and case research for validation of the developed maturity model. The developed maturity model with the set of dimensions and axes was, then, validated via case research involving 24 Portuguese manufacturing companies.

Our study contributes to the research field by proposing a more comprehensive and encompassing I4.0 digital maturity model that is supported by a theoretical lens and is empirically validated through multiple iterations. Our work highlights the relevance of the environmental dimension, neglected by existing literature. Future studies may focus on applying the digital I4.0 maturity model with the aim of understanding the role of environmental themes in the successful adoption and improvement of digital technologies. Also, the model can be further expanded to encompass companies from the service sector.

The first author was responsible for the conceptualization, definition and development of the methodology, data collection and analysis writing both the original draft and subsequent versions, as well as for providing data visualization. Apart from the supervisors, the additional authors were invited to contribute their knowledge of the methods applied, discuss the main outcomes, and provide contributions for the discussions on the innovations of the research.

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4. Overcoming barriers to digitalization: a European cross-country comparison[3]

The digital transformation of companies is at the forefront of the technology adoption literature and has been part of the European National Digital Strategies since the advent of Industry 4.0 paradigm. After multiple European initiatives to foster the adoption of digital technologies, the current DIGITAL programme combines previous efforts into a more focused approach targeting data-driven services, the use of artificial intelligence and the development of cybersecurity solutions. Yet, manufacturing organizations face a number of barriers to adopt digital technologies which are not part of the current national digital strategies. Considering these, we conducted a content analysis of 27 European National Digital Strategies to identify the initiatives to overcome the adoption barriers, supported by the DIGITAL programme's pillars. We have identified 94 initiatives and 17 sub-barriers. Our results demonstrate a concentration of initiatives towards investments and funding schemes, as well as development of regulatory frameworks and definition of digital strategy. We propose nine additional policies to complement the national digital strategies.

Keywords: Public Policy; Digitalization; Industry 4.0

4.1 Introduction

The role of digitalization for companies and nations has been an insurgent topic within the technology adoption literature (Hsu & Yeh, 2017; Tripathi & Gupta, 2021), where the effective use of digital technologies is portrayed as an important factor for competitiveness (Manufuture High-Level Group, 2018). This is mostly due to their possible applications towards achieving diversified demand profiles, efficient energy and material consumption and optimized use of productive resources (EFFRA, 2019). The digitalization of national industries can bring forth new business models supported by circular economy and the dawn of added-value products and services, such as smart products, servitization and digital finance (Geissbauer et al., 2016; Schumacher & Sihn, 2020). However, poorly planned digital transformation journeys can have negative

[3] This chapter is based on the following working paper:
Senna, P.P., Barros, A.C., Bonnín Roca, J. (2022). Overcoming barriers to digitalization: a European cross-country comparison. In preparation for submission to the Review of Policy Research.

consequences on the organizational and cultural aspects, such as a higher adversity to change acceptance by employees, job threatening activities and promote distancing in terms of hierarchical relationships on the labour market (Chiarini et al., 2020; Republic of Croatia, 2017). Therefore, when considering the national perspective of digitalisation and the achievement of its benefits, the role of industrial and digitalisation policies are critical.

The European Commission has made an effort to encourage EU members to consolidate their strategies through a Digitalisation National Initiative (European Commission, 2019a). Given that the adoption of Industry 4.0 incurs in high levels of investments, which is also a barrier to its adoption (Senna et al., 2022), a governmental intervention towards fostering R&D initiatives on the matter is not only justified, but also desirable (Audretsch et al., 2019; Bonnín Roca & O'Sullivan, 2020). One of the justifications is the fact that the digital transformation of companies goes beyond the simple implementation of technologies within factory shopfloors to the required infrastructure for communication, information and data flow, as well as urban mobility, all of which are network externalities (Link & Scott, 2010). More recently, scholars of the technology adoption field have tried to understand the role of digital technologies concerning the development and competitiveness of nations (e.g., Bravi and Murmura, 2021; Rocha et al., 2022). Some studies on the topic have focused in determining barriers to adopt digital technologies and/or industry 4.0 technologies (Kamble et al., 2019; Senna et al., 2022; Singh & Bhanot, 2020) while other studies focused on understanding the current maturity level of organizations on a nation-wide level (Tripathi & Gupta, 2021).

Nevertheless, there are very few studies that attempt to suggest formulations of policies or the results of policy implementation in a national-wide level (Nazarov & Klarin, 2020; Teixeira & Tavares-Lehmann, 2022). Our research attempts to overcome this gap by evaluating the European National Digital Strategies from all 27 European Union member-states and compare them to a set of barriers to the adoption of digital technologies. Our goal is to perform a content analysis of the European National Digital Strategies contrasted to the set of barriers to adopt digital technologies in manufacturing industries, while supported by the pillars of the European DIGITAL Programme, to depict the current initiatives to overcome each barrier and to propose additional initiatives for policymakers. To achieve this, we performed a content analysis of 31 documents for the European National Digital Strategies until 2023, at least. We coded each document through an explicit and rigorous coding structure (Gioia et al., 2012) and performed a content analysis in order to understand how the barriers to adopt digital technologies have been tackled by the national digital strategies. Moreover, we found gaps in terms of barriers to adopt digital technologies not yet tackled by the strategies and provided initiatives towards overcoming these barriers.

4.2 Theoretical Background

4.2.1 Barriers to industry's digitalization

The emergence of digital technologies, such as artificial intelligence (Denicolai et al., 2021) and cloud computing (Lu, 2017), has brought the promise of opportunities to improve manufacturing companies' productivity (Schumacher et al., 2016), the resilience of international supply chains (Büyüközkan & Göçer, 2018), and sustainability efforts towards a circular economy (Chauhan et al., 2022). For instance, digitalization may lead to a reduction of production costs (Ghobakhloo & Ching, 2019), decreased delivery times (Frederico et al., 2019), as well as products and services with added value that either complement or improve the company's business model (Büyüközkan & Güler, 2020). The path towards digitalization begins with a well-established digital strategy focused on the optimization of resources, and on carefully selecting target digital technologies, which will boost the organization's business model (Denicolai et al., 2021).

Despite the potential benefits of digital technologies, companies face numerous organizational, technological and environmental barriers when trying to adopt them. Firms may need to incur in high levels of investments (Kamble et al., 2018), face difficulties in defining a digital strategy (Stentoft & Rajkumar, 2020), and have a clear understanding of the benefits to the company regarding the technology choice and its business model (Stentoft et al., 2021). These barriers to adopt digital technologies can also be related to lack of management support (Isensee et al., 2020), legal issues (Shelbourn et al., 2005), lack of policies and standards (Singh & Bhanot, 2020), or a lack of support from the government (Büyüközkan & Güler, 2020; Ghadge et al., 2020).

Digital technologies also cause a disruption on the organization, as they require continuous training and skillset upgrading of their workforce, to keep up with the latest technological developments (Correia Simões et al., 2020; Nambisan et al., 2019). However, employees may exhibit a natural resistance to change (Frey & Osborne, 2017), resulting in suboptimal results when trying to implement digital technologies. To ameliorate these problems, companies should consider the organization's internal processes, culture and workforce before trying to implement emerging technologies (Horváth & Szabó, 2019; Kiel et al., 2017). Despite being neglected by organizations, the definition of the organization's digital strategy is key to the adoption of digital technologies (Kamble et al., 2018). This strategy definition can provide much-needed investment focus on the critical business processes and products, optimized resource management and allocation, and concentrated workforce efforts, which are even more important for SMEs (Denicolai et al., 2021).

There are also technological barriers faced by companies on this digitalization process. These barriers are related to technological complexity, which increases after each wave of technological development following Moore' law of log-linear relationship circuit density, increasingly more complex advances in computer time and lower costs per transistor, which result in higher volume and technical specifications of digital devices in operation (Ciarli et al., 2021). While advanced digital technologies may aid in reducing production complexity through the automation of routine and nonroutine tasks (Susskind & Susskind, 2015), the use of multiple digital devices from different manufacturers in a single production environment incurs in the need for multiple integration levels (i.e. communications, sharing of information, scheduling of operations), which contribute to an even higher level of technological complexity and interdependence (Denicolai et al., 2021; Macher, 2006). Organization's face difficulties updating existing equipment to enable digital capabilities, such as the possibility of remote access or the observation of production process in real-time (Zhou et al., 2017). Additionally, the increased interdependence of production equipment leads to the need to reformulate multiple levels of the firm's infrastructure, from the setup of on-site communications in all devices (i.e. production equipment, devices, wearables) to the physical placement of production equipment for production optimization according to on-going virtual simulations of the production process (Wang et al., 2016; Zahra et al., 2022). To enable the integration of the increasing number of digital devices, both at shop-floor level and at the administrative level, firms must rely either on educated and well-trained in-house IT staff, or in partnerships with R&D institutions and service providers, since this process often involves a complexity of operating systems, communications protocols, and computational languages (Cirillo et al., 2021; Frey & Osborne, 2017).

Organizations not only face technological and organizational barriers when looking to adopt digital technologies, but also environmental barriers which are external to the organization but affect the variables regarding the adoption process (Simões et al., 2019). One of these barriers relates to the technological complexity and interdependence issues. Apart from in-house efforts to address this concerns, another possible avenue goes through standardization initiatives (Pessot et al., 2020). These range from establishing process norms for exchange of information and data amidst the multiple digital devices (Cichosz et al., 2020), to established guidelines regarding the manufacturing of production equipment to enable a more seamless integration with existing equipment at the firm’s shopfloor (Singh & Bhanot, 2020), which are all still required to be developed. Another missing component for reducing technological complexities is the establishment of viable, comprehensive and widespread reference architecture models (Kamble et al., 2018), which provide the physical and virtual integration of multi-level components, devices and machinery, thus aiding in more seamless adoption of specific digital technologies (Geissbauer et al., 2016). Besides standardization efforts and reference architectures, companies also face difficulties regarding the lack of an established regulatory framework, either locally of regionally (Kumar et al., 2020). Within companies, the lack of regulatory framework corresponds to ill-devised policies which carry high uncertainty and risk levels, since they can become obsolete or unlawful once a set of specific regulations is defined, possibly leading to overwork of standardized work, workforce re-training and production downtimes (Kamble et al., 2018; Lin, 2016). From outside of the firm’s perspective, the regulatory framework requirements are related to safety of communications (European External Action Service, 2022), security of intellectual property – both virtual and physical (European Commission, 2022a) – and data privacy concerns (Calderaro & Blumfelde, 2022). Finally, organizations also face the lack of legal and contractual assurances (Shelbourn et al., 2005). Apart from establishing legal grounds to physical asset management, organizations are now faced with the need to secure their virtual assets, which are the digital representations of their products, services, production processes and value chain (Christians, 2017). As organizations move towards increasing use of simulation tools to digitally optimize their production process in the virtual environment, which generates virtual assets such as the simulated blueprint of their shop-floor, concerns of intellectual property in the virtual environment and of cybersecurity requirements become more prevalent (Khanzode et al., 2021; Li & Liu, 2021). We present below Table 13 with the identified barriers to the adoption of digital technologies for manufacturing companies, which is supported on the work from Senna et al. (2022).

TABLE 13 BARRIERS TO THE ADOPTION OF DIGITAL TECHNOLOGIES. ADAPTED FROM SENNA ET AL. (2022)

#	Barrier	Definition
1	Investments	High level of financial expenditures to develop and implement digital technologies, with increasing effect over SMEs due to unrealized return on investments and implementation risks.
2	Adaptive Organizational and Process Modifications	Organizational changes regarding strategy, cultural and hierarchical relationships. Process modifications related to internal and external integration and automation requirements.
3	Human Capital	Continuous training requirement, need for higher education, specialized courses and digital skills development.
4	Knowledge Management Systems	Adaptation of knowledge management systems to handle real-time data flow, analytics capabilities and redundancy on multiple levels.
5	Clear Comprehension of Digitalisation Benefits	Management and IT team's understanding of the technological benefits regarding the organization's business model and strategy.
6	Standardisation Efforts	Efforts to develop comprehensive, widespread and seamless standards for digital manufacturing machinery. Additional efforts on making standard certification less costly, which impacts SMEs the most.
7	Adaptive Retrofitting Implementation	Transformation of existing manufacturing equipment (e.g., legacy systems) into digitally-driven equipment capable of real-time data flow, autonomous setup and on-board decision-making.
8	Infrastructure	Robust resources, physical structures, IT and communications infrastructure required for the enabling of real-time IoT use, operations management on-and-off site, information flow and decision-making.
9	Security, Safety and Privacy Issues	Cybersecurity related to data security, information and access safety, and guaranteed non-intrusive privacy on the virtual environment.
10	Integration with existing technology	Easy assimilation of current equipment with enabling and emerging technologies, allowing for vertical and horizontal integration of IT and OT systems.
11	Regulatory Framework	Definition of policy frameworks regarding the multiple requirements of digital technologies, such as infrastructure development, virtual safety, data availability and communications protocols.
12	Legal and Contractual Assurances	Identification, definition and establishment of legal and contractual assurances for the virtual environment of manufacturing industries.
13	Off-the-shelf solutions	Development of one-size-fits-all solutions which are both flexible and integrated with distinct IT systems.

14	Digital Strategy	Definition of a digital strategy that encompasses organizational, technological and environmental aspects of the digital technologies' adoption.

4.2.2 Government functions and policy instruments to foster digitalization

European national governments recognize the prevalence of barriers to adopt digital technologies for manufacturing companies as a setback on the patch to the digitalization of industries (Svanberg, 2022). This is especially true in terms of global competitiveness, where latest reports have shed light on the outstanding performance of rival nations compared to European ones when considering the implementation of advanced manufacturing technologies, complex energy systems, renewables and communication infrastructure (European Competitiveness and Industry & Global Counsel, 2022).

Within this context, it is also important to note the role of governments, which has shifted throughout history. Previously considered as a (i) provider of public goods, that is, goods and services that can obtained or used by any citizen, the governments functions have increased to encompass a more active set of roles (Lin & Benjamin, 2018; Morgan and Tumlinson, 2019; Ostrom and Ostrom, 2019): (ii) self-preservation of citizens and the nations, (iii) conflicts supervision and resolution, (iv) economy regulation and distribution of income, (v) political and social rights protection. In the current digital era and the increasing considerations of environmental, social and governance regulations (ESG), as well as of the United Nations Sustainable Development Goals (SDGs; United Nations, 2015), previous literature has discussed if the role of governments should expand to accommodate new and more sustainable functions into the traditional set (Nyasha & Odhiambo, 2019). The integration of multiple government functions has also been a point of discussion in the literature (Broto Castán et al., 2012; Van Broekhoven and Vernay; 2018), with many authors advocating for the combination of ecological and socio-economical functions as means to provide greater performance and more sustainable development for companies in urban settings (Lovell and Taylor, 2013; Selman, 2009; Vreeker, 2006). This overview further encourages a possible revision of government functions to provide the support for economies in the digital era.

European nations are long-past the time when their competitiveness was not at risk, and are now on the tail of the digital transformation journey, leading to decreased market share, geopolitical relevance and industrial leadership standards (European Competitiveness and Industry & Global Counsel, 2022; Liu, 2022). This position is further exacerbated with the recent geopolitical turmoil caused by supply chain and energy disruptions as a result of the COVID-19 pandemic and the on-going military conflicts (Mariotti, 2022; Popescu et al., 2022). Notwithstanding the current scenario, the literature on innovation fostering and policy building is consensual in considering that the private market is not capable of upholding the necessary investment to realize the digital transformation on its own (Martin & Scott, 2000). Hence, there is a need for governments to step in and provide support in order to assure that the adoption of digital technologies reaches not only the industrial needs, but also benefits society (Mansell, 2021).

4.2.2.1 European digitalization initiatives

To foster the adoption of digital technologies, the European Union is constantly promoting and updating digitalization programmes, beginning with the Digital Single Market (DSM) programme to the Digitising European Industry (European Commission, 2018b, 2022b), culminating in the current DIGITAL programme (European Commission, 2022b). These initiatives are complimented by assessment tools to understand the current digitalization levels, such as the Digital Transformation Monitor (DTM) and Digital Transformation Scoreboard (DTS). Figure 10 demonstrates the synergies and characteristics of each of these European initiatives.

The European Commission launched in 2016 the **Digital Single Market (DSM)** initiative geared towards the adoption of industry practices that led to their digital transformation, with particular focus in manufacturing (European Commission, 2018b). Evolving from the European Single Market with aim to promote the digital transformation of analogical processes and the design of digital services, the DSM arose as one of the key pillars of the European Commission’s digital transformation initiatives (Schmidt & Krimmer, 2022). The DSM is supported by three pillars (Szczepanski, 2015): (i) Single Market Governance Tools – aims to promote e-government solutions for the EU member states, provide the infrastructure for the digital citizenship initiative, and implement the “Once-Only Principle” solution for EU citizens and businesses; (ii) Single Market Policy Areas – tackles the regulations and norms surrounding public procurement of goods and services in the digital age, as well as professional qualifications for government and public branches; (iii) Integration and Market Openness – looks to promote less bureaucratic norms for intra-community trade of goods and services, as well as facilitate the possibility for larger and widespread volumes of foreign direct investment.

The **Digitising European Industry (DEI)** initiative complements the DSM by presenting funding actions, initiatives and programs that promote the creation of digital European communities, digital industrial platforms, training initiatives and a robust regulatory framework for the digital era (European Commission, 2018b; Hervas-Oliver et al., 2020). The first pillar of the DEI – "*European Platform of national initiatives on digitizing industry*" – refers to the establishment of a set of funding initiatives at the EU member states level for the digitalization of the industries, with particular focus on the first stages of the digital transformation regarding the switch from manual processes to digital and virtual processes. It is considered the cornerstone of the DEI initiative, from which the other pillars can be developed and implemented (European Commission, 2018b). The second pillar aims to establish the digital communities for fostering rapid development and adoption of digital technologies throughout multiple industrial sectors, the so-called "*Digital Innovation for all: Digital Innovation Hubs (DIHs)*" pillar. DIHs are a one-stop-shop community environment, with self-administration and an established roadmap for fostering the development of digital technologies, through which companies can look for similar solutions between various industries in order to enable their digitalization and increase their competitiveness (Teixeira & Tavares-Lehmann, 2022). They are digital innovation centres that also aid suppliers and users of digital innovations to come together into focused funding project opportunities, supported by the Smart Specialization Strategy platform of the European Commission (European Commission, 2022b). When concerning the applicability of the initiatives, the European Commission devised the European Platform for National Initiatives as part of the third DEI pillar – "*A regulatory fit for the digital age*". Within this platform, the national governments could find the information of other digital national initiatives, promote financial support, and structure a coordinated regulatory effort on a regional level (European Commission, 2018b). Through this platform the European Commission also aimed to promote regulatory efforts for key areas of digital development, such as cybersecurity, data management and intellectual property of physical and virtual assets. Moreover, the European Commission moved beyond concerns regarding the macroperspective into a more micro-approach through the fourth pillar – "*Strengthening leadership through partnerships and industrial platforms*" – by promoting large-scale public-private partnerships and digital industrial platforms aimed at enabling leadership development for the digital era (European Commission, 2018c). These partnerships are part of an effort to enable shared experiences, collaboration in research and development, and the widespread knowledge of best practices on a regional level, all supported by funding scheme strategy (Smit et al., 2016). Finally, the fifth DEI pillar – "*Preparing Europeans for the digital future*" – refers to the European Commission's actions regarding the digital education and training for acquisition of digital skills of the workforce. Given the complex set of skills required for the development, adoption and implementation of digital technologies, the strategy is to promote lifelong learning and constant qualifications updates in an ongoing effort to provide trained and skilled labour for a more seamless transition into the digital era (European Commission, 2018c; Teixeira & Tavares-Lehmann, 2022).

To monitor the actions and development of the DSM and the DEI, the European Commission established the **Digital Transformation Monitor (DTM) and Digital Transformation Scoreboard (DTS)** tools (Berz, 2016). The reports present in the DTM aim to provide concise information on national policy initiatives for digitalization of industries and companies, objectives and challenges that can be tackled by policymakers regarding the digital transformation, possible synergies between national policies of multiple EU member states, and information on the measures for the DEI initiative. The DTS presented insights into the National Digital Strategies in terms of benchmarking of maturity levels, focus and objectives, challenges faced by the EU member states and common practices. Results from these assessments show the importance of industrial and research stakeholders to the development and implementation of the digital transformation, particularly when considering the development of novel solutions with existing technologies (European Commission & Executive Agency for Small and Medium-sized Enterprises, 2019). As part of the DTM, the DTS refers to four pillars that are used to evaluate the many aspects of the national industrial digital transformation (European Commission & Executive Agency for Small and Medium-sized Enterprises, 2019). Each of these pillars is assessed, generating a score that is combined for the final evaluation: (i) Indicator – measures the enablers and outputs of digital transformation resulting in the Digital Transformation Enabler's

Index, the Digital Technology Integration Index (DTII) and the ICT start-up Evolution Index; (ii) Survey – consists of a set of nine digital technologies and eight dimensions of analysis; (iii) Real-time data – a sense of the "digital pulse" regarding the volume, engagement and sentiment of key enabling technologies within specialized media and literature; (iv) Policy Analysis – comprised of the digital transformation performance analysis, the strengths and areas for improvement, a EU comparison analysis, and a "good policy" practices segment.

For the Multiannual Financial Framework 2021-2027, The European Commission has launched the **Digital Europe Programme (DIGITAL)**, which looks to provide all 27 EU nations with funding opportunities to define and implement a national digital strategy for their industries, citizens and public administrations (European Commission, 2021). The digital strategy for a nation comprises a set of policies to foster, enhance, update and/or implement digital technologies towards the digital transformations of businesses, citizenship and livelihood, public administrations, or a combination of these (European Commission, 2021). This European initiative aims to introduce the digital technologies and Industry 4.0 paradigms as key aspects of the European Innovation Policy, which promotes the successful development of high value added products and services, enabling European manufacturing industries as digital pioneers and innovators (Ciffolilli & Muscio, 2018). With an estimated budget of EUR 1.38bi, DIGITAL focuses mainly on the development of common data spaces, cloud-to edge infrastructure development, data-driven services and servitization capabilities, testing and experimentation facilities, security and usability of quantum communications infrastructure, and the development of digital skills in key capacity areas. Additionally, it also looks to foster initiatives for the development of widely used blockchain services, e-government and digital government actions, EU-wide digital identity, and investment platforms for strategic digital technologies. DIGITAL has initiatives on five key technological areas: high performance computing; cloud, data and artificial intelligence; cybersecurity; advanced digital skills development; and accelerator for the best use of digital technologies. Moreover, it is structured with actions that have close synergy with other European programmes, both from research and development as well as from the industrial implementation environment, such as Horizon Europe, Recovery & Resilience Facility, CEF digital and InvestEU (European Commission, 2021). The DIGITAL programme is tailored to support the digital transformation of the EU industrial ecosystems through funding schemes, upskilling initiatives, the development of European Digital Innovation Hubs (EDIHs), and the twin transitions towards a green, digital and sustainable EU industry (European Commission, 2021).

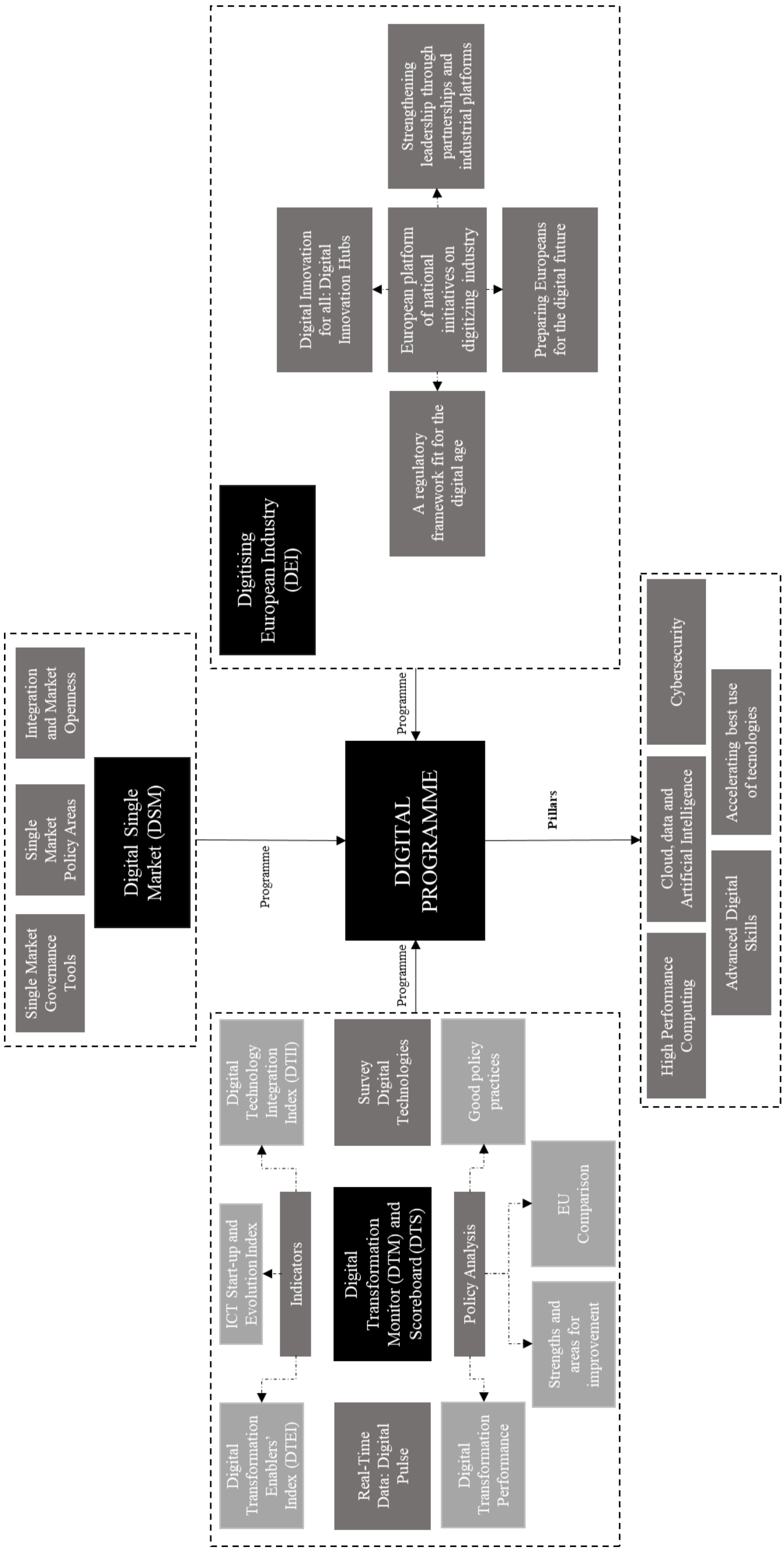

FIGURE 10 DIGITAL SUB PROGRAMMES AND TOPICS

4.2.2.2 Literature on policies for digitalization

When it comes to policymaking, the role of policies regarding the digitalisation of industries has only recently received attention by scholars (Bogumil-Uçan & Klenk, 2021; Liu, 2022). Scholars have investigated the issue through the identification of barriers to adopt digital technologies and propose mitigation actions, such as Kamble et al. (2018) and Tortorella et al. (2022). Still, more research is needed to investigate different strategies and policy mixes to foster digital technology adoption. These are a combination of policy instruments which are interrelated, aimed to achieve a desired outcome (Flanagan et al., 2011). In this research, we follow the definition of *policy* provided by Bauer (1968) and echoed in the works of Morgan (2017): "*Various labels are applied to decisions and actions we take, depending in general on the breadth of their implications. (...) For those that have the widest ramifications, and the longest time perspective, and which generally require the most information and contemplation, we tend to reserve the word policy"*. In accordance with this definition, we understand *public policy* as "*the sum of government activities, whether pursued directly or through agents, as those activities have an influence on the lives of citizens"* (Peters, 2018). Policy initiatives are made up of multiple policies, and can be defined as "*a plan or program that is intended to solve a problem* (Britannica, 2022). Examples of policy initiatives with multiple innovation policies are the "Mission Innovation" initiative – focusing on new clean energy technology, the "Global Covenant of Mayors for Climate and Energy" – aimed at climate solutions for urban sustainability transitions (Diercks, Larsen, & Steward, 2019), and the Canadian "Innovation and Skills Plan: Superclusters" – a finance initiative for the creation of 5 superclusters (Audretsch et al., 2020). Policy mixes are a set of multiple policy initiatives (Martin & Scott, 2000; Flanagan et al., 2011).

In literature, policy mixes are usually distinguished through different categorizations, such as mode of innovation (Martin & Scott, 2000) and types of firms (Zahra et al., 2022). Flanagan et al. (2011) distinguished policy mixes into four different categories – policy space, governance space, geographical space, time – and considers that policy mixes can have multiple interactions with/across the different dimensions, or they could also stand alone. Martin & Scott (2000) argue that institutional support frameworks should consider four different innovation modes – development of innovative inputs, application of innovative inputs, development of complex systems, high science-oriented technology – which dictate the appropriate policy response. Zahra et al. (2022) focused on the different types of firms related to their market strategy in order to shed light on their role within entrepreneurial ecosystems – digital disruptors, imitative followers, technology pioneers. The authors propose a digital technology framework promoting policies that enhance the entrepreneurship in ecosystems, particularly through the complementary characteristics and roles of new ventures, which aid companies in developing and sustaining their competitive advantage.

A different approach was proposed by Mansell (2021), who has focused on industrial economics to distinguish different policy strategies, most notably on Freeman's ICT paradigm-related adjustments – ambiguity, guiding principles and policy power and values. Mansell proposed three paradigm adjustment processes linked to policy recommendations - 5G innovation network and its capabilities, cloud innovation, and international taxation policies for the ICT paradigm. The changes follow the more recent European Commission understanding on the nature of digital business, where they "*have different characteristics than traditional ones in terms of how value is created, due to their ability to conduct activities remotely, the contribution of end-users in their value creation, the importance of intangible assets, as well as a tendency towards winner-takes-most market structures rooted in the strong presence of network effects and the value of big data*" (European Commission, 2018a). The taxation would be altered to enable a Digital Service Tax, where it would be collected when communications between human users of large digital platforms are involved, and when the purpose for data collection resides in monetary gains.

The policy literature also looks to compare policy mixes and strategies from multiple countries in an attempt to understand if similar approaches can be applied to multiple nations. Walwyn & Cloete (2020) made use of the technological innovation system (TIS) to understand the policy strategies in multiple industry fields of India, Estonia and South Africa – ICT, Banking and Financial Services, Manufacturing, Healthcare and Pharmaceuticals, Mining, Media and Entertainment, Logistics, Government and Public Sector, Education - and to provide policy recommendations. The authors use the OECD typology for innovation policy instruments (Meissner & Kergroach, 2021; OECD, 2012) to present a set of policy recommendations distinguished between supply and demand sides. They propose policies regarding investments for public communications infrastructure, workforce training, development of public digital platforms, and the adoption of a regional innovation approach to public services for digital workplaces – mainly public cloud and big data services. Alternatively, Audretsch et al. (2019) focused on understanding the innovative nature of start-ups and possible policy initiatives supported by reviewing 39 national policy initiatives with the goal to propose a process framework for policy recommendations that considered start-ups' antecedents, founding characteristics, behaviour, and policy outputs/impacts. On the European level, Teixeira & Tavares-Lehmann (2022) performed an exploratory research on the reports from the European Commission's Digital Transformation Monitor and consulting firms for 25 national initiatives, with the goal to understand the policies for adoption of Industry 4.0 technologies on all industrial sectors. The authors used the five main pillars of the digitizing European Industry initiative (DEI) to evaluate the National Digital Strategies, which consisted of (European Commission, 2018b). The authors also grouped 25 national digital strategies into six policy clusters according to the policies therein and their aim, scope and approach – (i) implementation of ICT infrastructure for the digitalization of economy, (ii) research, development and innovation (RD&I) initiatives for the development of smart products and services, (iii) adoption and implementation of emerging and enabling technologies, (iv) SMEs digitalization journey, (v) digital education and professional training, and (vi) promoting a robust regulatory framework and set of standardized norms that facilitate the adoption of digital technologies.

From these examples of the policy literature, there is not a consensus on the categorization of policy mixes for the adoption of digital technologies, as portrayed in our findings within Table 14 below. These studies do not directly relate the policy mixes to the barriers to adopt digital technologies. As pointed out by Nazarov and Klarin (2020), there is still a research gap concerning the understanding of policies for the digital transformation of nations. Following our findings from the literature review, there is still a lack of studies that consider analysing the European National Digital Strategies from the perspective of barriers to the adoption of digital technologies, and that go beyond a simple literature review. Our research looks to shed light on these research gaps.

TABLE 14 POLICY NEEDS FOR DIGITALIZATION

#	Barrier	Examples of policies to help overcome the barrier
1	Investments	• Support for venture capital markets (Martin & Scott, 2000)

		• RD&I investments, subsidies and funding for technology development (Martin & Scott, 2000; Teixeira & Tavares-Lehmann, 2022) • SMEs' investments and funding schemes (Teixeira & Tavares-Lehmann, 2022) • Investment in public infrastructure for connectivity and data, including policies for open access and architecture (Walwyn & Cloete, 2020) • Investment in public communications infrastructure to enable Digital Supply Chains (Aamer et al., 2022) • AMT adoption programmes – Government support for product innovation (Stornelli et al., 2021) • AMT adoption programmes – Promote assistance to SMEs seeking to upgrade to Industry 4.0 business model (Stornelli et al., 2021) • Foster the creation of platforms and funding schemes to aid domestic SMEs in reaching international markets through their digitalization (Denicolai et al., 2021)
2	Adaptive Organizational and Process Modifications	• Promote top management support within companies and associations to enable the digital transformation (Aamer et al., 2022) • Enable a widespread digitalization culture within the industrial sectors, particularly to resistant workforce, in order to provide a seamless transitioning environment to adopt digital technologies (Aamer et al., 2022)
3	Human Capital	• Promote digital skills development through digital education and digital literacy programs (Büyüközkan & Göçer, 2018; Teixeira & Tavares-Lehmann, 2022) • Develop the necessary human resources, especially in areas of software development, programming, data mining and digital intelligence (Sony & Naik, 2019; Walwyn & Cloete, 2020) • Promote training and knowledge sharing towards optimization of resources and specialization of workforce (Aamer et al., 2022; Denicolai et al., 2021) • Promote digital education programs, such as the Produktion2030's PhD School (Government Offices of Sweden, 2016) and the EIT Manufacturing Doctoral / Master Schools (EIT Manufacturing, 2020), that focus on the development of digital skills for target areas • AMT adoption programmes – Support for capability development (Stornelli et al., 2021)
4	Knowledge Management Systems	• Promote open and publicly available databases for R&DI (Bonnín Roca et al., 2016)
5	Clear Comprehension of Digitalisation Benefits	N/A
6	Standardisation Efforts	• Bridging institutions to facilitate standards adoption (Intarakumnerd & Goto, 2018; Martin & Scott, 2000) • Increase efforts of standardization to ease the adoption of digital technologies (Teixeira & Tavares-Lehmann, 2022) • Legitimize standardization efforts (Wiegmann et al., 2017)
7	Adaptive Retrofitting Implementation	N/A
8	Infrastructure	• Bridging institutions to facilitate development of infrastructure technology (Intarakumnerd & Goto, 2018; Martin & Scott, 2000) • Create ICT infrastructure to enable digitalization of economy (Teixeira & Tavares-Lehmann, 2022) • RD&I modernization of manufacturing facilities (Teixeira & Tavares-Lehmann, 2022) • Provide the infrastructure and teaching workforce for continuous training (Teixeira & Tavares-Lehmann, 2022)

		• Develop public/community digital platforms in areas of public interest (Walwyn & Cloete, 2020) • Promote the development and establishment of more robust cloud infrastructure given the rise of data volume (Mansell, 2021) • Increase the current and future cloud infrastructure computational capabilities to withstand the increasing complexity of AI-driven solutions, data-driven services and other cloud-intensive solutions (Mansell, 2021)
9	Security, Safety and Privacy Issues	• Increase the security of current cloud infrastructure as a counteract to national security and safety concerns (Mansell, 2021) • Enable propositions that counteract cybersecurity concerns, the openness of public networks and the known 5G technological vulnerabilities (Mansell, 2021) • Focus on fraud detection, digital citizenship protection and data sovereignty as pillars for building a robust cybersecurity system (Dobrolyubova, 2021) • Develop cybersecurity systems in parallel with IT systems development in order to enhance data authenticity, reliability and trust (Aamer et al., 2022)
10	Integration with existing technology	• Low-tech bridging institutions (extension services) to facilitate technology transfer (Martin & Scott, 2000) • High-tech bridging institutions to facilitate diffusion of advances in big research (Martin & Scott, 2000) • Promote integration with multiple devices within a digital supply chain, from different actors, in order to enhance information exchange and transparency (Aamer et al., 2022)
11	Regulatory Framework	• Promote the establishment of regulatory frameworks for digital enterprises (Teixeira & Tavares-Lehmann, 2022) • Provide enabling legal and regulatory frameworks, to enable easy and secure e-transactions, to prevent data appropriation by global corporations, and to regulate digital monopolies (Walwyn & Cloete, 2020) • Establish a supporting ecosystem for domestic digital firms through public procurement (demand-side support) (Edler & Georghiou, 2007; Walwyn & Cloete, 2020) • Implement e-government through contracting with local digital firms (Walwyn & Cloete, 2020) • Promote interdependence of political and economic powers of 5G innovation ecosystem (Mansell, 2021) • Promote a regional taxation model for ICT paradigm with particular focus on digital platforms (Mansell, 2021) • Decrease the inequality and unfairness of current taxation frameworks by implementing a Digital Services Tax focused on human user interaction and bit-rate charges for information exchange in the digital environment (Mansell, 2021) • Consider reduction of taxes related to the development, adoption and implementation of digital technologies by SMEs as a means to reduce overall costs (Denicolai et al., 2021) • Promote assessment of companies digital maturity levels and workforce digital skills as a precursors to providing acceleration and incubation programmes (Denicolai et al., 2021) • Incorporate e-government initiatives with intention of providing better services to citizens (Dobrolyubova, 2021)
12	Legal and Contractual Assurances	• Promote a solid legal framework for contracts leading to smaller digitalisation gaps and loop-holes (Schmidt & Krimmer, 2022) • Continuous amendments to existing legal frameworks (e.g. eIDAS regulation) to cover existing gaps (Schmidt & Krimmer, 2022)
13	Off-the-shelf solutions	N/A

14	Digital Strategy	• Promote definition of digital strategy and establishment of standards aimed at SME technology adoption (Teixeira & Tavares-Lehmann, 2022) • Adopt a regional innovation approach (e.g. supply public services to digital workplaces as a means of attracting entrepreneurs and employees) (Walwyn & Cloete, 2020) • High Cost of Capital – Promote decrease of high-complexity machinery costs (Stornelli et al., 2021) • High Cost of Capital – Outsourcing of data analysis services (Stornelli et al., 2021) • Promote digital strategy development focused on a specific form of digitalization (e.g. technology, market objective) (Aamer et al., 2022; Denicolai et al., 2021) • Foster SMEs adoption of digital technologies focused on either digitalization or sustainability, as opposed to a combination of both (Denicolai et al., 2021) • Promote reallocation of limited resources (investments, workforce) from digitalization to sustainability as the organization moves from domestic to international markets (Denicolai et al., 2021) • Digitalisation initiatives should be differentiated between European Commission and Member States, with involvement of business, universities and standardisation bodies (Schmidt & Krimmer, 2022) • European Commission should be responsible for agenda-setting; Member States and associated countries should be responsible for execution initiatives (Schmidt & Krimmer, 2022) • Establishment of mission-oriented consortia (Foray et al., 2012) • Establish Large-Scale Pilots (LSPs) as a framework to promote stakeholder participation, develop technical solutions and identify possible setbacks (Schmidt & Krimmer, 2022)

The assessment of existing barriers to the adoption of digital technologies in manufacturing industries, compared with existing policies from the literature to overcome these barriers, led us to conclude that there still are obstacles and barriers faced by companies during their digital transformation. Moreover, these barriers are not sufficiently studied and assessed by the policy literature, resulting in some barriers not being addressed, as presented in Table 14. Additionally, the literature on policies for digitalization did not focus on current European National Digitalization Strategies with the intent of identifying initiatives to overcome barriers to the adoption of digital technologies, particularly considering the DIGITAL programme and sub-programmes.

4.3 Methods

We applied content analysis (Berelson, 1952) to the European National Digitalization Strategies retrieved directly from the governmental bodies for each European Union Country. Content analysis is defined as a "*research technique for the objective,* *systematic, and quantitative description of the manifest content of a communication*" (Berelson, 1952 - p.18). It is, thus, a systematic and replicable technique used for synthesizing themes, concepts and ideas out of large volumes of textual data by converting these into categories through explicit rules of coding (Krippendorff, 2018; Stemler, 2000). Our aim is to shed light on the Research Question: "How can European National Initiatives be improved for the adoption of Industry 4.0 technologies?". More specifically, we set to identify the initiatives and barriers depicted on the European National Digital Strategies for adoption of i4.0 technologies. Moreover, we aim to map the identified initiatives and barriers according to established literature on barriers to adopt digital technologies (Senna et al., 2022). And, finally, we look to provide initiatives that tackle barriers not yet targeted by the European National Digital Strategies in order to improve the adoption of digital technologies.

4.3.1 Data Sources

We collected data from the 27 European Union Nations regarding their National Digital Strategy until 2025. Some documents spanned until 2030, and were also included in this review, however all evaluated aspects considered the deadline of 2023 to maintain validity across documents. The final set comprised of 31 National Digital Strategies and Initiative documents, retrieved directly from each nation's governmental branch for digital transformation, digital strategy or associated governmental agency specialized in the digital transformation of the nation. Most documents were retrieved directly from the European Commission's Digital Skills and Jobs Platform – European Initiatives' section (European Commission, 2019a), which is a repository for the 27 EU nation's digital strategy. Some of the documents focused solely on the governmental actions towards enhancing jobs and digital skills, to which they were complemented by ad-hoc searches for each country regarding their industrial digital strategy. Due to this fact, some countries were evaluated through more than one document. This strategy allowed for evaluating and comparing all countries regarding the holistic view of the industrial digital transformation, and not only the jobs, skills and educational digital transformation. 18 documents were originally in English, and for the remainder we used Google File Translator® to translate the original language to English (UK). The final set of documents and their characteristics is portrayed in Table 15 below.

TABLE 15 PROFILE OF POLICY DOCUMENTS USED FOR THE CONTENT ANALYSIS

Acronym (ISO, 1998)	**Nation**	**Document**	**Publishing Year**	**Period Covered**
AT	Austria	Digital Roadmap Austria (Republic of Austria, 2016)	2016	2025
AT	Austria	Digitalisation Report: Now for Tomorrow – Digitalisation growth for futureproofing (Republic of Austria, 2021)	2021	2030
BE	Belgium	Flanders in Transition: Priorities in Science, Technology and Innovation Towards 2025 (Flemish Council for Science and Innovation, 2014)	2014	2025
BE	Belgium	Digital Wallonia: Digital Strategy for Wallonia (Agence du Numérique, 2018)	2018	2025
BU	Bulgaria	Digital Bulgaria 2025 (Republic of Bulgaria, 2019)	2019	2025
CY	Cyprus	Digital Cyprus 2025 (Republic of Cyprus, 2019)	2019	2025
CZ	Czech Republic	Innovation Strategy of the Czech Republic 2019-2030 (Czech Republic, 2018)	2018	2030
DE	Germany	Digital Strategy 2025 (Federal Government of Germany, 2016)	2016	2025
DK	Denmark	Digitalisation that lifts society: the common public access digitization strategy 2022-2025 (Government of Danish Regions, 2022)	2022	2025
EE	Estonia	Estonia's Digital Agenda 2030: Development agenda of the field (Republic of Estonia, 2021)	2021	2030
EL	Greece	Digital Transformation Bible 2020-2025 (Government of the Hellenic Republic, 2021)	2021	2025
ES	Spain	Digital Spain 2025 (Government of Spain, 2022)	2022	2025
FI	Finland	Finland's digital compass (Government of Finland, 2022)	2022	2030
FR	France	Digital Transition Strategy 2021-2025 (AFD, 2021)	2021	2025
HR	Croatia	National development strategy of the Republic of Croatia until 2030 (Republic of Croatia, 2017)	2017	2030
HU	Hungary	National Digitalization Strategy 2021-2030 (Hungary, 2020)	2020	2030
IE	Ireland	Ireland's Industry 4.0 Strategy 2020-2025: Supporting the digital transformation of the manufacturing sector and its supply chain (Government of Ireland, 2019)	2019	2025
IT	Italy	National Recovery and Resilience Plan: Next Generation Italia (Italian Government, 2020)	2020	2026
LT	Lithuania	Lithuanian Industry Digitisation Roadmap 2019-2030 (Republic of Lithuania, 2019)	2019	2030
LU	Luxembourg	Digital Luxembourg Progress report: the evolution & the movement (Grand Duchy of Luxembourg, 2020)	2020	2025
LV	Latvia	Digital transformation guidelines for the year 2021-2027 (Republic of Latvia, 2021)	2021	2027
MT	Malta	Mìta Strategy 2021-2023 (Mita, 2021)	2021	2023
NL	Netherlands	Dutch Digitisation Strategy 2.0 (Netherlands, 2019)	2019	2023
PL	Poland	Digitization of the Chancellery of the Prime Minister (Republic of Poland, 2022)	2022	2029

PT	Portugal	Portugal Digital – Moving forward. Moving with a purpose: Portugal's Action Plan for Digital Transformation (República Portuguesa, 2020)	2020	2030
PT	Portugal	Portugal INCoDe.2030: National Digital Competences Initiative e.2030 (República Portuguesa, 2018)	2018	2030
PT	Portugal	Portugal i4.0 (Deloitte PT, 2016)	2016	2030
RO	Romania	Romania's Sustainable Development Strategy 2030 (Romanian Government, 2018)	2018	2030
SI	Slovenia	Slovenian Development Strategy 2030 (Republic of Slovenia, 2017)	2017	2030
SK	Slovakia	2030 Digital Transformation Strategy for Slovakia: Strategy for transformation of Slovakia into a successful digital country (Slovak Republic, 2018)	2018	2030
SW	Sweden	Smart industry – a strategy for new industrialisation for Sweden (Government Offices of Sweden, 2016)	2016	2023

4.3.2 Data Collection and Analysis

To reliably compare the National Digital Strategies, we made use of (Gioia et al., 2012) coding structure. The authors propose three levels for coding documents towards achieving comparable results: first order concepts, second order themes and aggregate dimensions. First order concepts are either extracted in-vivo from the documents or are given a code in order to signify the closest-to-source level of information possible. The second order themes are thematic categories used to aggregate similar first order concepts so that all similarities between different codes are grouped, while their discrepancies are noted. Finally, if necessary, aggregate dimensions are used to group second order themes so that all similarities on a given field are highlighted while presenting the possibility for highlighting discrepancies between very different aspects (Gioia et al., 2012). In our analysis we have considered barriers and initiatives found in the documents to be our first order concepts and second order themes, when necessary. And, in order to evaluate each National Digital Strategy with regards to the high-level barriers, we used the barriers to adopt industry 4.0 technologies portrayed by (Senna et al., 2022) as the aggregate dimensions of our coding structure.

Through content analysis of each document, all pertinent barriers, sub-barriers and initiatives were coded, and afterwards mapped to the 14 barriers to adopt i4.0. Content analysis was used given the advantage concerning the analysis and comparison of large volumes of textual information, most notably of the public sphere (Cann, 2021). The goal was to understand which barriers were portrayed in the National Digital Strategies, as well as their initiatives, and which barriers are missing from the European National Digital Strategies. The final coding structure resulted in 125 codes and 3924 coded segments, with two different coders, 14 barriers, 17 sub-barriers and 94 initiatives. Table 16 below displays the summary of the coding structure for each barrier, while Appendix 7.2 provides the full list of barriers, sub-barriers, initiatives, number of coded segments, and countries pertaining to each topic.

TABLE 16 SUMMARY OF THE CODING STRUCTURE

Barriers (# Coded Segments)	Sub-Barriers	Initiatives	Countries
Investments (337)	1	11	AT, BE, BU, CY, CZ, DE, EE, EL, ES, FI, FR, HR, HU, IE, IT, LT, LV, MT, NL, PL, PT, RO, SK, SW
Adaptive Organizational and Process Modifications (32)	0	4	AT, EE, EL, ES, FR, HR, HU, IE, SK, SW
Human Capital (822)	6	21	AT, BE, BU, CY, CZ, DE, DK, EE, EL, ES, FI, FR, HR, HU, IE, IT, LT, LU, LV, NL, PL, PT RO, SK, SI, SW
Knowledge Management Systems (40)	0	1	AT, BE, CZ, ES, FI, LT, LV, MT, NL, PL, RO, SK, SI
Clear Comprehension of Digitalisation Benefits (28)	0	2	BE, CZ, DE, IE, LT, LV, MT, NL, PL, SK
Standardisation Efforts (76)	0	3	AT, CY, CZ, DE, DK, EE, EL, FI, HU, IE, LU, LV, MT, SI
Adaptive Retrofitting Implementation (2)	0	1	IE
Infrastructure (593)	5	10	AT, BE, BU, CY, CZ, DK, DE, EE, EL, ES, FI, FR, HR, HU, IE, IT, LT, LU, LV, MT, NL, PL, PT, RO, SI, SK, SW
Security, Safety and Privacy Issues (337)	2	2	AT, BE, BU, CY, CZ, DE, DK, EE, EL, ES, FI, FR, HR, HU, IT, LU, LV, MT, NL, PL, PT, SI, SK
Integration with existing technology (47)	0	2	BE, BU, CY, CZ, DE, EE, EL, ES, HU, IE, LT, LV, MT, PL, PT, SI, SK, SW
Regulatory Framework (1156)	0	28	AT, BE, BU, CY, CZ, DE, DK, EE, EL, ES, FI, FR, HR, HU, IE, IT, LT, LU, LV, MT, NL, PL, PT, RO, SI, SK, SW
Legal and Contractual Assurances (75)	2	2	AT, CZ, DE, DK, EE, EL, ES, FR, HU, LT, LU, LV, MT, NL, PL, RO, SK, SW
Off-the-shelf solutions (1)	0	0	BU
Digital Strategy (378)	1	7	AT, BE, BU, CY, CZ, DE, DK, EE, EL, ES, FI, FR, HR, HU, IE, IT, LT, LU, LV, MT, NL, PL, PT, RO, SI, SK, SW

4.4 Findings

Overall, the European National Digital Strategies have focused primarily in five distinct issues: (i) the need for investment incentives (23 nations); (ii) the requirements surrounding education and training of human capital (22 nations); (iii) the needs related to infrastructure (22 nations); (iv) concerns related to security, safety and privacy issues (20 nations); (v) and the requirement for the definition of a digital strategy (20 nations). Apart from these, the National Strategies of most countries also considered aspects related to the definition of regulatory frameworks (17 nations) and the requirements regarding legal and contractual assurances (16 nations). On the opposite end, only one National Strategy mentioned the need for off-the-shelf solutions (Republic of Bulgaria, 2019), two mentioned the requirement for adaptive retrofitting implementation strategies (Government of Ireland, 2019; Republic of Latvia, 2021), and four consider to have actions related to knowledge management systems (Republic of Austria, 2021; Republic of Latvia, 2021; Republic of Lithuania, 2019; Romanian Government, 2018). Table 17 portrays a summary of the barriers observed in the European National Digital Strategies.

TABLE 17 SUMMARY OF BARRIERS CONTEMPLATED IN THE EUROPEAN NATIONAL DIGITAL STRATEGIES

	Barriers contemplated in the National Strategies														
	[1] Investments	[2] Adaptive Organizational and Process Modifications	[3] Human Capital	[4] Knowledge Management Systems	[5] Clear Comprehension of Digitalisation Benefits	[6] Standardization Efforts	[7] Adaptive Retroffiting Implementaiton	[8] Infrastructure	[9] Security, Safety and Privacy Issues	[10] Integration with existing technology	[11] Regulatory Framework	[12] Legal and Contractual Assurances	[13] off-the-shelf solutions	[14] Digital Strategy	TOTAL
Austria	X	X	X	X		X		X	X		X			X	**9**
Belgium	X							X						X	**3**
Bulgaria	X		X										X	X	**4**
Croatia	X		X						X		X				**4**
Cyprus	X		X			X		X	X	X	X			X	**8**
Czech Republic	X		X		X	X		X	X		X	X		X	**9**
Denmark			X			X		X	X			X		X	**6**
Estonia	X	X	X			X		X	X		X	X			**8**
Finland	X		X						X						**3**
France	X	X	X					X	X		X			X	**7**
Germany	X		X		X	X		X	X		X	X		X	**9**
Greece	X		X			X		X	X	X	X	X		X	**9**
Hungary	X	X	X					X	X	X	X	X			**8**
Ireland	X	X	X			X	X			X	X			X	**8**
Italy	X							X	X		X			X	**5**
Latvia	X		X	X	X		X	X	X	X	X	X		X	**11**
Lithuania	X		X	X	X			X		X	X	X		X	**9**
Luxembourg			X			X		X	X		X	X		X	**7**
Malta	X					X		X	X		X	X			**6**
Netherlands	X							X	X			X			**4**
Poland	X				X			X	X	X		X			**6**
Portugal	X		X											X	**3**
Romania	X		X	X				X			X	X		X	**7**
Slovakia	X	X	X					X	X			X		X	**7**
Slovenia			X			X		X	X	X				X	**6**
Spain		X	X					X	X			X		X	**6**
Sweden	X	X	X					X		X	X	X		X	**8**
TOTAL	**23**	**8**	**22**	**4**	**5**	**11**	**2**	**22**	**20**	**9**	**17**	**16**	**1**	**20**	

4.4.1 Investments

When considering the adoption of digital technologies, organizations usually tend to incur in high levels of investments, which can be of particular issue to SMEs (Ghadge et al. 2020; Kamble et al 2018). Unrealized return on investments and an increased risk related to the development and adoption of emerging technologies are also part of the financial expenditures related to digital technologies (Senna et al. 2022). European Nations take this matter seriously, considering it is the most noticeable barrier within national strategies, being mentioned by 23 out of 27 nations. However, the initiatives envisioned by European nations to tackle this barrier are not all the same.

Some nations chose to focus on the creation and development of attraction incentives for foreign investment and entrepreneurship development (CY, CZ, HU, HR, LV, PT, SW, SI). Others aimed on having a more robust funding initiatives schemes that encompass platform development (DE, EL, IT, NL), digital education (FR, IE, EE, LT), sustainability initiatives (EE, SW), standardization (AT, DE, EL, IE), and awareness (CZ, DE, FI, EE, PT, RO). Regarding the initiatives for platform development, Austria set forth a start-up enabling package that considered "*Risk capital bonus of 20% for investors to encourage investment in innovative start-ups; Increase in seed funding from AWS (Austrian Business Service) and allocation of the AWS Business Angel Fund*". Moreover, the package also considers the first stages of development by "*Funding for non-wage labour costs for the first three employees of innovative start-ups*". These initiatives are part of a platform developed for enabling innovative start-ups with intent to establish an investment foundation that will support the companies on their first stages of development (AT). On a different approach to platform development, Greece is looking to establish a Content Moderator platform responsible for integrating open data exchange standards, provide a real information system, supported by a level of business logic (e.g., in the form of rules and processes). The platform allows companies to exchange information through a Content Broker in a bid to make the process more secure, easy to use, coherent and collaborative. It will also be integrated with Public Administration open data information in order to increase the bureaucratic process regarding public documents (EL).

Interestingly, many countries opted to include initiatives related to innovation (18 nations) and infrastructure (17 nations), however these are at a higher level regarding the overall limits for implementation of more detailed initiatives on specific industries and fields. From these detailed initiatives we can highlight the need for Research, Development and Innovation Funding, which has been prominent for 10 nations (BU, CZ, DE, EE, EL, IE, IT, LV, SK, SW). For instance, the Czech government is looking to update the legislation regarding taxes for RD&I funding with intent in providing considerable tax deductions, while combining the effects of this measure with the creation of a robust education system for businesses to promote continuous training (CZ). With similar intent, the German government will introduce R&D tax breaks for SMEs with less than 1,000 employees in the form of tax allowances which can bolster the initial stages of these companies' development (DE).

Alternatively, Ireland wants to make use of existing State programmes both to provide direct RD&I grant supports through the governmental branches, and to promote the "*Future Growth Loan Scheme*", which sets a framework for enabling organizations' initial stages of development (IE).

4.4.2 Adaptive Organizational and Process Modifications

In order to adopt digital technologies, organizations must undergo changes to their organizational and operational process, of which we can highlight the decentralization approach, the use of autonomous robotics, and the complex IoT-embedded solutions that require integration of multiple systems and organizational areas of the company (Barros et al. 2017; Fantini et al. 2020; Senna et al. 2022). Given the incipiency of this barrier on the topic of digital technology adoption, only 8 nations have described this issue. To address this concern, the initiatives found in the national strategies are far and without a consensus. Some digital strategies elected to focus on initiatives for quality assurance of Information and Communication Technologies' implementation (EL, HU, SK), while others looked into providing changes to internal processes and adapting business models to accommodate for the emerging digital technologies (IE, HR, RO, SW). Two nations – Austria and Estonia – have presented digital strategies that combine these sets of initiatives with more cultural-driven actions. They have proposed work-from-home policies for organizations where non-essential workers can have more flexible hours, as well as constant educational strategies to dissipate aversion feeling for technology change – also regarded as change acceptance initiatives (AT, EE).

4.4.3 Human Capital

When considering the human capital, the barriers found in literature are related to the level of education, the skill of workers to accomplish their tasks, and the continuous training of the workforce to remain relevant both during and after the implementation stages (Dalmarco et al. 2019; Karadyi-Usta 2019; Senna et al. 2022). Considering that the adoption of digital technologies requires a multidisciplinary team with developed skills to tackle complex implementation and use-case situations, it is a relief to observe that this barrier is the second most prominent within the European National Digital

Strategies – with 22 nations pointing out the issue. The national strategies describe the need for Information and Communication Technologies' competencies, the lack of continuous training, and the lack of a digital education infrastructure targeting the Science, Technology, Engineering and Mathematics (STEM) system, especially for underrepresented groups (15 nations). Some strategies also depict the lack of working experience from tutors regarding online teaching and learning methods (AT, DE, HU, LV, RO), the lack of support for learning structuring (AT), and the lack of future job stability (SK, SW).

To address this issue, the majority of nations have focused on a group of initiatives that are similar in nature (20 nations): (i) the focus on digital inclusion and digital literacy from early school years and for the elderly; (ii) the development of digital skills through educational programs that target multidisciplinary components and the fusion of elementary topics into digital-driven solutions; (iii) and the continuous training of the workforce through recurring training sessions on emerging technologies in partnership with digital education organizations, innovation hubs and research and development centres. Additional initiatives include, for instance, the incentive of quality-of-life improvement activities off-work and the creation of high-quality jobs with high value added (SI). Also, initiatives concerning the awareness of digital skills through promoting the benefits of training activities and constant self-improvement are of interesting note (AT, CZ, DE, EL, IE, HR, HU, LV, PT), likewise the initiatives for increasing minorities participation in the digital working space (PT). There are also initiatives to address the possibility of expanding distance learning and the renewal of the educational curriculum to better represent the ratio of students that might elect this form of education here on out (AT, DE, EL, LU, LV, PT).

With regards to the organizations, there are initiatives depicting the retention and attraction of talents (BE, BU, CZ, DE, HR, HU, LU, PT, RO, SK, SW), as well as the incentive to demographic renewal and foreign workforce attraction (CZ, DE, DK, EE, EL, HR, LU, LV, NL, SI, SK, SW). Employability is also a prominent topic within the national strategies (mentioned by 14 nations), albeit rather vague when concerning the details, with the documents only representing the will to decrease the unemployment rates and increase employability of upcoming generations through digital education, but without more concrete actions to address current employability issues.

4.4.4 Knowledge Management Systems

An important aspect of the adoption of digital technologies is the surrounding systems that need to be integrated in order to provide a continuous flow of data and information, especially when considering real-time operations (Stentoft & Rajkumar 2020; Kamble et al. 2018; Senna et al. 2022). These systems are known as knowledge management systems, and are used in integration with IoT devices towards data-driven solutions, such as services in the post-sale of products or servitization and subscription-based services (Senna et al. 2022). Regarding the National Digital Strategies, very little is addressed on the topic. The only initiative regards public data availability for data-driven services provided by the national governments, which are in line with their strategies to transition into e-governments and digital governments altogether – mentioned by 12 nations. These initiatives encompass the availability of data through public access servers (AT, ES, FI, NL, PL), the use of open-source solutions with public repositories (LV, SI), public repositories for scientific publications and R&D results funded by governmental agencies (AT, CZ, PL, SK).

4.4.5 Clear Comprehension of Digitalization Benefits

Benefits related to the digitalisation of organisations are costs reduction, expansion of business opportunities and increased production efficiency (Senna et al. 2022). There are also benefits to the environment, namely the establishment of smart factories integrated with innovation centres and research and development institutions that can promote a fast-paced change of cultural mentality and digital education availability to the local market (Dalenogare et al. 2018). Despite these benefits, many companies and individuals still lack a clear comprehension about the benefits of adopting digital technologies and incurring in continuous digital education and digital skills training (Senna et al. 2022). As observed, National Strategies have already tackled the issue of digital education, but they do not, for the most part, refer broadly on initiatives for fostering knowledge of the digitalisation benefits to industrials and entrepreneurs. Only five national strategies mention the issue (CZ, DE, IE, LV, NL). One of the initiatives regards the expansion and intensification of consultation services with digitalisation guides in order to enhance SMEs and merchants' access to broad knowledge on ICT solutions (DE, LV). Another interesting initiative regards the creation of Smart Industry Field labs and hubs where entrepreneurs would receive education and research for digital innovation, would be able to experiment with hands-on digital solutions, would participate in co-creation innovation projects, and would have the assistance in finding suitable fundings (NL).

4.4.6 Standardization Efforts

The implementation of digital technologies requires many interoperability activities and integration of multiple systems in order to achieve its full potential, which highlights the need for standardisation efforts that are comprehensive and widespread (Senna et al. 2022). Despite the urgent need address this concern, and the critical role that governmental bodies have in making the standardisation more seamless and agile, not even half of the national digital strategies have identified this issue (11 nations), and actions regarding it are seldom standardised on their own. Some nations have elected to focus on promoting communication process standardisation efforts, much in synergy with their own communication infrastructure development (AT, CY, DE, DK, EE, FI, LU, MT, SI). Other nations are directing efforts towards the Industry 4.0 standards initiatives, mostly through widespread information and use of the standards already in place through the Reference Architecture Model for Industry 4.0 – RAMI 4.0 (Hernández et al. 2020; AT, CZ, DE, DK, EE, EL, IE, HU, LV). Apart from these, there are only two nations – Czech Republic and Ireland – which are enforcing initiatives to promote educational standards regarding the online and remote learning for new generations (CZ, IE).

4.4.7 Adaptive Retrofitting Implementation

When considering the digital transformation of production equipment, companies must also address the concerns regarding connecting legacy systems to digital machinery, which either occurs on a stage-by-stage approach or through the adaptive retrofitting implementation of the legacy systems for digital capabilities (Senna et al. 2022).

Despite being a common and reoccurring problem for organisations, with companies having to adapt their equipment after every major technological leap, the national digital strategies have yet to take interest on the matter. The only nation that has considered efforts for the adaptive retrofitting implementation is Ireland (IE). On their document, the Irish Government looks to create and promote access to demonstrator facilities where entrepreneurs can carry out hand-on experimentation, identify and address technical challenges during the implementation stages including issues related to the integration of digital technology into legacy systems. In essence, it looks to promote a safe laboratory environment for testing and full-proofing solutions that tackle the seamless integration of multi-generation equipment, and, in-so-doing, enhance the circular factor and sustainability of the production cycle (IE).

4.4.8 Infrastructure

Enabling the digital transformation requires a robust infrastructure, either the building/structural, or communication and IT, given the prevalence of real-time information and data flows, data-driven services and resource-intensive production (Kadaryi-Usta, 2019; Kiraz et al. 2020). Due to the critical role that national and local governments have in establishing the required infrastructure, and the impact that a well-defined and operational infrastructure has on the production efficiency of industries, it is only fitting that the European National Digital Strategies would address this concern with multiple initiatives. Tied in with the issues regarding Human Capital, being observed for 22 nations, the lack of well-developed and robust infrastructure functions as another weight in the delicate balance needed to foster the adoption of digital technologies.

We also observed a few additional barriers highlighted by the Digital National Strategies regarding the infrastructure topic. One of these is the lack of initiatives to promote smart cities – present for 11 nations, tied in with another identified issue in the form of a lack of communication and IT infrastructure – observed for 17 nations. These issues are even more prominent when considering the immediate environment of the industrial facilities, with special focus on the last operation of the production cycle – the delivery. Hence, for 9 nations there was also a lack of backbone transport infrastructure network, which is combined with a lack of urban mobility infrastructure initiatives.

To tackle these critical concerns, the European nations have drawn several initiatives. By far, the most prevalent initiative regards the development and establishment of data-related infrastructure and of public digital infrastructure – present in all 22 nations. Specifically, the initiative regards the creation of public databases for public data access that can aid in infrastructure optimization, either through the resource route (i.e., real-time energy distribution optimization, use of materials), or through the delivery/transportation route (i.e. optimization of routes, public transport information, public delivery companies information). Apart from these, there are also initiatives regarding setting up accelerators and incubators targeting infrastructure companies (AT, DE, EL, ES, IE, HU, MT, NL), development of an online platform for entrepreneurship fostering and contact sharing (ES), and the inclusion of adaptive risk management strategies regarding building and maintaining public infrastructure (NL, SK). Finally, there is one particular initiative that sets itself apart from the rest and targets the residential scheme for multinational employees (NL). Coupled with SME-driven initiatives to foster foreign investment and entrepreneurship onto the Netherlands, the National government aims to create a residence scheme for essential foreign employees (i.e. non-EU countries' citizens) as part of promoting demographic renewal and managing city-wide transport that optimizes time-to-office (NL).

4.4.9 Security, Safety and Privacy Issues

The increasing use of communications for data and information flow, combined with the adoption of digital production equipment, sets the scene for a new wave of cybersecurity threats (Stentoft & Rajkumar 2020; Xu et al. 2018). Not only that, but the European Union's directive to promote digital citizenship through a competence framework (European Commission, 2019b) mean that the cybersecurity of Europeans is at the forefront of the EU governments. Most notably, issues related to the identification verification, authorization procedures and protocols, privacy and system access are expected to rise with the digitalisation of nations (Senna et al. 2022). It is, evidently, a major concern, corroborated by its presence in 20 European National Digital Strategies. Specifically, two detailed concerns were pointed out: (i) lack of trust on digital solutions security – 15 nations; (ii) and lack of consumer-oriented data sharing safety.

To tackle both, the national strategies depict initiatives targeting data security on both ways of the business-to-government link – 19 nations. On this matter, this Austrian government looks to set up the "once only" principle – all relevant data will only be submitted once to the authorities and will automatically be available for download on a range of official channels through a unique communication connection (AT). In line with this approach, the Danish government will update their policy to "*allow citizens to easily get an overview of, give and revoke consent for data to be shared and used*" (DK). Many nations are of a similar mindset, albeit not so specific, with a common objective: to promote trust in government-related information sharing, on the availability and security of data, and in the administrative safety of private identities (EE, EL, FI, FR, HU, LV).

Another initiative, from the French government, regards the development of a digital identity system in partner countries with focus on controlling the significant risks that these interconnected sharing systems may pose for individual freedoms (FR). Such initiative goes in accordance with the "*agreement between the European Commission and the USA on an EU-US privacy Shield for transatlantic data communication*", which ensures privacy and protection of trade secrets and national security – also considered by the German government (DE). Combined with this approach, the Belgium regions of Flanders is looking to establish advanced encryption technology for intellectual property protection, due to the region's strong scientific position and solid international reputation (BE). The cybersecurity concern is widespread to the point that minor European nations, such as Bulgaria, are establishing the foundations to provide a "*modern framework and a stable environment*" for a national cybersecurity system (BU). A novel approach on the topic comes from the Dutch. Their National Strategy details an implementation of five projects for citizens, business, institutions and government agencies supported by blockchains, which will increase identity safety, restructure the pensioning system, provide transparent, reliable and fair supply chains for logistics, and promote easiness of credential verification for education institutions (NL). As part of the NL DIGITAAL – the Data Agenda Government – this initiative is combined with AI solutions focused on ensuring data accessibility, data-driven problem resolution, responsible data use and advanced legislation and regulations (NL).

4.4.10 Integration with existing technology

The complex nature of advanced manufacturing technologies requires the design, development and implementation of technological solutions with an integration mindset, leading to the need for a seamless integration of existing equipment and new machinery to not substantially disrupt the production process (Flatt et al., 2016; Pedone & Mezgár, 2018). The main challenge is the retrieval of data from multiple sources, which involves complex computational solutions for the translation of different information into a single universal set of data (Pedone & Mezgár, 2018). 18 countries mention aspects related to seamless integration with existing technology in manufacturing industries. When it comes to sets of initiatives, the national strategies focus on two approaches: (i) scientific (RD&I) infrastructure development (BU, EE, EL, SI, SK, SW); (ii) Collaboration initiatives with Factories of the Future (FoFs; BE, CZ, DE, EL, ES, HU, IE, LV, MT, PL, PT, SI, SK).

The development of scientific infrastructure will serve as a testing facility for integrating solutions before their implementation into the factories' shopfloors. Additionally, as pointed out by the Bulgarian national strategy, the "*construction, maintenance and access to modern research infrastructures guarantee high quality of conducted research, (…) promotion of entrepreneurship through the possibility of generating new knowledge and its transfer in the country's economy*." (BU). Moreover, the Bulgarian government points out the relevance of the electronic scientific infrastructure, which is formed by a digital laboratory where researchers and practitioners can share common solutions both in person and through remote access (BU). The Greek national strategy goes a step beyond, stating that these scientific infrastructures can also serve as repositories for testing grounds both with manufacturing data and with public administration information, in a bid to integrate not only the equipment within a shopfloor but also the information flow between the multiple levels of the organizations' value chain (EL). Complementary, the Estonian national strategies envisions the use of these digital laboratories for research on cybersecurity-related research and development, greatly enhancing the security and safety of the integration process during the implementation stage (EE).

Building on the scientific infrastructure initiatives, the national strategies also consider a set of collaboration initiatives with Factories of the Future, which are manufacturing shop-floors with enhanced digital technologies and capability of expansion for a more virtual approach to manufacturing (IT, BE). These initiatives look to upgrade existing factories to accommodate for the requirements of a digital manufacturing environment. In line with this thought, Belgium regions are promoting investment initiatives to upgrade the manufacturing factories, claiming outcomes in the form of significant reduction of resources and energy consumption, leading to significant decrease in operational costs and enhancing the "flexibility of the Flemish production apparatus, so that it can repost to market dynamics with twice the speed." (BE). On a similar approach, the Czech initiative mentions the establishment of a system to uphold resource optimisation and environmental protection (CZ). With a more organisational mindset, the Greek initiative considers a governance model to shape and institutionalize "*(...) interoperability between co-competent services and bodies (...)*", in a bid to promote better information exchange both within companies and between business and governmental agencies (EL). The Portuguese government, through the PSA Mangualde Consortium, aims to develop technologies and solutions to kick-start the intelligent transformation of factories, through a €12 million investment and focusing on collaborative robots, advanced tracking and tracing systems (e.g., through the use of virtual and artificial realities), autonomous guided vehicles and digital manufacturing production cells (PT).

4.4.11 Regulatory Framework

Fostering the adoption of digital technologies and their implementation within manufacturing industries is at the forefront of governmental policies, most notably since the establishment of the Industry 4.0 paradigm as a public policy for industrial development and business model improvement (Kagermann et al., 2013). These policies are part of a regulatory framework devised to provide legal safety, intellectual property and innovation security, privacy and cybersecurity legal framework, IT development standards adopted at the infrastructure level, and parametrization for the interaction between humans and equipment for the establishment of collaborative work (Ghadge et al., 2020; Stentoft et al., 2021). Not surprisingly, this is the central topic observed on all national strategies. Despite agreeing on the overall topic of presenting initiatives either to create, or to develop existing, regulatory framework for the adoption of digital technologies, the actions proposed by the national strategies differ on their scope and focus.

The first topic of focus of the initiatives regards fostering circular economy (BE, DE, DK, HR, RO). On this, the Belgium governments of Wallonia and Flanders recognize the prominent role of circular economy as a long-term ambition for resource management and energy consumption reduction (BE). The country's proposal on the topic is to aid companies during the product design stage to incorporate circular economy as a design principle, which can be achieved through a set of regulations to promote design standards for key manufacturing sectors with this principle as core concern (BE). Similarly, the Croatian government includes circular management of spaces and buildings as part of their industrial regulatory framework, in the form of incentivized regulations for less carbon-intensive industries that can objectively prove their sustainability contributions through transforming their manufacturing facilities (HR). The Danish government goes a step beyond by establishing a circular data bank to collect "*valid data on waste, raw materials and materials to pave way for greater reuse and recycling, new green business models and reduce the need for disposal and incineration of scarce resources.*" (DK).

Another regulatory framework focus refers to cooperation initiatives, which is present in 25 national digital strategies. These initiatives are usually described as cooperation efforts for RD&I between European members, normally fostered through European framework programmes such as the Horizon 2020 and Horizon Europe (AT, DE, ES, HR, PT), as well as other European actions such as the Electronic Components and Systems for European Leadership (ECSEL), ERA-Nets, EUREKA and Eurostars initiatives (AT, PT). Additionally, some national strategies look to establish their networks off-seas, such as the Austrian OPEN AUSTRIA initiative which seeks to establish Austrian companies in the Silicon Valley (AT) and the Estonian effort to "*promote the cross-border and global exchange of (personal) data between countries (…) and activities (…) [to] advance and ensure the global development and use of human-centric and reliable technology.*" (EE, MT). Complementary, other countries looked to provide a more robust internal framework targeting strategic alliances between national and European universities (BU, CZ, DE, ES, FI, HR, IE, NL, PT, PL, SW). These initiatives are supported by public multi-lateral agreements of information sharing among the governments which help in fostering knowledge sharing and dissemination, especially between leaders and followers of the digital transformation (CZ, DE, IE, PT, SW). Another cooperation initiative is the "*organisation of thematic technology missions of Czech experts to countries with cooperation potential*", which can either be within the European community or internationally, and function as scouting parties for the establishment of new bi-lateral / multi-lateral agreement arrangements (CZ, IE). The Slovakian government provides a more detailed approach by looking to amend their legislation, particularly Act No. 311/2001 of the Labour Code, in such a way as to "*simplify the employment rules for entrepreneurs operating in several EU countries in the digital economy, as well as the rules of taxation and regulation compliance for a faster expansion of Slovak businesses to other EU countries*" (SK).

The crucial point of regulatory framework initiatives regards the policies for innovation fostering. These can range from actions and initiatives towards promoting fair competition, the use of regulated online markets, transportation and shipping regulatory proceedings (particularly when involving autonomous vehicles), to infrastructure construction proceedings. Moreover, policies can incorporate aspects related to data regulation compliance, legal security framework, public and/or private financing initiatives, digital education policy and workforce development, and electronic exchange of information. All 25 countries have provided multiple initiatives for each of these subtopics, where the data regulation and legal security framework are, by far, the most referenced (22 national strategies). One example of a very prominent initiative repeated in 15 national strategies is the need to develop specific measures to ensure transparency and data protection in individual pricing processes following the General Data Protection Regulation (GDPR) act. This is usually combined with an initiative to modernize the Internet regulation policy, with particular focus on cybersecurity law. One example of such initiative is the Austrian proposal of enabling "*notification obligations for operators of essential services, CSIRTs, definition of international cooperation and also national and international contact points*" (AT). Another initiative that accompanies the same mindset if the French proposal to draft a regulation to identify and authenticate citizens for public access services, achievable through "*digital identity systems in partner countries, focusing on controlling the significant risks that these systems pose for individual freedoms*" (FR). Complementary, the Latvian government looks to establish a regulatory act in accordance with their

Digital Technology Management Law, and which must "*include the requirement that before the creation of any ICT service, state authorities are obliged to identify its potential cybersecurity risks by performing a cybersecurity risk analysis*" (LV). On the legal framework perspective, most initiatives regard the protection of intellectual property rights and patents with commercial potential (17 national strategies). An example of the Latvian understanding of how to incorporate these objectives into the regulatory framework. In the Latvian government's understanding, the "*set of measures should be such that it ensures adequate security and confidentiality of personal data*", going even further by detailing that such personal data processing should happen under a technologically neutral manner (risk-free of political bias; LV). Luxembourg has implemented the "*MyGuichet.lu*" platform which corresponds to these expectations given its foundation on a regulatory act for household property laws that are valid both in the physical environment as well as in their digital and virtual forms (LU). The Portuguese set of initiatives focus not only on the intellectual property rights of products and services, but also in regulating public administration and business' proceedings regarding continuous training of their workforce with respect to adequate cybersecurity measures (PT). Additionally, the Portuguese Action Plan for Digital Transition drafts an initiative to reduce legislative and bureaucratic barriers to the free flow of data and the development of an ethical data usage guide, in accordance with the EU Regulation 2018/1907 of the European Parliament and Council, as well as the "*transposition of the European Directive 2019/1024 on open data and the re-use of public sector information*" (PT).

A last topic within the regulatory framework is the establishment of the electronic government, also known as the digital government, noted by 24 national strategies. The initiatives on this topic refer to the creation of digital identities, such as the ID Austria (AT), as well as promoting the optimization, digitization and modernization of public administration and judiciary (AT, BU, CZ, DE, EE, EL, ES, HU, IT, PL, PT). The core concern is to provide a digital environment for citizens as a "one stop solution", where a wide array of access channels will be available, from the personal identification suite, standardization norms and procedures, citizen data regarding public services (to the extent of law, which usually exclude the criminal act and other information safeguarded by confidentiality terms), public administration records and open data repositories. Moreover, it will serve as a platform to access third party services through a safe and comfortable digital government platform.

4.4.12 Legal and contractual assurances

Apart from the regulatory framework, the adoption of digital technologies also requires a set of legal and contractual assurances with particular focus on virtual assets, both regarding the products and services, as well as the production processes (Ghadge et al., 2020; Kamble et al., 2018). The digitalization of firms leads to the establishment of a virtual identity for the firm, functioning as a digital representation of the physical infrastructure and production processes, where organizations can perform optimization experiments and design improvements of their products and services (Ghadge et al., 2020; Stentoft et al., 2021). 18 national strategies reference aspects related to legal and contractual assurances, where some focus more on the identification of sub-barriers while others are more concern with providing initiatives.

The main obstacles observed within the national digital strategies are the lack of e-commerce legal assurance (DE, EL, LU, PL, SK), and the lack of digital information sharing amid peers (AT, DE, DK, EE, EL, LT, MT, NL, SK). The German national strategy focus on issues related to cross-border e-commerce legal obstacles and their effect on the availability and access of private individuals and companies to a larger assortment of goods and services at lower prices (DE). On a similar note, Luxembourg notes the recent online market development and their prominent role during crisis and local disruptions, particularly during the COVID-19 pandemic (LU). To this end, a few countries are promoting initiatives to establish legal frameworks for online markets and smart contract sharing through digital platforms (EL, LU). An example of such initiative comes from Greece, in the form of a pilot platform that is supported by Electronic Catalogues (eCatalogues), Framework Agreements and Dynamic Purchasing Systems, with intent on establishing Electronic Stores (eShops) and Electronic Markets (eMarketplaces) (EL). Another similar solution comes in the form of providing legal assurances for novel electronic payment methods such as the use of Near Field Communication contactless solutions (HU, NL, PL), which require additional guarantees in the backend portion of the transaction in order to ensure that all financial information is shared between the parties during a transaction process in a seamless, fast, and easy to use fashion.

As stated, the national strategies also reference difficulties regarding digital information sharing. The main obstacle on this topic regards the creation of an all-access, open data information platform that is safe, secure, and provides high levels of privacy, while also allowing the access to individuals and companies when conducting their business amid peers (DE, EE, NL, SK). Possible solutions to this issue arise from initiatives regarding the establishment of a Digital Single Market on a national level, which would function as a centralized information hub for business creation and open data availability (AT, EE, EL). Complementary to this initiative is the action to revise the current telecommunication regulations, which must "*include flexible approaches in selecting regulation instruments, creating investment incentives for broadband deployment, appropriate use of (...) over-the-top services (OTTs) [and] a minimum level of harmonisation of consumer rights (...)*" (DE, EL). Another initiative in a similar mindset is the development of legal frameworks targeting the integration of national industries to the international value chains (LT). Another set of initiatives regard the strengthening of intellectual property protection laws, particularly for the virtual assets of firms (CZ). In a similar fashion, Malta has proposed initiatives targeting the creation of a "*comprehensive information security framework to uphold the confidentiality, integrity and availability of Government's digital assets while enhancing cybersecurity at a national level.*" (MT).

4.4.13 Off-the-shelf solutions

The constant development of manufacturing technologies and information systems exponentially increase the complexity level of current available solutions, which is exacerbated by the greater development of customized solutions. This scenario hinders the existence of off-the-shelf solutions, which can greatly aid smaller companies in their digital transformation journey by reducing expenditures related to development and testing of custom-made solutions, favouring a more standardized approach when adopting equipment and technologies that are not part of the products and services offered by the company (Senna et al., 2022). However, digital off-the-shelf solutions can only be offered when predetermined conditions are already well under development, such as the IT infrastructure, the establishment of communications and information exchange protocols, interoperability solutions and full integration with legacy systems (Barros et al., 2017). The only mention to this issue was within the Bulgarian national strategy, where the document refers to the need to have more coordinated and efficient ICT solutions for industries, particularly the "*ready-made solutions to be adapted in favour of increasing productivity.*" (BU). Despite identifying the issue, the national strategy does not provide a concrete initiative to overcome this barrier.

4.4.14 Digital Strategy

The definition of a digital strategy is a critical concern regarding the adoption of digital technologies (Müller et al., 2018). When defining the digital strategy, the organization should consider the vision, mission and values, as well as the main objective to be achieved with the digital transformation (Stentoft & Rajkumar, 2020). Organizations that do not have a well-defined digital strategy, with a detailed action plan, and that is spread out within the organization as a cultural transition towards a new business model will face severe challenges both in the adoption stages as well as in the maintenance stages of digital technologies (Ghadge et al., 2020; Stentoft & Rajkumar, 2020). With such a crucial role in the adoption process, it makes sense to observe the prominence of this barrier on the European National Digital Strategies, being present in every national strategy. In a broad sense, the focus was mostly on digital strategy initiatives for fostering business innovation (12 national strategies), for providing competitive advantage and boost (24 national strategies) and for promoting synergetic development through interorganisational cooperation (20 national strategies). This last topic is a direct counterpoint to the sub-barrier identified, which related to the collaboration initiatives between Public-Private entities (AT, BU, CZ, EL, LU, LT, LV, SK).

The lack of collaboration initiatives is seen as a cause to the poor business potential and decrease business value creation opportunities (BU). One example of such shortcoming is the "*lack [of] a system to incentivise spin-offs, start-ups, and the creation of natural cooperation between students and companies in advanced technologies, including the establishment of their own companies (…)*" (CZ). Another prominent example is the lack of metrics available to assess the synergies created between public-private entities, hence leading the policymakers to propose generic initiatives with very little impact (EL). To overcome these issues, the Greek government has proposed the development and implementation of a digital maturity assessment system for documentation of their current and future stages – the Digitometer – which can support companies, especially SMEs, in seeking out necessary aid from public bodies, research centres and funding initiatives for specific goals (EL). This initiative would have the additional advantage of serving as a kick-off stage to the definition of a digital strategy, considering the maturity assessment models, when devised focusing on roadmapping establishment, often consider the management and technical aspects of the current and future technological stages (Büyüközkan & Göçer, 2018; Kiel et al., 2017). Luxembourg goes one step further by proposing the Infrachain initiative, which is a blockchain-driven platform serving as the foundation for public-private partnerships in a safe environment, while using the security and peer-to-peer characteristics of the distributed ledger technology to promote collaboration and cooperation actions (LU). The Infrachain initiative also considers the use of smart contracts – virtual contracts with legal bindings that are automatically amended for each new transaction – which promotes the establishment of legal framework for the digital business era.

As pointed out, most national strategies' initiatives for digital strategy definition focus on business innovation. These can either be general, such as the Czech "*Competitive and innovative economy*" – which is a set of five different initiatives at a high level serving as guidelines for the development of more detailed public policies at a later stage (CZ), or they can be more detailed, such as the Portuguese "*Next47*" – which is an independent business unit for entrepreneurs that is responsible for the research and development of disruptive solutions, as well as for accelerating the implementation of emerging technologies on the manufacturing sector (PT). Another interesting approach to this is the proposition to introduce a sustainability mindset into the definition of the organization's digital strategy, which can be achieved through advanced manufacturing technologies and data-driven services tailored towards a positive environmental impact (AT, BE, CY, CZ, DK, EE, EL, FI, FR, HR, HU, LV, SI, SK, SW). A worth-note initiative on this topic comes from the French government, "*Aim for digital sobriety*", which seeks to perform constant analysis of digital projects in accordance with the Paris Agreement to select candidates for funding schemes and innovation programmes, in a bid to transform the current industry into an environmentally driven sector (FR). The national strategies also propose to have a target focus regarding the digital technologies and their business innovation capabilities, such as the Finnish and Portuguese strategies on artificial intelligence and data-driven services (FI, PT) and the Czech "*Smart Specialisation Strategies*", a group of technologies that include laser, nanotechnology, biotechnology, artificial intelligence, and energy-saving solutions (CZ).

4.5 Discussion

4.5.1 Similarities and improvements

When comparing the analysis of the European National Digital Strategies with the objectives and scope of European Commission's DIGITAL Programme (European Commission, 2021), it is clear that most of the national initiatives contemplate the key areas of the newly established programme. The DIGITAL Programme focuses on three different technologies – Cloud computing, artificial intelligence and cybersecurity – as well as data spaces, green digital services, development of digital skills and initiatives to accelerate the implementation of digital technologies through the depiction of best use cases (European Commission, 2021).

To this end, the national strategies depict several initiatives regarding advanced manufacturing technologies which also consider the development and use of cloud services, artificial intelligence and cybersecurity solutions. Some countries, such as Finland and Portugal, as focusing specifically on these technologies to promote their industries in a bid to establish a competitive advantage and to serve as knowledge hub for the European industries (FT, PT). Cloud services are present in most of the national strategies, either as a deployment of a physical servers or through the development of cloud-based services. Moreover, countries are using data-driven services in a bid to promote green solutions, following the findings from Mansell (2021) and Denicolai et al. (2021). Additionally, the national strategies are also using the established data infrastructure to promote open data access, which will aid in decreasing bureaucratic processes and increasing the safety and agility of information sharing amid peers. With regards to the cybersecurity capabilities, the national strategies follow the propositions from the literature regarding development and use of cybersecurity solutions to promote a safer environment for communications, online market commerce and data sharing between public and private actors (Aamer et al., 2022; Mansell, 2021; Schmidt & Krimmer, 2022). Countries are more concerned with developing cybersecurity solutions that enable the digital citizenship, promote data sovereignty, and prevent frauds on the virtual environment, closely related with the propositions by (2021).

Concerning initiatives for promoting *digital education and enhancement of digital skills*, national strategies propose a number of actions that target the improvement of digital literacy and skills for the future generations, closely resembling the policies proposed in the literature (Büyüközkan & Göçer, 2018; Stornelli et al., 2021; Teixeira & Tavares-Lehmann, 2022). Some strategies, such as the Swedish policy (SW), go a step beyond by detailing initiatives to promote formal higher education which can increase the advanced skills of the future workforce, such as the establishment of master and doctoral degrees for the STEM field, which is a major concern of the educational pillar from the DIGITAL Programme (European Commission, 2021; Government Offices of Sweden, 2016). Moreover, a few national strategies also promote initiatives concerning the attraction of highly skilled workforce (BE, BU, CZ, DE, HR, HU, LU, PT, RO, SK, SW), and to use the digital literacy education to combat future unemployment (PT). Perhaps as a consequence of recent disruptive events, some national digital strategies also focus on the development of educational programs targeting the distance learning, both from the view of training teachers and professors, and from the view of enabling impactful learning for students and pupils (AT, DE, EL, LU, LV, PT). To this end, the national strategies depict investment grants and funding schemes, development and implementation of mobile applications, development of a specific education curriculum for online and distance learning, as well as the development of a centralized teaching and learning platform (AT, DE, EL, ES, HU, LU, LV, NL, PT, RO, SK). To promote the adoption of digital technologies, national strategies made use of collaboration and cooperation initiatives, as well as international scouting initiatives, in an effort to identify the best uses and examples of developed solutions that can benefit their industries. These cooperation and collaboration initiatives are both with research institutions and universities, as well as between governments to establish regulatory frameworks for the fostering of common accelerating initiatives. This approach is also supported in the literature, namely through the policy propositions of establishing a supporting ecosystem for domestic digital firms

(Edler & Georghiou, 2007), adopting a regional innovation approach (Walwyn & Cloete, 2020), and the establishment of mission-oriented consortia (Foray et al., 2012).

When it comes to the barriers to adopt digital technologies, the national strategies provide several initiatives to overcome them. As depicted, the national digital strategies are heavily focusing on *investment and funding initiatives*, efforts to promote the *development and establishment of regulatory frameworks* for the digital era, and the *implementation of ICT-enabling infrastructure*. These are all supported by the literature, which promote the possibility for use of venture capital markets (Martin & Scott, 2000), investments and development of public infrastructure for connectivity and data (Walwyn & Cloete, 2020), and promote a solid legal and regulatory framework for digital companies (Schmidt & Krimmer, 2022; Teixeira & Tavares-Lehmann, 2022). Moreover, the national strategies consider tax reforms to enhance the business value of digitalized companies, in accordance with the propositions by Denicolai et al. (2021).

Nevertheless, the national strategies could be enhanced by the literature regarding the development of *regulatory framework* and *legal and contractual assurances*. Specifically, the literature provides initiatives for implementing a Digital Services Tax focused on human user interaction and bit-rate charges, as well as initiatives to promote the interdependence of political and economic powers considering emerging and enabling technologies, such as the 5G innovation ecosystem (Mansell, 2021). On the opposite spectrum, the current literature can benefit from the national strategies regarding establishment of regulatory frameworks by considering possible effects on digitalization from initiatives for local market fairness (AT, DE, LU, RO, SK), the establishment of online markets (AT, DE, EL, LU, MT, NL, SK) and the infrastructure construction proceedings (CZ, DE, EL, HU, RO). On this topic we would add the possibility of incorporating regulations on financial markets that benefit from green digital services, especially benefits targeting taxation of venture capitals that have measurable impact on the United Nations Sustainable Development Goals (United Nations, 2015). Moreover, the national strategies should consider policies for the digital marketplace with respect to digital currencies, which can impact the digital transformation of companies that choose to modify their business models and income framework (Alahmadi et al., 2022; Chawla & Goyal, 2021).

The national strategies provide initiatives to enable de *definition of digital strategies* which considers the organisational characteristics and competitiveness

(Aamer et al., 2022). As stated, the focus of the initiatives from the national strategies refers to business innovation and cooperation actions. In terms of *definition of digital strategy*, national strategies can benefit from the literature considering initiatives that enable a more focused approach to the organization's digital strategy (Denicolai et al., 2021) and the use of outsourcing strategies for non-essential technologies and services (Stornelli et al., 2021). On a similar mindset, national strategies could consider initiatives that promote reallocation of resources from digitalization to sustainability when companies are shifting their market focus from the domestic to the international environment (Denicolai et al., 2021). With regards to *cooperation and collaboration initiatives*, the national strategies could be further improved by incorporating internationalization efforts towards the creation and/or wider deployment of Digital Innovation Hubs as centralized workplaces for the development and testing of novel digital solutions (Hervas-Oliver et al., 2020). Complementary to this, Schmidt and Krimmer (2022) propose the use of Large-Scale Pilots (LSPs) as a framework to promote stakeholder participation, develop technical solutions and identify possible setbacks, functioning as a prime example of a interorganizational initiative. To these, we propose the initiative to take an agile project management mindset (Cooper & Sommer, 2018) when defining the digital strategy, thus incorporating the outcome expected from the digitalization journey, the required resources, defining the roadmap of actions and timeline of implementations, as well as milestones and intermediate deliverables, which all can increase success chances of adoption of digital technologies. Table 18 summarizes the number of initiatives to tackle each barrier for each of the European national digital strategies.

TABLE 18 SUMMARY OF INITIATIVES TO OVERCOME EACH BARRIER IN THE EUROPEAN NATIONAL DIGITAL STRATEGIES

	Initiatives for each barrier in the National Strategies														
	[1] Investments	[2] Adaptive Organizational and Process Modifications	[3] Human Capital	[4] Knowledge Management Systems	[5] Clear Comprehension of Digitalisation Benefits	[6] Standardization Efforts	[7] Adaptive Retroffiting Implementaiton	[8] Infrastructure	[9] Security, Safety and Privacy Issues	[10] Integration with existing technology	[11] Regulatory Framework	[12] Legal and Contractual Assurances	[13] off-the-shelf solutions	[14] Digital Strategy	TOTAL
Austria	7	3	15	1		2		7	2		24	1		6	**68**
Belgium	1		5		2			2	1	1	10			3	**25**
Bulgaria			7					1	1	1	9			1	**20**
Croatia	3	1	9					2			15			5	**35**
Cyprus	4		4			1		2	1		12			2	**26**
Czech Republic	8		9	1	1	2		5	2	1	15	1		5	**50**
Denmark			4			2		2	2		6	1		1	**18**
Estonia	5	2	4			2		5	2	1	10	1		1	**33**
Finland	2		5	1		1		3	2		10			4	**28**
France	4		6					5	2		6	1		4	**28**
Germany	8		13		2	2		3	2	1	14	2		3	**50**
Greece	5	1	9			2		7	2	2	14	2		4	**48**
Hungary	7	2	10			2		5	2	1	12	2		3	**46**
Ireland	6	1	6		1	3	1	2		1	5			2	**28**
Italy	4		3					3	2		8			2	**22**
Latvia	4		14	1	2	2		5	2	1	10	1		3	**45**
Lithuania	5		3					1			5	1		2	**17**
Luxembourg			12	1		2		4	2		10	2		2	**35**
Malta	2			1	2	2		4	2	1	12	1		1	**28**
Netherlands	4		7	1	2			7	2		12	2		2	**39**
Poland	1		4	1	2			2	2	1	9	2		2	**26**
Portugal	3		13					1	1		11			3	**32**
Romania	4	1	8	1				4			12			3	**33**
Slovakia	5	1	12	1	1			6	2	2	18	1		6	**55**
Slovenia	1		8	1		2		3	2	1	6			4	**28**
Spain	2		6					7	2		10			2	**29**
Sweden	5	1	7							1	4			5	**23**
TOTAL	**100**	**13**	**203**	**11**	**15**	**27**	**1**	**98**	**40**	**16**	**289**	**21**	**0**	**81**	**915**

4.5.2 Neglected barriers

The least tackled barriers on both the literature and European national digital strategies are the need for off-the-shelf solutions, the need for adaptive retrofitting implementation solutions, the requirement to use knowledge management systems, and the need to promote a clear comprehension of digitalization benefits.

Concerning the need for off-the-shelf solutions, the national strategies have a single mention to this issue from the Bulgarian digital strategy, which simply recognizes the issue without providing a possible initiative to overcome it. The development of off-the-shelf solutions is closely related to the standardization efforts, given that these solutions are standardized and tailored to be offered in large scales (Barros et al., 2017).

Yet, national strategies could make use of interorganizational efforts, such as research centres and Digital Innovation Hubs, as promoters of off-the-shelf solutions tailored for specific sectors (e.g., automotive, cork, footwear). These institutions centralize the development and testing of multiple novel digital solutions and could be part of a national initiative to disseminate ready-made solutions for SMEs which cannot afford the costs of development, and which do not have a critical need for custom-made digital solutions. Such initiative could come in the form of *funding for the testing of already developed solutions on multiple companies as Proof of Concepts in order to move them to a large-scale adoption level*. Additionally, the same funding could have a different section dedicated to technology providers that are going to focus on enhancing the capabilities of these ready-made solutions for specific sectors, such as modules that are more important for one sector compared to another. Another possible policy is the *incubation of awarded solutions from Hackathons and other business competitions towards enhancing their large-scale adoption, with particular focus on SMEs and key sectors for the nations.*

The requirements for adapting legacy systems to integrate with novel digital solutions, commonly referred as the adaptive retrofitting implementation process, is another point of concern for companies that embarking on their digitalization journeys, with special attention to smaller organizations that already have decades of market presence (Müller et al., 2018; Stock & Seliger, 2016). Yet, it is only mentioned by the Irish national strategy as a broad initiative mostly related to the identification of requirements for the integration of legacy systems (IE). On this matter, *the national strategy can* combine their initiatives related to the definition of digital strategies in order to *include a requirements' definition stage and a digital maturity assessment of existing equipment*, both part of the initiative to provide digitalization funding. Additionally, *in partnership with RD&I centres and technology developers, national strategies could develop a set of services targeting the adaptation of current equipment to enable digital capabilities such as implementation of universal protocols for communications between the older equipment computational languages and more novel approaches to systems optimizations*. Alternatively, these *services can target the development of flexible modules that can be attached to legacy systems*, which would provide conversion of analog inputs/outputs to their digital counterpart, while also being responsible for the communication of these information to the enterprise management systems or manufacturing execution systems. *The policy initiatives can be a dedicated funding scheme for supporting RD&I centres and technology providers to promote these services, targeting key sectors and smaller organizations.*

Efforts to promote the clear comprehension of digitalization benefits are mostly focusing the awareness initiatives for organizations within the national digital strategies (DE, IE). The strategy for the topic is to deploy assistance programmes, mostly targeting SMEs, to provide information, finance investments and raise awareness of the existence and benefits of digital technologies and the digitalization of organizations (DE). Another approach comes from the Dutch government, which proposes the implementation of smart industry field labs and hubs which, among other responsibilities, will also promote awareness through the possibility of conducting experiments in a controlled environment with decreased risks (NL). We agree with these initiatives and would suggest the remaining European National Digital Strategies to incorporate them in their policy mixes. Moreover, we go one step beyond by *proposing that these smart industry field labs, hubs and DIHs are used as networking grounds between the companies, functioning in close partnership with industrial associations and practitioners, and providing the possibility of knowledge sharing through hands-on workshops, awarding challenge competitions and other incentive forms that can bring the industrial field into a networking environment.*

Finally, considering the availability and use of knowledge management systems, both the literature and the national digital strategies provide the same initiative. This policy refers to efforts in enabling public data availability for data-driven services, which can be achieved through the establishment of open data hubs and databases with increased access to the industrial sectors (Bonnín Roca et al., 2016). Additionally, *national digital strategies can benefit from promoting funding schemes for development and implementation of standards aimed at knowledge management systems*, thus decreasing the complexity and confusion both at the development stage of knowledge management systems, and at the adoption stage considering required digital skills by the workforce. An advantage of such initiative is that it provides a solid foundation for the improvement of smaller organizations’ knowledge management systems without incurring in expenditures related to development and testing of unorthodox solutions, which can be cumbersome and are often poorly documented, thus leaving a knowledge gap that hinders the full exploit of its capabilities. The proposed policies are depicted in Table 19 below.

TABLE 19 POLICY SUGGESTIONS TO OVERCOME NEGLECTED BARRIERS

ID#	Barrier	Suggestions of policies to overcome the barrier
4	Knowledge Management Systems	• Provide incentive schemes for development and implementation of standards for knowledge management systems to decrease complexity and confusion at both the development and adoption stages.
5	Clear Comprehension of Digitalisation Benefits	• Use the smart industry field labs and hubs as networking training camps, in close partnership with industrial associations and practitioners, with knowledge sharing activities, challenge competitions and other networking fostering initiatives.
7	Adaptive Retrofitting Implementation	• Include on the definition of digital strategy a requirements' definition stage and digital maturity assessment of existing equipment, both part of the initiative to provide digitalisation funding. • Propose development of set of services targeting the adaptation of current equipment to enable digital capabilities, in partnership with RD&I centres and technology developers, such as implementation of universal communication protocol capabilities, or the development of flexible models attached to legacy systems that can be integrated into novel enterprise resource management systems. • Promote a dedicated funding scheme for supporting RD&I centres and technology providers to promote adaptative retrofitting services targeting selected key sectors (e.g. metalwork, footwear) and smaller organisations.
13	Off-the-shelf solutions	• Provide incentive to interorganizational collaborations (RD&I centres, DIHs) as promoters of off-the-shelf solutions tailored for specific sectors (e.g., automotive, cork). • Promote test funding schemes for developed solutions on multiple companies as Proof of Concepts, in order to move them to large-scale production and adoption. • Promote funding schemes for technology providers that aim to enhance the capabilities of ready-made solutions for specific sectors. • Provide incubation of awarded solutions from competitions to increase the speed of their large-scale adoption, with particular focus on SMEs and key sectors.

4.5.3 I4.0 Digital Maturity Model, European national digital strategies, and the functions of government in the digital era

We have also conducted a content analysis of the European national digital strategies with regards to the dimensions, axes and vectors of the digital maturity model proposed on the second study. The aim was to understand to what extent did national strategies considered the topics evaluated by the digital maturity model, and whether there were gaps on the national digital strategies. We found that all dimensions, axes, and vectors were contemplated on the initiatives from the European national digital strategies, albeit on different degrees of detail.

On the **Technology dimension**, most initiatives targeted the infrastructure, data technologies and advanced manufacturing technologies, whereas the technologies for smart products and services (smart solutions and smart design) were the least tackled. National strategies could provide more detailed initiatives to enhance the development of smart products and services, either through the establishment of training facilities to provide digital skills for smart design, or through incentives to implement innovation labs focusing on intelligent solutions to already established products, which would reduce the risk of development failure while improving products usability and added value.

On the **Organization dimension**, initiatives focused on the definition of strategy and the improvement of human resources through training and education. Yet, governance, culture and processes (especially quality and engineering) were lacking initiatives. Hence the digital strategies would be improved by incorporating policies for these topics, which can help organisations in improving their digital maturity level. On the governance topic, national strategies can be improved through policies for the establishment of standard working for human-machine collaboration. On culture, policies can aim to promote an entrepreneurial spirit on the workforce through group training and through incentives for companies that make use of more democratic decision-making schemes which foster leadership and ownership mindsets. On processes, policies can provide investment incentives for companies to pursue quality and engineering certifications, which can enhance their production processes and streamline the product development cycles.

Regarding the **Environment dimension**, initiatives are mostly focused on legal and regulatory aspects, as well as on interorganizational aspects such as cooperation and collaboration actions. However, there is a lack of initiatives for market positioning, that is, on how companies define and use their digital strategies in order to position themselves on the markets. Following Aamer et al. (2022) and Denicolai et al. (2021) works, initiatives on this topic should be aimed towards establishing a well-focused digital strategy. On countries with less developed industries, this means that national digital strategies should target a specific set of key sectors within manufacturing for the first stages of digitalisation, or a particular digital technology that can set the national industry apart from the others within and outside the European community.

Considering the barriers and requirements for the adoption of digital technologies, in particular those of Industry 4.0, there is pressing need to update the functions of governments to provide the support for the European economies. On this topic, the traditional roles of government (see section 4.2.2) can be expanded by including the following: (i) to provide goods and services, namely the infrastructure for the development and successful adoption of communications technologies and energy demands of companies (as observed by policies on section 4.4.8); (ii) to expand the self-preservation of citizens and nations by incorporating aspects of the e-government and digital government, as well as the virtual representation of citizens (illustrated by sections 4.4.9 and 4.4.10); (iii) to expand legal and regulatory frameworks to account for the digital representation of organisations and, in doing so, serving as the mediation actor for resolution of conflicts within the virtual environment (as seen on section 4.4.9); (iv) to promote economic regulation through policies that enable the sustainable development of organizations both physically and virtually, and in such a matter as to allow markets to cooperate and collaborate harmoniously (noted through sections 4.4.1, 4.4.9 and 4.4.14).

4.6 Conclusion

During out study, we set forth to analyse the European Digital National Strategies and their initiatives to overcome barriers to adopt digital technologies in manufacturing from the literature, while being supported by the European DIGITAL programme. By performing content analysis on the national strategies, we observed similarities and a focus on initiatives that target investment, funding schemes, regulatory framework, and business innovation strategy definitions. On the other hand, we found evidence of lacking initiatives for overcoming the need of retrofitting existent machinery, integrating with legacy systems, providing large-scale off-the-shelf solutions, and promoting clear comprehension of the digitalization benefits. We have identified a set of 94 initiatives and 17 sub-barriers, which were categorized according to the set of 14 barriers to adoption of digital technologies observed in the literature. Our findings demonstrate that all national digital strategies incorporate initiatives for each key area of the DIGITAL programme. Furthermore, many of the identified initiatives are supported by literature, increasing the validity of the proposed actions. We have provided nine policy recommendations to overcome barriers not sufficiently tackled by literature, while extending the literature on the topic by identifying missing initiatives found in the national digital strategies. Our results can aid policymakers into improving the national digital strategies in an effort to consider a broader scope of industrial organizations. The main limitations of our study regard the need to empirically validate our policy recommendations and to expand the content analysis towards barriers to adopt digital technologies on other sectors, such as services.

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5. Conclusions

After evaluating the different aspects surrounding the adoption, implementation and policies for digital technologies in the manufacturing industry of the Digital Era, it became clear that many of the difficulties faced by companies during this digitalization process are not focused on the implementation of technologies, but on adapting the existing organizational structure and culture, and on understanding, as well as making use of, the available external incentives. These include the multiple funding and innovation schemes, the possibility to co-develop technologies in innovation centres, the capability to have synergies with research centres and technology providers in order to scale up solutions, and the possible cooperation with similar companies to develop common technologies that are not part of the core business. On the organizational perspective, companies face the difficulties of a workforce that is not sufficiently trained, does not possess the required digital skills, does not consider the required knowledge of functions available on already implemented technologies, and are not open to willingly accept the technological changes. Moreover, the management needs to shift their mindset towards promoting a digital culture within the company, looking to acquire and retain highly skilled talents, and provide incentives for leadership development of key collaborators to lead groups that have elements with vastly different skillsets. The availability of investment schemes is currently high, but it often focuses on the development of technologies without considering the additional requirements for its successful adoption.

Considering the barriers and requirements for the adoption of digital technologies, in particular those of Industry 4.0, there may be an opportunity to update the functions of governments to provide the support for the European economies. On this topic, the traditional roles of government (see section 4.2.2) could be expanded by including the following: (i) to provide goods and services, namely the infrastructure for the development and successful adoption of communications technologies and energy demands of companies (as observed by policies on section 4.4.8); (ii) to expand the self-preservation of citizens and nations by incorporating aspects of the e-government and digital government, as well as the virtual representation of citizens (illustrated by sections 4.4.9 and 4.4.10); (iii) to expand legal and regulatory frameworks to account for the digital representation of organisations and, in doing so, serving as the mediation actor for resolution of conflicts within the virtual environment (as seen on section 4.4.9); (iv) to promote economic regulation through policies that enable the sustainable development of organizations both physically and virtually, and in such a matter as to allow markets to cooperate and collaborate harmoniously (noted through sections 4.4.1, 4.4.9 and 4.4.14).

5.1 Main findings

The first study resulted in a set of 14 barriers to adopt Industry 4.0 digital technologies for manufacturing organizations. When evaluating their interrelationship, 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. 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. The first study contributions are 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.

The second study resulted in the systematic review of 45 digital maturity model for manufacturing organizations, and the proposition of a novel digital maturity model which was empirically validated. The systematic review portrayed a lack of focus on the environmental dimension of organizations, leading to a poor evaluation of the organizations' digital maturity level. A digital maturity model was proposed and empirically validated to amend this issue, and to serve a encompassing benchmarking tool for organizations that are beginning their digital transformation journey. This digital maturity model is comprised of three dimensions: technology, organization and environment. Moreover, it considers 12 different axes and 50 items, and assesses the organizations on a six-point scale. The second study contributes to the research field by proposing a more comprehensive and encompassing Industry 4.0 digital maturity model that is supported by a theoretical lens and is empirically validated through multiple iterations. Our work highlights the relevance of the environmental dimension, neglected by existing literature.

In the third study, we used the set of 14 barriers to adopt digital technologies from the first study to evaluate the European national digital strategies. Through content analysis, we identified a set of 94 initiatives and 17 sub-barriers, categorized according to the set of 14 barriers to adoption. We observed similarities and a focus on initiatives that target investment, funding schemes, regulatory framework, and business innovation strategy definitions. We also found evidence of lacking initiatives for overcoming the need of retrofitting existent machinery, integrating with legacy systems, providing large-scale off-the-shelf solutions, and promoting clear comprehension of the digitalization benefits. Our findings demonstrate that all national digital strategies incorporate initiatives for each key area of the DIGITAL programme. Furthermore, many of the identified initiatives are supported by literature, increasing the validity of the proposed actions. We have provided nine policy recommendations to overcome barriers not sufficiently tackled by literature and national digital strategies, while extending the literature on the topic by identifying missing initiatives found in the national digital strategies. Our results can aid policymakers on improving the national digital strategies.

5.2 Main contributions

This thesis makes original contributions to research, practice and policy. First, it contributes to the field of research dedicated to technology management and technology adoption by improving the literature on barriers to adopt digital technologies. We provide the literature with a novel barrier – "Lack of off-the-shelf solutions" – as well as with the prioritization and categorization of barriers according to the TOE framework. We also contribute to research by providing a digital maturity model for manufacturing companies that encompasses the synthesis of established models found on literature and enhances them through additional topics regarding the external factors of organizations for adoption and implementation of digital technologies. Secondly, we contribute to practice by identifying barriers to adopt digital technologies in manufacturing companies and proposing recommendations to overcome these barriers, which can be employed by managers and practitioners on their organisations. Additionally, we provide manufacturing companies with a digital maturity assessment tool to evaluate current and future digital maturity levels in order to define and monitor their digital transformation strategy. Finally, we contribute to policy by analysing current European national digital strategies with regards to the barriers to adopt digital technologies, identify policy gaps and propose policy recommendations to improve the national strategies.

5.3 Recommendations for the Industry 4.0 Portuguese Programme

The policies depicted in the documents for the Industry 4.0 Portuguese Programme only focus on six barriers to adopt digital technologies, according to our findings from the third study: (1) Investments, (3) Human Capital, (8) Infrastructure, (9) Security, Safety and Privacy Issues, (11) Regulatory Framework, and (14) Digital Strategy. These six barriers are well covered by a multitude of initiatives. However, the Portuguese national digital strategy could be improved by incorporating many of the policies depicted on other European strategies as well as on the literature and on our policy recommendations. To this end, we provide Table 20 below with a summary of policies for each barrier not yet tackled by the Industry 4.0 Portuguese Programme.

TABLE 20 POLICY RECOMMENDATIONS FOR THE PORTUGUESE DIGITAL STRATEGY

#	Barrier	Examples of policies to help overcome the barrier
2	Adaptive Organizational and Process Modifications	• Promote top management support within companies and associations to enable the digital transformation (Aamer et al., 2022) • Enable a widespread digitalization culture within the industrial sectors, particularly to resistant workforce, in order to provide a seamless transitioning environment to adopt digital technologies (Aamer et al., 2022) • Promote modernisation of organisational frameworks to account for flexible working conditions, such as the remote working paradigm (AT, ES, HU) • Establish guidelines for the constant discussion on the advantages of organisational modifications, in particular the

		use of novel technologies and production methods, in order to promote change acceptance (AT, EE)
4	Knowledge Management Systems	• Promote open and publicly available databases for R&DI (Bonnín Roca et al., 2016) • Provide incentive schemes for development and implementation of standards for knowledge management systems to decrease complexity and confusion at both the development and adoption stages.
5	Clear Comprehension of Digitalisation Benefits	• Promote awareness for organisations through assistance programmes to provide information on the benefits of digitalisation (DE, IE) • Implementation of smart industry field labs and hubs, which will promote awareness through hands-on experimentation in a controlled, riskless environment (NL) • Use the smart industry field labs and hubs as networking training camps, in close partnership with industrial associations and practitioners, with knowledge sharing activities, challenge competitions and other networking fostering initiatives.
6	Standardisation Efforts	• Bridging institutions to facilitate standards adoption (Intarakumnerd & Goto, 2018; Martin & Scott, 2000) • Increase efforts of standardization to ease the adoption of digital technologies (Teixeira & Tavares-Lehmann, 2022) • Legitimize standardization efforts (Wiegmann et al., 2017) • Promote the use of open standards in public administration and for state-owned companies, which should have scheduled migration paths to allow adaptation in terms of development and investments (AT, CZ) • Create a technical Digital Single Market, where EU standardisation can keep up with global technological advances, mostly in terms of communication and IT standards (DE) • Promote the development of open standards for online platforms to facilitate market entrance to new competitors (LU) • Incorporate standardisation practices and development in the public administration through a suite of digital architecture frameworks, policies, guidelines, standards, and roadmaps (MT) • Provide a supportive and predictable system of standardisation and accreditation, which can be fostered through high-tech companies financed by the national government (SI)
7	Adaptive Retrofitting Implementation	• Include on the definition of digital strategy a requirements' definition stage and digital maturity assessment of existing equipment, both part of the initiative to provide digitalisation funding. • National strategies a set of services targeting the adaptation of current equipment to enable digital capabilities, in close relationship with RD&I centres and technology developers, such as implementation of universal communication protocol capabilities, or the development of flexible models attached to legacy systems that can be integrated into novel enterprise resource management systems. • Promote a dedicated funding scheme for supporting RD&I centres and technology providers to promote adaptative retrofitting services targeting selected key sectors (e.g. metalwork, footwear) and smaller organisations.
10	Integration with existing technology	• Low-tech bridging institutions (extension services) to facilitate technology transfer (Martin & Scott, 2000)

		• High-tech bridging institutions to facilitate diffusion of advances in big research (Martin & Scott, 2000) • Promote integration with multiple devices within a digital supply chain, from different actors, in order to enhance information exchange and transparency (Aamer et al., 2022)
12	Legal and Contractual Assurances	• Promote a solid legal framework for contracts leading to smaller digitalisation gaps and loop-holes (Schmidt & Krimmer, 2022) • Continuous amendments to existing legal frameworks (e.g. eIDAS regulation) to cover existing gaps (Schmidt & Krimmer, 2022) • Improve existing legal structures to accommodate e-commerce and novel online marketplace developments (DE, EL, NL) • Promote intellectual property laws that consider the virtual assets of organisations, particularly the digital products and services (CZ, EE). • Provide incentives for the development of ethical use of technologies as a precondition on contracts (DK) • Incorporate digital currency laws and smart contracts characteristics as national legislations in order to support these new digital agreements (LV)
13	Off-the-shelf solutions	• Provide incentive to interorganizational collaborations (RD&I centres, DIHs) as promoters of off-the-shelf solutions tailored for specific sectors (e.g., automotive, cork) • Promote test funding schemes for developed solutions on multiple companies as Proof of Concepts, in order to move them to large-scale production and adoption • Promote funding schemes for technology providers that aim to enhance the capabilities of ready-made solutions for specific sectors • Provide incubation of awarded solutions from competitions to increase the speed of their large-scale adoption, with particular focus on SMEs and key sectors

5.4 Limitations and future work

Regarding the first study, there is a 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. Also, 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. Future studies should also focus on assessing the relationships between the barriers identified on this research by means of structural equation modelling analysis.

Concerning the second study, future studies may focus on applying the digital Industry 4.0 maturity model with the aim of understanding the role of environmental themes in the successful adoption and improvement of digital technologies. Also, the model can be further expanded to encompass companies from the service sector.

With respect to the third study, the main limitations regard the need to empirically validate our policy recommendations and to expand the content analysis towards barriers to adopt digital technologies on other sectors, such as services.

6. References of Introduction and Conclusion

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Appendices
7. Appendices

7.1 Referred Data for Chapter 3

APPENDIX 1 MATURITY MODELS REVIEWED

ID	Reference Short (Author, Year, Title)	Objective	Applied Technique/ Methodology	Field of Application	Application Geography
1	Büyüközkan, G., & Güler, M. (2020). Analysis of companies' digital maturity by hesitant fuzzy linguistic MCDM methods.	Provide a tool for consistent integration of various factors through weighting system that reflect the companies' preferences	Hesitant Fuzzy Linguistic (HFL) Analytic Hierarchy Process (AHP) Additive Ratio Assessment (ARAS)	Digital Banking	Turkey
2	Santos, R.C. and Martinho, J.L. (2019). An Industry 4.0 maturity model proposal.	Propose a self-assessment maturity model to assess industrial capabilities related to industry 4.0 concepts and technologies	Maturity Model Development Process	Automotive	Brazil
3	Lin, T. C., Wang, K. J., & Sheng, M. L. (2020). To assess smart manufacturing readiness by maturity model: A case study on Taiwan enterprises.	Assess the level of Taiwanese manufacturing companies and the discrepancy in evaluation and execution of strategies to implement I4.0.	Clustering Analysis	Manufacturing Companies	Taiwan
4	Pacchini, A. P. T., Lucato, W. C., Facchini, F., & Mummolo, G. (2019).	Propose an approach to measure the degree of readiness of a manufacturing organization in relation to the implementation of I4.0	Society of Automotive Engineers J4000 Case Research	Auto-parts manufacturing	Brazil
5	Mittal, S., Khan, M. A., Purohit, J. K., Menon, K., Romero, D., & Wuest, T. (2020). A smart manufacturing adoption framework for SMEs.	Develop and evaluate an SME-centric Smart Manufacturing (SM) adoption framework that provides manufacturing SMEs with the appropriate, easy-to-use tools and guidance to support their SM journey.	Case Research Framework Development	Jewellery Manufacturing Kitchen Manufacturing	India
6	Krykavskyy, Y., Pokhylchenko, O., & Hayvanovych, N.	Identifying Supply Chain development	Survey research	Manufacturing Companies	Ukraine

	(2019). Supply chain development drivers in industry 4.0 in Ukrainian enterprises.	drivers under I4.0 conditions.	Stratified Proportional Sampling		
7	Rossini, M., Costa, F., Tortorella, G. L., & Portioli-Staudacher, A. (2019). The interrelation between Industry 4.0 and lean production: an empirical study on European manufacturers.	Examining the impact of the association between the adoption of Lean Production and Industry 4.0 on the improvement levels of manufacturers' operational performance	Survey research Multivariate Technique Analysis	Manufacturing Companies	Europe
8	Castelo-Branco, I., Cruz-Jesus, F., & Oliveira, T. (2019). Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union.	Measure the degree of adoption of I4.0 in manufacturing firms across EU countries	Econometrics Factor Analysis Clustering Analysis	Manufacturing Companies	European Union
9	Lokuge, S., Sedera, D., Grover, V., & Dongming, X. (2019). Organizational readiness for digital innovation: Development and empirical calibration of a construct.	Derive a robust and validated organizational readiness for digital innovation model that is simple, generalizable, and allows for useful and pragmatic assessment	Case Research Expert Elicitation Formative Multidimensional Construct Development Survey research	Manufacturing Companies	Europe Asia Australia
10	Gürdür, D., El-khoury, J., & Törngren, M. (2019). Digitalizing Swedish industry: What is next?: Data analytics readiness assessment of Swedish industry, according to survey results.	Investigate the data analytics maturity of Swedish industry from different industrial backgrounds	Survey research	Manufacturing Companies	Sweden
11	Colli, M., Berger, U., Bockholt, M., Madsen, O., Møller, C., & Wæhrens, B. V. (2019). A maturity assessment approach for conceiving context-specific roadmaps	Introduces a novel approach for structuring the assessment procedure aimed to facilitate the contextualization of the assessed organizations and the identification of	Design Science Problem-Based Learning	Manufacturing Companies	Denmark

	in the Industry 4.0 era.	context-specific improvement recommendations	Case Research		
12	Trstenjak, M., Cajner, H., & Opetuk, T. (2019). Industry 4.0 readiness factor calculation: Criteria evaluation framework.	Development of a readiness factor for I4.0 service companies through the definition of a criteria evaluation framework	Case Research	Manufacturing Companies	Croatia
13	Manavalan, E., & Jayakrishna, K. (2019). A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements.	Review various aspects of enabling technologies and I4.0, with focus on IoT, to explore potential opportunities for IoT embedded sustainable supply chain for I4.0 transformation. Proposition of a conceptual framework for assessing the readiness of the SC organization to meet I4.0 requirements.	Content Analysis	Manufacturing Companies Logistics Companies	Unspecified
14	Bibby, L., & Dehe, B. (2018). Defining and assessing industry 4.0 maturity levels–case of the defence sector.	Propose an assessment framework for measuring I4.0 maturity of a focal firm compared against organisations on its supply network.	Case Research Expert Elicitation	Defence Sector	United Kingdom
15	Sjödin, D. R., Parida, V., Leksell, M., & Petrovic, A. (2018). Smart Factory Implementation and Process Innovation: A Preliminary Maturity Model for Leveraging Digitalization in Manufacturing Moving to smart factories presents specific challenges that can be addressed through a structured approach focused on people, processes, and technologies.	Investigate innovation in manufacturing in five factories, identification of key challenges related to smart factory implementation and propose a maturity model for smart factory implementation	Case Research	Automotive	Sweden Brazil Germany

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16	Asdecker, B., & Felch, V. (2018). Development of an Industry 4.0 maturity model for the delivery process in supply chains.	Develop a maturity model for the delivery process of manufacturing companies, in order to provide a collection of best practices as well as flexible & customizable modeling architecture for specific characteristics and peculiarities of an organization	Design Science Case Research Maturity Model Development Process Survey research	Industrial Electric Equipment	Unspecified
17	Ganzarain, J., & Errasti, N. (2016). Three stage maturity model in SME's toward industry 4.0.	Propose a process model as guiding framework for I4.0 implementation and identification of opportunities for diversification.	Process Model Methodology	Manufacturing Companies	Unspecified
18	Alcácer, V. *et al.* (2021). Tracking the maturity of industry 4.0: the perspective of a real scenario.	Development of I4.0 Readiness assessment tool to evaluate the perception of companies regarding barriers for I4.0. Identification of new barriers for emerging I4.0 technologies	Survey research	Manufacturing Companies	Portugal
19	Rahamaddulla, S. R. B., Leman, Z., Baharudin, B. T., & Ahmad, S. A. (2021). Conceptualizing Smart Manufacturing Readiness-Maturity Model for Small and Medium Enterprise (SME) in Malaysia.	Propose a conceptual framework for readiness-maturity assessment and proposed SME tailored model framework.	Content Analysis	Manufacturing Companies	Malaysia
20	Chatterjee, S., Rana, N. P., Dwivedi, Y. K., & Baabdullah, A. M. (2021). Understanding AI adoption in manufacturing and production firms	Understand the influence of environmental, technological and social factors in the adoption of artificial intelligence embedded technology in the	Technology Acceptance Model (TAM) Technology-Organization-Environment	Manufacturing Companies	India

	using an integrated TAM-TOE model.	context of digital manufacturing	Framework (TOE)		
			Survey research		
			Partial Least Squares (PLS)		
21	Gökalp, M. O., Gökalp, E., Kayabay, K., Koçyiğit, A., & Eren, P. E. (2021). Data-driven manufacturing: An assessment model for data science maturity.	Propose a Data Science Maturity Model (DSMM) for manufacturing organizations with roadmapping tool for continuous improvement	Systematic Literature Review	Consumer Goods	Europe
			Expert Elicitation	Energy	Asia
			Case Research	Industrial Equipment Manufacturing	Americas
22	Amaral, A., & Peças, P. (2021). A Framework for Assessing Manufacturing SMEs Industry 4.0 Maturity.	Proposal of a holistic SME-tailored framework for comprehensive and high-granularity assessment of companies' maturity levels	Content Analysis	Manufacturing Companies	Unspecified
23	Çınar, Z. M., Zeeshan, Q., & Korhan, O. (2021). A Framework for Industry 4.0 Readiness and Maturity of Smart Manufacturing Enterprises: A Case Study.	Propose a modular MM and a generic readiness framework integrated with technology forecasting for smart manufacturing enterprises	Content Analysis	Auto-parts manufacturing	Turkey
			Inductive Approach		
			Case Research		
			Survey research		
			Data Analysis		
24	Zoubek, M., Poor, P., Broum, T., Basl, J., & Simon, M. (2021). Industry 4.0 Maturity Model Assessing Environmental Attributes of Manufacturing Company.	Present a maturity model dealing with environmental manufacturing processes in a company.	Value Stream Mapping (VSM)	Manufacturing Companies	Unspecified
25	Czvetkó, T., Honti, G., & Abonyi, J. (2021). Regional development potentials of Industry 4.0: Open data indicators of the Industry 4.0+ model.	identify regional potential of Industry 4.0 by developing a regional industry 4.0 readiness model and specific indicator system.	Expert Elicitation	Manufacturing Companies	Europe
			Sum of Ranking Differences (SRD)		
			PROMETHEE II		
			Principal Component Analysis (PCA)		
			Correlation Analysis		

26	Woo, J. H., Zhu, H., Lee, D. K., Chung, H., & Jeong, Y. (2021). Assessment Framework of Smart Shipyard Maturity Level via Data Envelopment Analysis.	Development and application of an innovative smart manufacturing maturity level assessment for smart shipyard manufacturing.	Survey research	Shipbuilding	South Korea
			Data Envelopment Analysis		
27	Bastos, A., De Andrade, M. L. S. C., Yoshino, R. T., & Santos, M. M. D. (2021). Industry 4.0 Readiness Assessment Method Based on RAMI 4.0 Standards.	Identification of I4.0 key enabling technologies and readiness indicator elements. Development of a readiness assessment tool contextualizing RAMI4.0 into smart manufacturing processes and technologies.	Survey research	Automotive	Brazil
28	Benešová, A., Basl, J., Tupa, J., & Steiner, F. (2021). Design of a business readiness model to realise a green industry 4.0 company.	Evaluate 28 existing maturity models within the Green-driven context based on EU Green Deal initiative. Development of basic dimensions through survey questionnaire to address the missing green-sustainable aspects.	Business Environmental Theory	Industrial Electric Equipment	Czech Republic
			Survey research		
29	Antony, J., Sony, M., & McDermott, O. (2021). Conceptualizing Industry 4.0 readiness model dimensions: an exploratory sequential mixed-method study.	Conceptualize an Industry 4.0 readiness model for manufacturing, services, small and medium-sized enterprises, and large enterprises. The development and conceptualization of the model is achieved through an exploratory mixed method for critical evaluation of the model's dimension.	Grounded Theory	Manufacturing Companies	Unspecified
			Open Coding	Service Companies	
			Axial Coding		
			Selective Coding		
			Survey research		
			Econometrics		
30	Saad, S. M., Bahadori, R., & Jafarnejad, H. (2021). The smart SME technology readiness assessment methodology in the	Proposing the Smart SME Technology Readiness Assessment (SSTRA) methodology for SME's assessment of Industry 4.0	Analytic Hierarchy Process (AHP)	Manufacturing Companies	United Kingdom

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	context of industry 4.0.	technology readiness focusing on the smart product design phase.			
31	Tripathi, S., & Gupta, M. (2021). A holistic model for Global Industry 4.0 readiness assessment.	Development of a readiness assessment model of nations supported by analysis of several global indices and academic Industry 4.0 research.	Systematic Literature Review	Manufacturing Companies	Unspecified
32	Caiado, R. G. G., Scavarda, L. F., Gavião, L. O., Ivson, P., de Mattos Nascimento, D. L., & Garza-Reyes, J. A. (2021). A fuzzy rule-based industry 4.0 maturity model for operations and supply chain management.	Development of a fuzzy logic-based I4.0 Maturity Model for smart operations and supply chain management.	Focus Group Expert Elicitation Fuzzy Logic Monte Carlo Simulation Case Research	Manufacturing Companies	Unspecified
33	Wagire, A. A., Joshi, R., Rathore, A. P. S., & Jain, R. (2021). Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice.	Develop a self-assessment Industry 4.0 maturity model for Indian manufacturing organizations.	Design Science Expert Elicitation Analytic Hierarchy Process (AHP) Case Research	Manufacturing Companies	India
34	Chonsawat, N., & Sopadang, A. (2020). Defining SMEs' 4.0 readiness indicators.	Definition of readiness indicators to assess and support SMEs toward Industry 4.0. Model development based on bibliometric techniques to identify influential aspects of SMEs' I4.0 readiness factors.	Systematic Literature Review Visualization of Similarities (VoS) Pearson statistics	Plastic Shoe Manufacturing	Thailand
35	Pirola, F., Cimini, C., & Pinto, R. (2020). Digital readiness assessment of Italian SMEs: a case-study research.	Development of a digital readiness assessment model for SMEs and identify I4.0 roadmapping priorities	Case Research	Manufacturing Companies	Italy

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36	Rafael, L. D., Jaione, G. E., Cristina, L., & Ibon, S. L. (2020). An Industry 4.0 maturity model for machine tool companies.	Development of an I4.0 Maturity Model specifically for Machine Tool (MT) organizations	Case Research	Machine Tool Companies	Europe
			Expert Elicitation		
37	Turisova, R., Sinay, J., Pacaiova, H., Kotianova, Z., & Glatz, J. (2020). Application of the EFQM Model to Assess the Readiness and Sustainability of the Implementation of I4. 0 in Slovakian Companies.	Adapting the European Foundation for Quality Management (EFQM) model to assess integration level of complex safety into management systems and the impact of digitalization on Occupational Health and Safety (OHS)	European Foundation Quality Management Model (EFQM)	Manufacturing Companies	Slovakia
			Survey research		
38	Fareri, S., Fantoni, G., Chiarello, F., Coli, E., & Binda, A. (2020). Estimating Industry 4.0 impact on job profiles and skills using text mining.	Development of a measurement tool for quantifying the readiness of employees belonging to a big firm in the context of Industry 4.0.	Data-driven approach	Manufacturing Companies	Unspecified
			Case Research		
39	Rauch, E., Unterhofer, M., Rojas, R. A., Gualtieri, L., Woschank, M., & Matt, D. T. (2020). A maturity Level-Based assessment tool to enhance the implementation of industry 4.0 in small and Medium-Sized enterprises.	Development of an Industry 4.0 maturity assessment model for SMEs targeting Industry 4.0 strategy definition and roadmapping building.	Content Analysis	Manufacturing Companies	Italy
			Case Research		Austria
					Slovakia
					United States
40	Kääriäinen, J., Pussinen, P., Saari, L., Kuusisto, O., Saarela, M., & Hänninen, K. (2020). Applying the positioning phase of the digital transformation model in practice for SMEs: toward systematic development of digitalization.	Development of a self-assessment industry 4.0 readiness model for SMEs.	Case Rese	Manufacturing Companies	Finland
				Process Companies	
				Service Companies	

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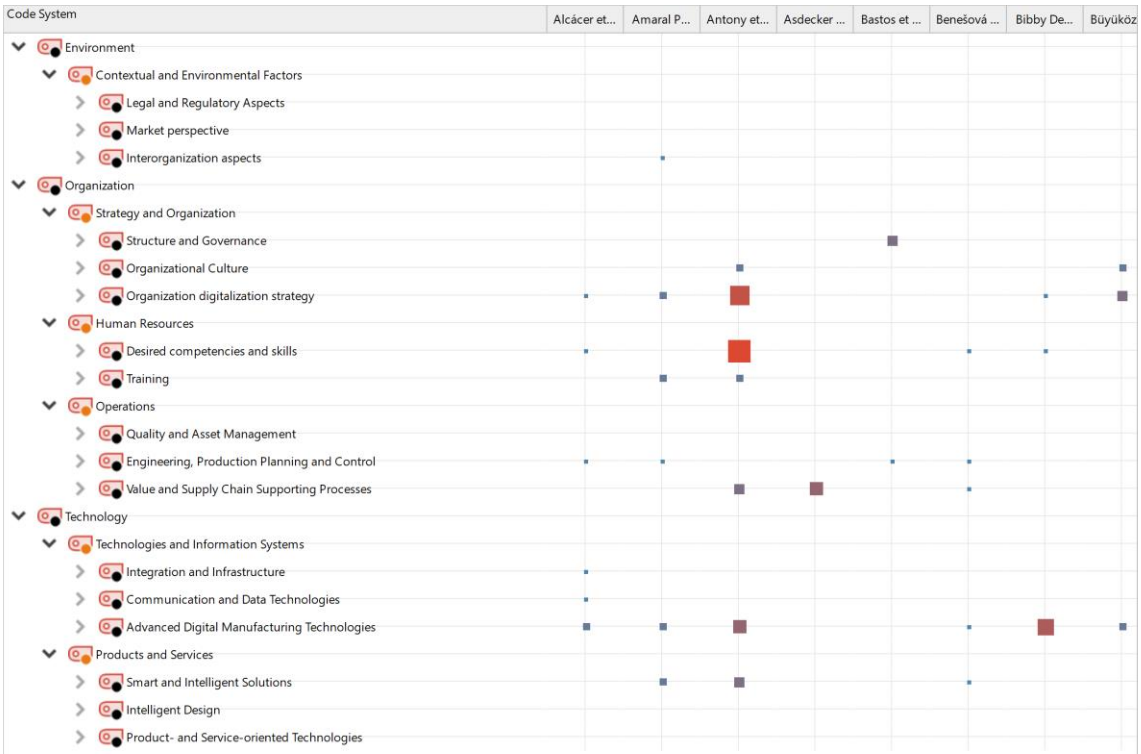
41	Glogovac, M., Ruso, J., & Maricic, M. (2020). ISO 9004 maturity model for quality in industry 4.0.	Development of a Quality 4.0 maturity model supported on the ISO 9004:2018 framework.	ISO 9004:2018 framework	Manufacturing Companies	Serbia
			Survey research	Service Companies	
			Confirmatory Factor Analysis (CFA)		
			Structural Equation Modelling (SEM)		
42	Schumacher, A., & Sihn, W. (2020). A strategy guidance model to realize industrial digitalization in production companies.	Development of a fully digital roadmapping suite for Industrial Digitalisation, with digital maturity model assessment, toolkit implementation and KPI-monitoring systems for manufacturing companies.	Design Science	Manufacturing Companies	Austria
			Expert Elicitation		
			Case Research		
43	Moura, L. R., & Kohl, H. (2020). Maturity Assessment in Industry 4.0–A Comparative Analysis of Brazilian and German Companies.	Application of the VDMA maturity model to highlight differences between Brazilian and German Manufacturing Companies.	VDMA Maturity Model	Food and Beverages	Brazil
			Expert Elicitation	Plastic Manufacturing	
				Metalworking	Germany
				Chemical	
				Furniture	
				Clothing	
44	Sassanelli, C., Rossi, M., & Terzi, S. (2020). Evaluating the smart maturity of manufacturing companies along the product development process to set a PLM project roadmap.	Development of a digital and lean maturity model with benchmarking capabilities, which supports PLM digitalisation project roadmapping	Content Analysis	Advanced Industrial Machinery Manufacturing	Italy
45	Nasrollahi, M., & Ramezani, J. (2020). A model to evaluate the organizational readiness for big data adoption.	Development of an Organizational Readiness model for Big Data adoption considering the main criteria and issues established in the literature.	Content Analysis	Manufacturing Companies	Unspecified
			Principal Component Analysis (PCA)		
			Fuzzy Best-Worst Method (FBWM)		

APPENDIX 2 MAXQDA CODING STRUCTURE FOR THE DIGITAL MATURITY MODELS



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7.2 Referred Data for Chapter 4

APPENDIX 3 DETAILED DESCRIPTION OF SUB-BARRIERS AND INITIATIVES FOR EACH BARRIER, DISPLAYING THE NATIONAL DIGITAL STRATEGIES AND NUMBER OF CODED SEGMENTS

Barrier (Countries)	# Segments	Sub-Barriers (Countries)	# Segments	Initiatives (Countries)	# Segments
Investments (AT, BE, BU, CY, CZ, DE, EE, EL, FI, FR, HR, HU, IE, IT, LT, LV, MT, NL, PL, PT, RO, SK, SW)	46	Lack of RD&I Funding (BU, CZ, DE, EE, EL, IE, IT, LT, SK, SW)	19	Entrepreneurship and investment attraction (CY, CZ, HR, HU, LV, PT, SI, SW)	14
				National Funding Initiatives (AT, BE, CY, CZ, DE, HR)	9
				National Funding Programmes Platform development (AT, DE, EL, HU, IE, IT, LT, LV, NL, RO, SK, SW)	29
				Digital education funding (AT, DE, EL, ES, FR, HU, IE, IT, LT, LV, NL, PL, SK)	26
				Funding for sustainability initiatives (CZ, EE, FR, SW)	10
				Innovation funding (AT, CY, CZ, DE, EE, EL, ES, FI, FR, HR, HU, IE, IT, LT, MT, NL, RO, SK, SW)	110
				Funding for Standardization (AT, DE, EL, IE)	4
				Funding for Infrastructure (AT, CY, CZ, DE, EE, EL, FR, HR, HU, IE, IT, LT, LV, MT, NL, RO, SK)	47
				National Funding Initiatives - Awareness (CZ, EE, HU, PT, RO)	5
				National Funding Initiatives - Credit Line (CZ, DE, EE, FI, PT)	8
				RD&I targeted tax reduction initiatives (AT, CZ, DE, HU, IE, LT, SK, SW)	9

Barrier (Countries)	# Segments	Sub-Barriers (Countries)	# Segments	Initiatives (Countries)	# Segments
Adaptive Organizational and Process Modifications (AT, EE, ES, FR, HU, IE, SK, SW)	10	N/A		Quality assurance in ICT implementation (EL, HU, SK)	3
				Work from home (AT, ES, HU)	5

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				Digitalisation of internal processes and business models (AT, EE, ES, HR, IE, RO, SW)	9
				Change acceptance (AT, EE)	5

Barrier (Countries)	# Segments	Sub-Barriers (Countries)	# Segments	Initiatives (Countries)	# Segments
Human Capital (AT, BU, CY, CZ, DE, DK, EE, EL, ES, FI, HR, HU, IE, LT, LU, LV, RO, SI, SW)	54	Lack of future job stability (SK, SW)	2	Promote quality-of-life improvement activities (SI)	1
		Distance Learning - Lack of support for learning structuring (AT)	1	Promote the creation of high-quality jobs with high value added (SI)	2
		Digital Education Infrastructure - Lack of STEM system (AT, CZ, EL, HU, LU, LV, SK)	13	Demographic renewal and foreign attraction (CZ, DE, DK, EE, EL, HR, LU, LV, NL, SI, SK, SW)	19
		Lack of working experience with online teaching and learning (AT, DE, HU, LV, RO)	6	Talent attraction and acquisition initiatives (BE, BU, CZ, DE, HR, HU, LU, PT, RO, SK, SW)	19
		Lack of continuous training (CZ, DE, EL, HR, HU, LU, LV, NL, PT, RO, SI, SK, SW)	19	Awareness of digital skills (AT, CZ, DE, EL, HR, HU, IE, LV, PT)	17
		Lack of ITCE competencies (BU, CZ, DE, EL, FR, HR, HU, LV, PT, SI, SK, SW)	30	Unemployment and minorities (PT)	1
				RD&I talent (AT, CZ, EE, DE, HU, LU, PT, RO, SI, SK, SW)	21
				Digital Inclusion and Literacy (AT, BE, BU, CY, CZ, DE, DK, EE, EL, ES, FI, FR, HR, HU, IT, LU, LV, NL, PL, PT, RO, SI, SK)	90
				Digital Education Funding - Grants and Scholarships (HU)	1
				Distance Learning (AT, DE, EL, LU, LV, PT)	14
				Distance Learning - Mobile Applications (AT)	1
				Distance Learning - Education curriculum platform (AT, DE, ES, LU, LV, NL, RO, SK)	16
				Distance Learning - Effect of digitalisation on distance learning (AT, LV)	2
				Distance Learning - Centralized learning Platform (AT, LV, PT)	4
				Digital Education Infrastructure (AT, BE, BU, CZ, DE, EL, ES, FI, HR, HU, IE, LU, LV, NL, PL, PT, RO, SI, SK)	57

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				Digital Education Infrastructure - Digital Educational Resources (AT, BU, DE, FR, LU, LV, PT, SK)	17
				Use of digital devices (AT, HU, LV, SK)	5
				Digital Education (AT, BE, BU, CY, CZ, DE, EL, ES, FI, FR, HR, HU, IE, IT, LT, LU, LV, NL, PL, PT, RO, SI, SK, SW)	147
				Employability (AT, DE, DK, EL, FR, HR, IE, LU, LV, NL, PT, SI, SK, SW)	41
				Promote digital skills development (AT, BU, CY, CZ, DE, EE, EL, ES, FI, FR, HR, HU, IE, IT, LU, LT, LV, NL, PL, PT, RO, SI, SK, SW)	140
				Workforce training (AT, BE, BU, CY, CZ, DE, DK, EL, ES, FI, FR, HR, HU, IE, LU, LT, LV, PT, RO, SI, SK, SW)	82

Barrier (Countries)	**# Segments**	**Sub-Barriers (Countries)**	**# Segments**	**Initiatives (Countries)**	**# Segments**
Knowledge Management Systems (AT, BE, LT, LV, RO)	11	N/A		Public data availability for data-driven services (AT, CZ, ES, FI, LU, LV, MT, NL, PL, RO, SI, SK)	29

Barrier (Countries)	**# Segments**	**Sub-Barriers (Countries)**	**# Segments**	**Initiatives (Countries)**	**# Segments**
Clear Comprehension of Digitalisation Benefits (CZ, DE, IE, LT, LV, PL)	10	N/A		Promote awareness of IoT benefits (CZ, DE, IE, LV, MT, NL, PL, SK)	12
				Development of Smart Devices (BE, DE, LV, MT, NL, PL)	6

Barrier (Countries)	**# Segments**	**Sub-Barriers (Countries)**	**# Segments**	**Initiatives (Countries)**	**# Segments**
Standardisation Efforts (AT, CY, CZ, DE, DK, EE, EL, IE, LU, LV, MT, SK)	22	N/A		I4.0 Standards initiatives (AT, CZ, DE, DK, EE, EL, HU, IE, LU, LV, MT, SI)	25
				Educational standards initiatives (CZ, IE)	2
				Standardised communication processes (AT, CY, DE, DK, EE, EL, FI, HU, IE, LU, LV, MT, SI)	27

Barrier (Countries)	**# Segments**	**Sub-Barriers (Countries)**	**# Segments**	**Initiatives (Countries)**	**# Segments**
Adaptive Retrofitting Implementation (IE)	1	N/A		Integration with legacy systems (IE)	1

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Barrier (Countries)	# Segments	Sub-Barriers (Countries)	# Segments	Initiatives (Countries)	# Segments
Infrastructure (AT, CZ, DE, DK, EE, EL, ES, FR, HU, IT, LU, LT, LV, MT, NL, RO, SI, SK, SW)	37	Lack of supportive infrastructure - financing system (AT, LV, SI)	4	Online Platform for Entrepreneurship (ES)	2
		Lack of initiatives to promote Smart Cities (AT, BE, CZ, DE, EE, FR, HR, LU, LT, LV, RO)	17	Residence scheme for multinational employees (NL)	1
		Lack of backbone transport infrastructure network (AT, CZ, DE, EE, FR, HU, LV, RO, SK)	15	Accelerator and incubator initiatives (AT, DE, EL, ES, HU, IE, MT, NL)	14
		Lack of urban mobility infrastructure initiatives (AT, CZ, DE, EE, FR, LV, RO, SK)	16	Smart Cities initiatives (AT, CZ, DE, EE, EL, ES, FR, HU, IT, LU, LT, LV, MT, NL, RO, SI, SK)	41
		Lack of Communication and IT Infrastructure (AT, CY, DE, DK, EE, EL, ES, HU, IT, LU, LV, MT, NL, PL, RO, SI, SK)	74	Intelligent Transport Systems Development Action Plan (AT, CZ, EE, EL, ES, FR, LV, NL, RO, SK)	19
				Smart mobility services for materials (AT, CZ, EE, EL, ES, FR, HU, LV, NL, RO, SK)	26
				Adaptive risk management (NL, SK)	2
				Quantum Computing Infrastructure (AT, EL, FI, LU)	5
				Data-related infrastructure (AT, BE, CY, CZ, DE, DK, EE, EL, ES, FI, FR, HR, HU, IE, IT, LU, LV, MT, NL, PL, RO, SI, SK)	194
				Develop Public Digital Infrastructure (AT, BE, BU, CY, CZ, DK, EE, EL, ES, FI, FR, HR, HU, IT, LU, LV, MT, NL, PL, PT, SI, SK)	126

Barrier (Countries)	# Segments	Sub-Barriers (Countries)	# Segments	Initiatives (Countries)	# Segments
Security, Safety and Privacy Issues (AT, CY, CZ, DE, DK, EE, EL, ES, FR, IT, LU, LV, MT, NL, PL, SI, SK)	55	Lack of consumer-oriented data sharing capability (CY, FI, HU, MT)	4	Data security Business-to-Government (AT, CY, CZ, DE, DK, EE, EL, ES, FI, FR, HU, IT, LU, LV, MT, NL, PL, SI, SK)	105
		Lack of trust on digital solutions security (AT, DE, DK, EE, EL, ES, FR, HU, LU, LV, MT, NL, PL, SI, SK)	37	Cybersecurity (AT, BE, BU, CZ, DE, DK, EE, EL, ES, FI, FR, HU, IT, LU, LV, MT, NL, PL, PT, SI, SK)	136

Barrier (Countries)	# Segments	Sub-Barriers (Countries)	# Segments	Initiatives (Countries)	# Segments
Integration with existing technology (AT, CY, CZ, DE, DK, EE, EL, ES, FR)	11	N/A		Scientific (RD&I) Infrastructure Development (BU, EE, EL, SI, SK, SW)	12
				Collaboration initiatives with FoFs (BE, CZ, DE, EL, ES, HU, IE, LV, MT, PL, PT, SI, SK)	24

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Barrier (Countries)	# Segments	Sub-Barriers (Countries)	# Segments	Initiatives (Countries)	# Segments
Regulatory Framework (AT, CY, CZ, DE, EE, EL, FR, HR, HU, IE, IT, LU, LT, LV, MT, RO, SW)	51	N/A		Circular Economy benefits and initiatives (BE, DE, DK, HR, RO)	10
				Cooperation initiatives (AT, BE, BU, CZ, DE, EE, EL, ES, FI, FR, HR, HU, IE, IT, LU, LT, LV, MT, NL, PL, PT, RO, SI, SK, SW)	117
				Regulatory Framework for fair competition (AT, DE, LU, RO, SK)	6
				Regulatory framework for online markets (AT, DE, EL, LU, MT, NL, SK)	11
				Regulatory framework for transport (AT, CZ, SK)	10
				Regulation for infrastructure construction proceedings (CZ, DE, EL, HU, RO)	17
				Data regulation compliance (AT, DE, DK, EE, EL, ES, FR, HR, HU, IT, LU, LV, MT, NL, PL, PT, RO, SI, SK)	106
				Legal security regulatory framework (AT, BU, CZ, DE, DK, EE, EL, ES, FI, FR, HU, IT, LU, LV, MT, NL, PL, PT, SI, SK)	128
				Regulatory framework for public and/or private financing (CZ, DE, HR, HU, LT, RO, SK)	30
				Regulatory framework for education policy (AT, BE, CZ, ES, HR, HU, LV, RO, SK)	23
				Regulatory framework for electronic communications (AT, BE, BU, DE, EE, EL, ES, HU, LV, MT, NL, PL, SK)	35
				Regulatory framework to improve workforce (BE, CZ, ES, HR, PT, RO, SK)	15
				Establishing Regulatory Framework for Innovation Fostering (AT, BE, BU, CZ, DE, EE, EL, ES, FI, HR, HU, IE, IT, LU, LT, LV, MT, NL, PL, PT, RO, SK, SW)	79
				Collaboration entities (AT, BE, BU, CY, CZ, DE, EE, EL, ES, FR, HR, HU, IE, LU, LT, LV, MT, NL, PL, PT, RO, SI, SK, SW)	114
				Digital Research, Development and Innovation (AT, CZ, DE, EL, HU, IE, IT, LU, MT, NL, RO, SI, SK)	48
				Digital Economy (AT, BE, BU, CY, CZ, EE, FI, HR, LV, NL, RO, SK, SW)	24
				IT Benefits (AT)	2

				Public Administration System (AT, NL, PT)	4
				Digital Government (AT, BE, BU, CY, CZ, DE, DK, EE, EL, ES, FI, FR, HR, HU, IT, LU, LV, MT, NL, PL, PT, RO, SI, SK)	160
				IT systems (AT, CY)	4
				E-government (AT, BE, BU, CY, CZ, DK, EE, EL, ES, FI, FR, HR, HU, IT, LV, MT, PL, PT, SK)	55
				Government effectiveness (AT, CY, SK)	5
				Guiding principles (AT, CY, EL, FI, HR, PT)	14
				Digitalization vision (AT, CY, FI, HR)	5
				Strategic framework for digitalization projects (AT, CY, HR)	6
				Digitalization action plan (AT, CY, HR)	3
				IT Consolidation policy (AT, BE, BU, CY, CZ, DK, EE, EL, ES, FI, HR, IE, IT, LU, LT, MT, NL, PL, PT, SK)	55
				National digitalization strategy (AT, CY, CZ, DE, EL, FI, MT, PT)	19

Barrier (Countries)	# Segments	Sub-Barriers (Countries)	# Segments	Initiatives (Countries)	# Segments
Legal and Contractual Assurances (CZ, DE, DK, EE, EL, ES, HU, LU, LV, MT, RO, SK, SW)	16	Lack of e-commerce legal assurance (DE, EL, LU, PL, SK)	5	E-Commerce legal simplification initiatives (DE, EL, HU, LU, NL, PL, SK)	8
		Lack of Digital Information Sharing amid peers (AT, DE, DK, EE, EL, LT, MT, NL, SK)	11	Improving Business-to-Government bureaucracy (AT, CZ, DE, DK, EE, EL, ES, FR, HU, LU, LT, LV, MT, NL, PL)	35

Barrier (Countries)	# Segments	Sub-Barriers (Countries)	# Segments	Initiatives (Countries)	# Segments
Off-the-shelf solutions (BU)	1	N/A		N/A	

Barrier (Countries)	# Segments	Sub-Barriers (Countries)	# Segments	Initiatives (Countries)	# Segments
Digital Strategy (AT, BE, CY, CZ, DE, DK, EL, ES, FR, IE, IT, LT, LV, PT, RO, SI, SW)	41	Lack of Collaboration initiatives between PPPs entities (AT, BU, CZ, EL, LU, LT, LV, SK)	17	Open Science Strategy (AT, EL, SK)	5
				Boosting state-owned assets (HR)	1

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	Sustainability through AMTs or Data-driven solutions (AT, BE, CY, CZ, DK, EE, EL, FI, FR, HR, HU, LV, SI, SK, SW)	34
	Research-to-Market Technology Transfer (AT, CZ, DE, FI, HR, SI, SK, SW)	22
	Strategy for competitiveness boost (AT, BE, CY, CZ, DE, EL, ES, FI, FR, HR, HU, IE, IT, LU, LT, LV, NL, PL, PT, RO, SK, SW)	111
	Business Innovation (AT, BE, BU, CZ, FI, FR, HR, PT, RO, SI, SK, SW)	30
	Interorganizational Cooperation (AT, CZ, DE, EL, ES, FR, HU, IE, IT, LT, LU, LV, MT, NL, PL, PT, RO, SI, SK, SW)	117

Appendix 4 MAXQDA Coding Structure for the European National Digital Strategies

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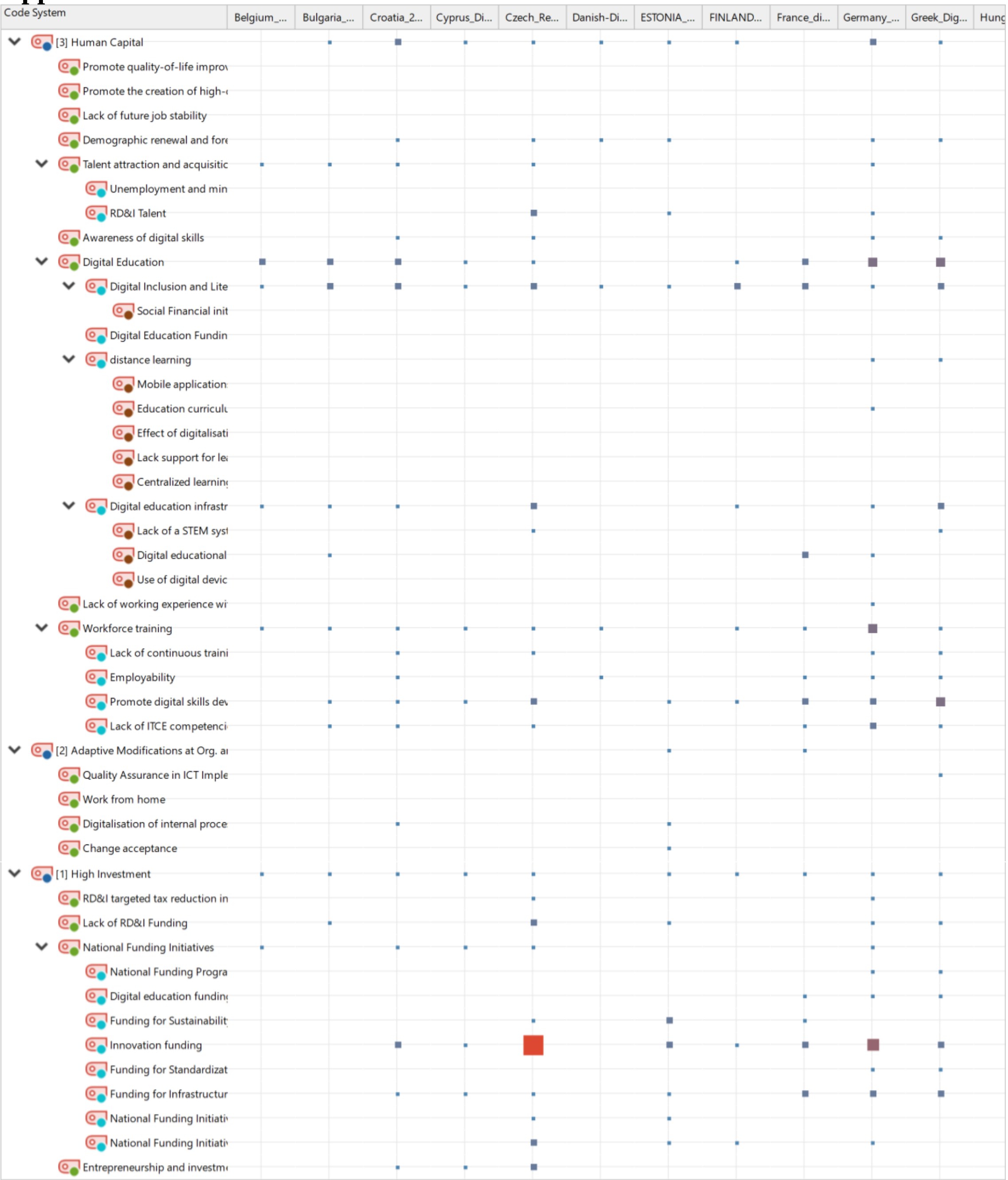

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