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Exploring paths underlying Industry 4.0 implementation in manufacturing SMEs: a fuzzy-set qualitative comparative analysis

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Abstract

Purpose – The purpose of this article is to develop a configurational approach based on the TOE framework (technology, organization and environment) to understand the degree of implementation of I4.0 technologies in manufacturing small- and medium-sized enterprises (SMEs). Specifically, the study considers technological infrastructure and competence, I4.0 integration capabilities, organizational agility and strategic flexibility, environmental dynamism and industry-specific forces as simultaneous pre-conditions for achieving an effective implementation of I4.0 technologies.

Design/methodology/approach – This study uses the fuzzy-set qualitative comparative analysis (fsQCA) methodology as it allows for asymmetric and configurational-focused testing of proposition and sound theoretical development. In total, 305 responses were collected through a survey administered to SME managers in Europe and the United Kingdom (UK).

Findings – The study examines the influence of technology, organizational and environmental aspects on I4.0 technologies implementation in SMEs. High I4.0 degree of implementation is structured around 5 configurations, while other 4 configurations are related to low levels of I4.0 implementation.

Originality/value – This study proposes a configurational approach for SMEs to become I4.0 ready and how they may successfully implement I4.0 technologies. Such findings represent an original and novel contribution to existing research, offering a broad view on the I4.0 implementation by manufacturing SMEs.

Keywords Industry 4.0, Digital technologies, SMEs, TOE framework, fsQCA, Configurational approach
Paper type Original article

1. Introduction

Over the last decade, business environments have been increasingly impacted by advanced digital technologies capable of disrupting the way firms traditionally operate (Hanelt *et al.*, 2021; Ustundag and Cevikcan, 2017). Industry 4.0 (I4.0) can be defined as a new production model that incorporates the integration of physical objects, humans and smart machines with the goal of creating an integrated system capable of collecting, sharing and analyzing data in real-time, also known as a cyber physical system (CPS) (Cimini *et al.*, 2021). Technologies that enable I4.0 include Automation, Robotics, Industrial Internet of Things (IIoT), big data analytics (BDA), artificial intelligence (AI), cloud computing, sensors, radio frequency identification (RFID) and advanced manufacturing technologies (AMTs) (Kumar and Bathia, 2021; Rajput and Singh, 2019).

Many I4.0 supporting actions have been undertaken worldwide, such as "Industrie 4.0" in Germany, "Made in China 2025)," "Made in India Initiative," "Industria 4.0 Law" in Italy and the "Smart Manufacturing Leadership Act" by the US Congress. The US, China, Germany, UK and France have the highest incidence of digitalized manufacturing processes according to the Cisco (2020) "Digital Readiness Report". Correspondingly, the US I4.0 market approached $50 billion in 2021, Chinese firms, pushed by large corporations such as Foxconn and Xiaomi, invested more than $10 billion over the last year, and the EU-27 and the UK I4.0 markets were valued at about $25 billion in 2020 (Texeira and Tavares-Lehmann, 2022).

Initially, the adoption of such technologies was a phenomenon mainly associated with large manufacturing corporations, with small- and medium-sized enterprises (SMEs) lagging behind (Agostini and Filippini, 2019; Agostini and Nosella, 2019; Rialti *et al.*, 2019). As contended, one reason for this was the high investment costs required for I4.0, which were often deemed too significant for these types of firms, as the benefits and return on investment of these technologies were uncertain. Han and Trimi (2022) also noticed that managers of SMEs often believed their businesses did not generate enough data to justify deploying BDA and AI for significant results. However, in recent times, the trend of I4.0 adoption in SMEs has changed. More tools have become customizable, scalable and less expensive, and more manufacturing SMEs have started adopting I4.0 technologies to replace existing, non-cost-effective procedures (Szalavetz, 2019).

Despite the increasing adoption of I4.0 technologies by SMEs, it has been observed that these businesses often struggle in the post-adoption stages due to a lack of the necessary capabilities to properly utilize advanced technologies (Sony *et al.*, 2022). The complexity of these technologies, which requires the re-training of the workforce or changes to traditional working procedures, prevents SMEs from fully benefiting from the increased information derived from I4.0 (Schönfuß *et al.*, 2021). Indeed, the adoption of I4.0 in SMEs does not necessarily correspond to the complete implementation of these technologies (Qin *et al.*, 2016). In this perspective, implementation is a process aimed at the routinization of the usage of a technology (Bruque and Moyano, 2007).

Also, in spite of the growing body of literature on I4.0 adoption, research on the implementation of I4.0 in SMEs is still in its early stages. Virmani *et al.* (2021) have focused on the exploration of the main building blocks of I4.0 compliant production lines, identifying the key technologies necessary for manufacturing businesses. Duman and Akdemir (2021) observed how businesses implementing I4.0 technologies may increase profitability, sales, production speed, reduce costs and improve quality. In addition to the limited literature available, research on the implementation of I4.0 in SMEs also rarely adopts a holistic perspective (Frank *et al.*, 2019). Some authors have indeed considered the importance of technological characteristics in relation to I4.0 implementation (Duman and Akdemir, 2021), while others have focused on the organizational characteristics and the role of managers in promoting I4.0-based practices (Chatterjee *et al.*, 2021).

The study of the factors that contribute to the success of I4.0 implementation within SMEs is of paramount importance for both academic and practical reasons. From an academic perspective, it provides insights into the complex and multifaceted nature of technological implementation in SMEs, which can inform the development of more robust theoretical frameworks. From a practical perspective, it can help SMEs identify key success factors and strategies for implementing digital technologies, leading to improved competitiveness and sustainability. Furthermore, understanding the success factors of I4.0 implementation in SMEs is important for policymakers and practitioners as it can inform the development of policies and programs aimed at supporting the digitalization of SMEs, which are the backbone of many economies worldwide. Thus, the present study aims to enrich the extant academic debate with the simultaneous test of multiple groups of variables in determining the successful I4.0 integration, specifically focusing on I4.0 degree of implementation by SMEs (Sony and Naik, 2020). The three dimensions identified by the technology–organization–environment (TOE) framework (Tornatzky and Fleisher, 1990), namely technical, organizational and environmental factors, have been considered. The TOE framework has been deemed a parsimonious model to explore the antecedents of implementation processes, as technology availability needs to be supported by organizational factors such as agility or flexibility and by external pressures (Lu and Ramamurthy, 2011; Zhu *et al.*, 2010). Thus, the research question of this study is as follows:

RQ1. How do technological, organizational and environmental factors interrelate in shaping SMEs' I4.0 technologies degree of implementation?

Precisely, the present study focuses on EU-27 and UK SMEs that have adopted I4.0 technologies to explore which factors are enacting a complete (high) or partial (low) degree of implementation.

2. Theoretical background

2.1 SMEs and I4.0: a theoretical lens

The I4.0 concept involves the transformation of traditional business paradigms into smart ones, in which humans and machines are interconnected through the use of technologies (Alacer and Machado, 2019). The academic debate on I4.0 has mainly focused on large manufacturing firm (Agostini and Filippini, 2019; Agostini and Nosella, 2019; Rialti *et al.*, 2019). I4.0 technologies demonstrated their greatest potential in mass production. Still, large corporations only constitute a small portion of the realities within the manufacturing industry (Garzoni *et al.*, 2020).

Research on I4.0 and SMEs originated in the fields of engineering management and IT. Würtz and Kölmel (2012) observed how IT infrastructure serve as the foundation of smart factory initiatives in SMEs. In detail, IT infrastructure is composed by all the hardware such as wiring, interfaces and any other basic IT technology (i.e. internal servers). These elements need to be settled as a unicum system capable of data transmission and gathering from/to any production and decision phases. Ideally, an optimal IT infrastructure should be projected to reach the machines and tools which are going to be interconnected during the 4.0 transformation. IT infrastructure then is the prerequisite for SMEs wishing to increase machine coordination and digitize their operations (Rialti *et al.*, 2019). The adoption and implementation of I4.0 can lead to significant benefits for SMEs (Szalavetz, 2019). However, the elaboration of adequate IT infrastructure comes with financial costs, which may pose a critical challenge for SMEs. Likewise, projecting these systems may be extremely burdening for management, as any business need to identify the structure for its characteristics.

Another key aspect that makes it more challenging for SMEs to implement I4.0 technologies is then the lack of scale and resource constraints (Eggers, 2020). Scholars have noted that SMEs may encounter different problems compared to larger businesses when striving for I4.0 readiness. In particular, SMEs may lack the production volumes to justify investments in I4.0 and digital culture, making them more resistant to initiating new projects. Masood and Sonntag (2020, p. 2) argued that "SMEs tend to face greater financial and knowledge resource constraints", as they may lack the necessary economic assets for investment and the necessary capabilities to manage the technologies. Cimini *et al.* (2021) also highlighted that organizational resistance to change is one of the main factors limiting digitalization in SMEs. Many SMEs do not pursue I4.0 due to economic-financial, cultural, competency, resource, technical and legal constraints (Orzes *et al.*, 2019).

Moreover, scholars investigated which best practices from large corporations can be transferred to SMEs for the implementation of I4.0. SMEs that adopt and rely on I4.0 technologies have been found to be more resilient and capable of exploiting limited resources and adapting to diverse production demands (Kumar and Bathia, 2021; Messeni Petruzzelli *et al.*, 2021). Han and Trimi (2022) argued that by leveraging I4.0 technologies, SMEs can increase their competitiveness and responsiveness through improved collaboration with value chain partners and emerging as innovative partners for their larger B2B clients (Ahmad *et al.*, 2020).

There are various theoretical perspectives used to study the success of technological implementation in SMEs, such as the technology acceptance model (TAM) and diffusion of innovation (DOI) (Chatterjee *et al.*, 2021). However, most of these frameworks only explore specific groups of variables, failing to grasp how technological, organizational and environmental factors simultaneously affect the implementation of digital technologies in SMEs. In this regard, the TOE framework (Tornatzky and Fleisher, 1990) has consistently proved its usefulness in several diverse technology implementation studies, such as enterprise resource planning (Awa and Ojiabo, 2016), customer relationship management technologies (Cruz-Jesus *et al.*, 2019), social commerce (Abed, 2020), cloud computing (Al-Hujran *et al.*, 2018), BDA (Ullah *et al.*, 2021) and I4.0 (Raut *et al.*, 2020; Messeni Petruzzelli *et al.*, 2021; Shet and Pereira, 2021).

Thus, the TOE framework offers a valuable lens for examining I4.0 implementation within an organization. Its focus on the interplay between technology, organization and environment aligns well with the complexity and multi-faceted nature of I4.0 and allows for a comprehensive examination of the technological, organizational and environmental factors that influence the success of I4.0 implementation within an organization. Specifically, the technology component allows for an examination of the technological capabilities and limitations of I4.0 implementation, the organization component takes into account the internal organizational factors that influence the success of I4.0 implementation, and the environment component allows for a comprehensive examination of the external factors that impact I4.0 implementation.

Technological infrastructures and I4.0 integration capabilities and procedures are essential for organizations to fully leverage the potential of I4.0 and gain a competitive advantage (Bag *et al.*, 2021; Cruz-Jesus *et al.*, 2019; Duman and Akdemir, 2021). Organizational agility and strategic flexibility are crucial for organizations to adapt to the rapidly changing technological landscape and respond to emerging opportunities and threats (Chatterjee *et al.*, 2021; Cegarra-Navarro *et al.*, 2016; Zhou and Wu, 2010). Industry-specific forces and environmental dynamism are important factors that shape the overall I4.0 landscape and impact the ability of organizations to compete in their respective industries (Kumar and Bhatia, 2021; Takata, 2016). Thus, through the examination of these factors, we aim to gain a holistic understanding of the impact of I4.0 on organizations and identify key success factors. Consistently, we focus on each of the three dimensions constituting the TOE framework. Based on a literature analysis, we chose to focus on the role of technological infrastructures and I4.0 integration capabilities and procedures at the technological level, organizational agility and strategic flexibility at the organizational level and industry-specific forces and environmental dynamism at the environmental level.

2.2 Technological factors underlying I4.0 implementation in SMEs

Considering the TOE framework, we argue that successful implementation of I4.0 technologies in SMEs depends on technology-related factors (Correani *et al.*, 2020). In such a regard, a robust IT infrastructure built on an architecture capable to successively support key I4.0 technologies, could enable a smoother implementation of advanced I4.0 solutions (Ustundag and Cevikcan, 2017). For instance, a robust IT infrastructure need to be capable to support the flow of massive amount of data and should constitute of server adept to real-time data collection and storage. These characteristics are crucial for the successful successive implementation of I4.0 technologies such as the IoT and AI (Lardo *et al.*, 2020; Oliveira-Dias *et al.*, 2022). Moreover, IT infrastructure should be designed to ensure the necessary network security to warrant the safe operation of I4.0 application which could be rooted on it. Overall, the IT infrastructure's adequacy is a critical factor in a firm's digital transition (Rialti *et al.*, 2019). Likewise, it has been deemed necessary for any business not only to have a suitable infrastructure, but also the competences to maintain it functional. In relation to infrastructure, competences to make it work are related to successful digital transition as they facilitate internal online collaboration and eases the implementation processes (Monostori, 2014).

Also, the successful implementation of I4.0 technologies in SMEs is dependent on the existing technical capabilities about the specific technologies of the organization (Shet and Pereira, 2021). If SMEs are weak in term of I4.0 specific capabilities, the implementation of the technologies may prove to be challenging. The acquisition of capabilities in an organization is henceforth crucial for the successful implementation of I4.0 (Bag *et al.*, 2021). As postulated by TOE, technology is not purposeful by itself if the organization is lacking the knowledge to make it work (Tornatzky and Fleischer, 1990). The effects generated by I4.0 are thereby related to the characteristics of the implemented technologies and the organization's technical competence to make it work along with the capabilities to apply the front-end technologies (i.e. capabilities spanning the entire business and extending their reach in the supply-chain). While soft skills are generally relevant for organizational change, the competencies are the ones that effectually make a technology generate meaningful results (Shet and Pereira, 2021).

2.3 Organizational characteristics underlying I4.0 implementation in SMEs

Digital transformation requires structural modifications in SMEs (Nambisan *et al.*, 2019) and, to address this, firms have to attain the development of organizational and managerial practices and be ready to manage dynamic changes (Agostini and Filippini, 2019). Still, SMEs are often less inclined to implement new I4.0 technologies as compared to large corporations due to the lack of skilled workforce, effective human resource management, financial flexibility and managerial resources and capabilities (Horváth and Szabó, 2019). This lack might considerably reduce the SMEs ability to evaluate the benefits and costs of I4.0 technologies and to perform effective implementation (Bosman *et al.*, 2020; Messeni Petruzzelli *et al.*, 2021).

A study conducted by McKinsey (2016) emphasizes how the ultimate outcome of I4.0-related projects across SMEs depends on the coordination across organizational units, the capability to sense future scenarios and readiness to cope with environmental change. Mittal *et al.* (2018) noted that the organizational structure of SMEs is often not sufficiently flexible to experiment and consider I4.0 implementation initiatives. Moreover, the authors observed that SMEs' decisions in many cases are not aligned with external changes and do not rely on an agile and flexible paradigm.

These peculiar characteristics make it particularly relevant to investigate how their organizational agility and strategic flexibility influence the degree of I4.0 implementation. In fact, the constraints and limits related to firm size put high pressure on SMEs. In this context, SMEs' abilities to assess the benefits and costs of I4.0 technologies (Khin and Kee, 2022), coordinate the various organizational units and effectively manage human resource are critical determinants of their organizational agility (Doz, 2020; Ferraris *et al.*, 2022). In parallel, the capability to sense future scenarios, the readiness to cope with dynamism, the ability to collect external information and responsiveness to change widely entail the strategic flexibility of SMEs (Brozovic, 2018; Rialti *et al.*, 2020; Stentoft *et al.*, 2021).

Following the TOE framework, we argue that organizational characteristics play a significant role in facilitating or inhibiting the implementation of I4.0 technologies. The internal structure of firm has direct influences on learning rate and capability to adapt or implement new solutions (Sorenson, 2003). Precisely, the levels of organizational agility and flexibility affect the degree of implementation of I4.0 technologies. Organizational agility and flexibility – measures of the capability of SMEs to adapt to complex situations – have frequently been associated with improved adoption and implementation of digital technologies (e.g. Rialti *et al.*, 2020).

Organizational agility refers to the capacity to adapt to changing patterns of resource deployment in a deliberate and strategic manner, while also being able to quickly and efficiently respond to new opportunities and challenges (Doz and Kosonen, 2007). Firms with higher levels of organizational agility constantly sense new opportunities and are ready to shift their business paradigm accordingly (Doz and Kosonen, 2010). Such an agile structure allows firms to be quicker in strategy formulation and implementation, leveraging on superior market intelligence and ability to create assets, capabilities and knowledge, co-evolving in a coordinated and prompt way (Najrani, 2016). Thus, agile firms have capacity to integrate, build and reconfigure internal and external resources to capture and create new value (Doz and Kosonen, 2010). Some authors have stressed how SMEs may benefit from agility in technology permeated environments (Chan *et al.*, 2019; Doz, 2020). These businesses with lean structures and smaller scales may incur lower costs when reconfiguring their business models. Managers play a fundamental role in this process as they are often the ones to sense the need for change in the organization. Research by Neirotti *et al.* (2017) shows that agile SMEs can adapt to new technologies and perform better.

I4.0 technologies offer an opportunity for SMEs to achieve higher automation of business lines, better control over production processes and improved coordination through resource optimization and cost monitoring (Egger and Masood, 2020). Agile SMEs may be able to adopt these technologies more quickly than their rivals and have a higher capability to implement them in their business models. Hadjielias *et al.* (2022) found that SMEs' agility enables them to leverage I4.0 technologies to create value. Therefore, we contend that the greater the level of organizational agility, the greater the degree of implementation of I4.0 technologies.

Strategic flexibility is also critical for combining different IT technologies, business resources and capabilities and adapting to the environment in order to enhance I4.0 technologies implementation (Herhausen *et al.*, 2020). Strategic flexibility is defined as the firm's ability to respond to changes in the dynamic business environment in order to achieve its objectives, with the support of knowledge and superior capabilities (Brozovic, 2018; Fachrunnisa *et al.*, 2020). Strategic flexibility encompasses firm proactiveness, responsiveness to change and the ability to deal with environmental dynamism and uncertainty (Rialti *et al.*, 2020). Strategic flexibility is crucial in adapting business paradigms quickly for new growth opportunities (Brozovic, 2018; Fachrunnisa *et al.*, 2020; Rialti *et al.*, 2020). Research shows that strategic flexibility is a fundamental lever for SMEs looking to increase their competitiveness, which can only be achieved through innovation and creativity.

SMEs seeking to integrate I4.0 technologies within their operations must prioritize the cultivation of strategic flexibility. This encompasses not only the ability to adapt and evolve the internal organizational infrastructure, but also the capacity to attend to the nuances of supply chain mechanisms and acquire the necessary technological capabilities (Herhausen *et al.*, 2020). According to Lu and Ramamurthy (2011), flexible SMEs can better recognize and absorb new technological competences within their production processes.

2.4 Environmental factors underlying I4.0 implementation in SMEs

Business environments are the arenas in which firms carry out their activities (Tornatzky and Fleischer, 1990). These environments create pressure on firms to constantly compete in order to maintain their competitive position (D'Aveni *et al.*, 2010). Increasing uncertainty requires firms to adapt to changes in the environment. Scholars have observed that this dynamic environment leads firms to be proactive and use internally developed knowledge (Pérez-Luño *et al.*, 2014). However, the effects of environmental dynamism may vary across industries (Schilke, 2014). In fact, the environmental characteristics of different industrial sectors make them different in terms of competition, technological presence and stability on the demand side (Kumar and Bhatia, 2021).

In this vein, the relationship between environmental dynamism and Porter's forces and technologies is a complex one (Pérez-Luño *et al.*, 2014; Takata, 2016). On the one hand, environmental dynamism can have a positive influence on the implementation of digital technologies by SMEs (Björkdahl, 2020). Rapid technological advancements and increased competition can create a sense of urgency for SMEs to adopt digital technologies to stay competitive and remain relevant in their industry (Björkdahl, 2020). Environmental dynamism can offer SMEs opportunities for innovation as it forces them to adapt and find new ways of doing things to remain competitive (Kumar and Bathia, 2021; Molina-Castillo *et al.*, 2022). This can lead to the development of new products, services and processes that can give SMEs a competitive advantage (Suarez and Lanzolla, 2007).

On the other hand, environmental dynamism and Porter's forces can also have a negative influence on the implementation of digital technologies by SMEs. The rapid pace of technological change can make it difficult for SMEs to keep up and invest in the right digital technologies (Brettel *et al.*, 2014; Kafetzopoulos *et al.*, 2020). For example, increased competition can make it difficult for SMEs to differentiate themselves and justify the cost of implementing digital technologies. Furthermore, the threat of new entrants and the bargaining power of buyers and suppliers can also make it difficult for SMEs to secure the necessary funding and resources to implement digital technologies (Jansen *et al.*, 2006; Kumar and Bhatia, 2021).

Environmental pressures pose particular challenges for SMEs (Masood and Sonntag, 2020). Despite their structural limitations, SMEs must quickly and proactively adapt to changing environments to effectively compete and maintain their competitive position (Molina-Castillo *et al.*, 2022). Additionally, SMEs must navigate the specific forces that characterize each industry, which are contingent on various contextual factors and industrial characteristics (Porter, 1980). The level of environmental dynamism and the magnitude of these forces can greatly affect the degree of I4.0 implementation (Kumar and Bhatia, 2021). An aspect that supports this is the unique structure of SMEs, which puts them at a disadvantage compared to larger corporations, making them more vulnerable to environmental forces and more likely to respond and explore new solutions to preserve their business viability (Eggers, 2020).

To optimize their efforts, SMEs must implement quick strategies and be ready to take advantage of new growth opportunities. In high-dynamic environments, firms should accelerate the integration of I4.0 technologies as a response to uncertainty (Gillani *et al.*, 2020). On the other hand, for SMEs wishing to implement I4.0, environmental dynamism could be a driving force to capitalize on previous efforts and explore available technologies in new ways in their operations (Martinez-Conesa *et al.*, 2017). Zhang and Zhu (2021) observed that SMEs operating in competitive environments are more engaged in knowledge creation and disruptive innovation compared to those operating in non-turbulent markets.

Similarly, as Porter (1980) argued, industry forces influence a firm's competitive advantages and performances. Industry forces create competition among existing firms, threats for new entrants, threats from substitute firms and the bargaining power of buyers and suppliers (Takata, 2016). The interaction between SMEs, competitors and customers can also be helpful in generating new ideas and influencing their willingness to integrate them into their business practices (Pérez-Luño *et al.*, 2014). Therefore, consistent with the TOE framework, we argue that environmental factors affect the degree of I4.0 technologies implementation in SMEs.

Building on the previous insights about the potential role of technological, organizational and environmental factors in affecting the I4.0 degree of implementation in SMEs, the following proposition has been developed.

> Single causal conditions (e.g. technological, organizational and environmental) may be present or absent within configurations for I4.0 degree of implementation, depending on how they combine with other causal conditions

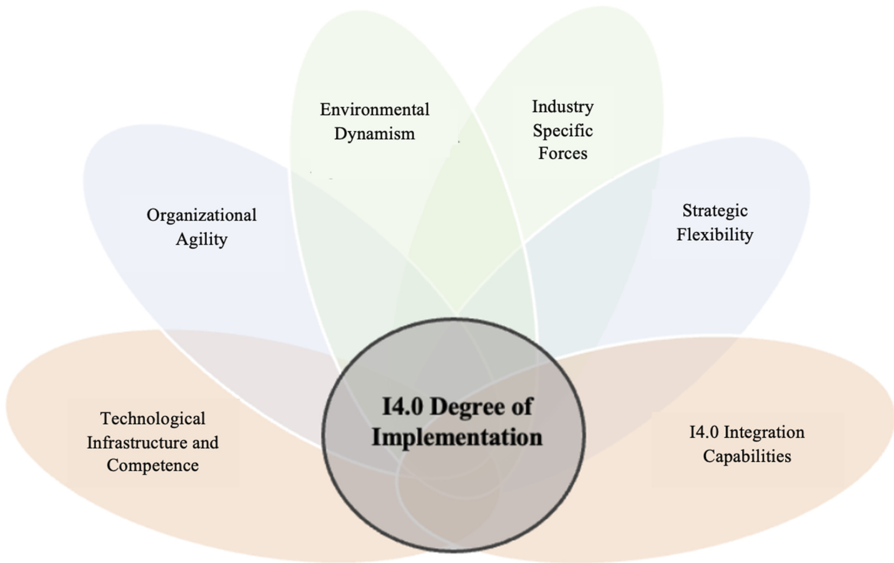
The developed research model is illustrated in Figure 1.

3. Method

3.1 Data collection

This study employs a survey methodology to gather data from managers working in SMEs based in Europe and the UK that have already adopted some I4.0 technologies. To focus on the target population, the sample was drawn from managers working in firms with less than 250 employees, specifically within the manufacturing sector as it is the area where the concept of I4.0 finds its most complete realization.

To ensure the quality of the questionnaire, the authors sought feedback from entrepreneurs prior to its final submission. After receiving confirmation of its quality, the survey was distributed to a panel of SMEs managers from the relevant countries through a market analysis firm. A total of 736 managers from SMEs that met the initial screening criteria of location, size and I4.0 adoption were identified.



Source(s): Authors' elaboration

Figure 1.
Research model

The questionnaire was intended to be completed by upper, middle and junior managers as the processes for full implementation of I4.0 are managed by SMEs' upper echelons. The survey aimed to understand the potential for the realization of the I4.0 paradigm as a whole, rather than the adoption of a specific enabling technology. After eliminating responses with missing data and those that failed validity checks, a sample of 305 responses (response rate of 41.44%) was collected. Data about the respondents can be found in Table 1.

All respondents in this study identified the firm they work for as technology-intensive and utilizing I4.0 technologies. To ensure a diverse and representative sample, the collected data includes a heterogeneous group of managers from various small and medium-sized enterprises within the manufacturing sector. To prevent any issues of single source bias, no reference to the proposed model in Figure 1 was shared with respondents, and the survey questions were structured in a manner that did not allow for detection of any cause-and-effect relationships.

Furthermore, to ensure the validity of the data, measures were taken to address potential response bias. The Harman's (1976) single factor test was conducted through exploratory factor analysis using SPSS 28.0 statistical software. The results revealed that the first factor accounted for only 28.03% of the total variance, which falls below the 50% threshold. This suggests that there is no notable bias present in the responses.

3.2 Variable measurement

The questionnaire utilized in this study included six independent variables and one dependent construct. Responses were collected using a seven-point Likert scale, ranging from "Strongly Disagree" to "Strongly Agree".

To investigate the technological factors, two variables were selected: Technological Infrastructure and Competence (Cruz-Jesus *et al.*, 2019) and I4.0 Integration Capabilities (Bag *et al.*, 2021). The Technological Infrastructure and Competence variable was measured using

Respondents' characteristics					
Age			*Gender*		
18–30	115	37.71%	Male	242	79.34%
31–45	146	47.87%	Female	63	20.66%
46–60	36	11.80%			
>60	8	2.62%			
Industry expertise			*Position in the firm*		
1–5 years	126	41.31%	Upper manager	73	23.93%
6–10 years	68	22.30%	Middle manager	129	42.30%
>10 years	111	36.39%	Junior manager	103	33.77%
Firms' characteristics					
Sector			*Technological level*		
Computer and electronics manufacturing	31	10.16%	High-tech	258	84.59%
Construction	16	5.24%	Low-tech	47	15.41%
Information services and data processing	79	25.90%			
Manufacturing	38	12.47%			
Product development	32	10.49%			
Other manufacturing	109	35.74%			
Size					
<5	46	15.08%			
5–20	59	19.35%			
21–50	55	18.03%			
51–250	145	47.54%			

Source(s): Authors' elaboration

Table 1. Sample descriptive statistics

a four-item scale that assessed the importance of having both adequate IT infrastructure and competence and the necessary capabilities to implement I4.0 (Cruz-Jesus *et al.*, 2019). The I4.0 Integration Capabilities variable was assessed with a three-item scale that evaluated the importance of having consistent capabilities in applying I4.0 front-end technologies and base technologies (adapted from: Bag *et al.*, 2021).

From the perspective of organizational context, Organizational Agility was measured using a six-item scale from Cegarra-Navarro *et al.* (2016), which explored the firm's ability to respond to customer needs, demand fluctuations and market changes. Strategic Flexibility was measured using a six-item scale from Zhou and Wu (2010), which analyzed how the firm allocates organizational resources to support its product strategies.

The environmental factors were represented by the variables of Environmental Dynamism (Kumar and Bhatia, 2021) and Industry Specific Forces (Takata, 2016). Environmental Dynamism was measured using a five-item scale which emphasized the level of changes that may occur in the market in which the organization operates. Industry Specific Forces was assessed using a six-item scale, which examined how factors such as price, competition, customer and supplier power may shape the firm's performance.

The dependent variable, I4.0 implementation, was measured using a scale adapted from Dixit *et al.* (2022). Sample items included statements such as "Our firm implements software to exchange data with other devices and systems over the internet" and "Our firm implements technologies to analyze real-world action." The construct was measured using a nine-item scale covering aspects of automation processes, sensors, RFID, IoT, service-oriented architecture and interactions between processes and humans. Low responses indicated a basic use of I4.0 technologies while high responses indicated the achievement of an I4.0 compliant status with full technological implementation.

3.3 Descriptive statistics and validity assessment

In order to analyze the reliability and validity of the measurement scale used in this study, various statistical tests were conducted. Specifically, internal consistency of the scales was assessed through calculations of Cronbach's alpha, Composite Reliability (CR) and Average Variance Extracted (AVE). As shown in Table 2, all values were significant and above 0.7 except for one construct, which had a value close to 0.69. However, this value was deemed acceptable as per several empirical studies (Lou *et al.*, 2022). Additionally, CR calculations revealed values between 0.832 and 0.965, indicating good reliability for all variables as the scores exceeded the 0.7 threshold. The AVE also exceeded 0.5, reaching thresholds of 0.873, with only one value at 0.48.

Table 3 shows the correlations between the various constructs. All variables were found to be correlated, presenting optimal values. As suggested by Lou *et al.* (2022, p. 87), this outcome is consistent with the logic of qualitative comparative analysis (QCA), in which "each causal condition is not isolated but has certain connections with other conditions".

4. fsQCA analysis and results

To test our proposition, we employed the fuzzy-set qualitative comparative analysis (fsQCA) method. According to Ragin (2008), fsQCA is a comparative configurational methodology that utilizes set theory and fuzzy logic. The primary objective of fsQCA is to identify a set of configurations and pathways that are sufficient to explain a given outcome (Woodside, 2014). A configuration consists of factors or conditions that can be positive, negative, or absent (Ragin, 2008). The underlying assumption of this methodology is that cause-and-effect relationships are subject to limitations, and it is necessary to consider the concept of complex causality and asymmetric relationships.

Constructs and items	Loadings	α	CR	AVE
Technological infrastructure and competence				
TC1	0.937	*0.952*	*0.965*	*0.873*
TC2	0.939			
TC3	0.933			
TC4	0.929			
I4.0 integration capabilities				
IIC1	0.911	*0.926*	*0.953*	*0.872*
IIC2	0.954			
IIC3	0.936			
Organizational agility				
AG1	0.794	*0.831*	*0.876*	*0.544*
AG2	0.797			
AG3	0.703			
AG4	0.759			
AG5	0.634			
AG6	0.727			
Strategic flexibility				
FL1	0.684	*0.798*	*0.858*	*0.502*
FL2	0.683			
FL3	0.681			
FL4	0.694			
FL5	0.734			
FL6	0.773			
Environmental dynamism				
ED1	0.608	*0.703*	*0.832*	*0.501*
ED2	0.735			
ED3	0.783			
ED4	0.651			
ED5	0.746			
Industry specific forces				
ISF1	0.585	*0.697*	*0.845*	*0.480*
ISF2	0.697			
ISF3	0.592			
ISF4	0.785			
ISF5	0.789			
ISF6	0.682			
I4.0 degree of implementation				
IDI1	0.618	*0.861*	*0.901*	*0.508*
IDI2	0.689			
IDI3	0.779			
IDI4	0.758			
IDI5	0.815			
IDI6	0.634			
IDI7	0.598			
IDI8	0.721			
IDI9	0.768			

Source(s): Authors' elaboration

Table 2.
Factors loadings and reliability analyses

As per Woodside (2014), fsQCA seeks to identify conditions that are sufficient but not necessary to cause an outcome. Rather than estimating the net effects of independent variables on the

Table 3.
Correlations and descriptive statistics

Variables	1	2	3	4	5	6	7
1. Technological I and C	1.000						
2. I4.0 integration capabilities	0.818**	1.000					
3. Agility	0.467**	0.402**	1.000				
4. Strategic flexibility	0.424**	0.407**	0.645**	1.000			
5. Environmental dynamism	0.273**	0.293**	0.366**	0.368**	1.000		
6. Industry specific forces	0.115*	0.154**	0.274**	0.293**	0.334**	1.000	
7. I4.0 degree of implementation	0.626**	0.638**	0.393**	0.556**	0.393**	0.313**	1.000
Mean	5.125	4.675	5.153	4.838	4.833	4.334	4.898
Standard deviation	1.605	1.708	0.992	0.970	0.995	0.853	1.170

Note(s): ** indicates 1% significance level
Source(s): Authors' Elaboration

outcome, fsQCA explores the relationships between a given construct and all binary combinations. This methodological approach provides an opportunity to identify relevant configurations that yield high performance in the outcome condition (Kraus *et al.*, 2018).

The appropriateness of this methodology is demonstrated by the proliferation of empirical studies that use fsQCA. For example, Yu *et al.* (2022) used a fuzzy-set approach to demonstrate the impact of collective reputation cognition on innovation performance. Yue *et al.* (2021) studied the impact of post-acquisition control strategy and cross-border acquisition on the performance of SMEs. Lou *et al.* (2022) explored the impact of supplier selection and control mechanisms on incremental and radical innovations. Indeed, fsQCA analysis explores the possible complex causal relationships between antecedent conditions and an outcome variable (Fiss, 2011). Due to the interrelated nature of the external and internal factors that influence the implementation of a new technological paradigm such as I4.0, fsQCA is highly appropriate for this study as it allows us to understand which configurations combining technological, organizational and environmental aspects are most likely to generate effects on the degree of I4.0 implementation. The fsQCA approach offered the possibility to evaluate the best configuration without being biased by individual perceptions about factors that may be *a priori* identified as more relevant than others.

4.1 Variable calibration

The initial step in the fsQCA analysis process is variable calibration (Lou *et al.*, 2022). For this purpose, the raw data must be transformed into a set with values falling in the range of 0–1. In line with the logic of Fiss (2011), a variable can be considered as fully belonging to the fuzzy set when the value is 1, and with the fuzzy set of 0, a certain variable is under non-membership.

We employed the direct approach to calibrate the six causal conditions and the outcome variable, transforming the data into the log-odds metric with all values between 0 and 1. Three cutoff points were established as follows: 0.95 = full membership threshold; 0.50 = crossover point; 0.05 = non-membership threshold. To determine which values in our dataset correspond to 0.95, 0.50 and 0.05, we used percentiles as it allows calibration of any measurement regardless of its original value. The calibration values for all conditions are tabulated in Table 4.

4.2 Necessary conditions and truth table

After the calibration of the raw data, we entered the identification phase of the necessary conditions that produce a specific outcome. A necessary condition implies that if a specific condition is absent, the result will not occur. According to Ragin (2008), a causal condition is considered necessary when its score exceeds 0.9. As shown in Table 5, each causal condition cannot be considered individually, since the values associated with both a high I4.0 degree of

Variables	Thresholds Full membership (0.95)	Cross over point (0.5)	Full non-membership (0.05)
Technological I and C	7.000	5.500	1.250
I4.0 Integration Capabilities	7.000	5.000	1.000
Agility	6.500	5.166	3.266
Strategic flexibility	6.333	4.833	3.166
Environmental dynamism	6.400	4.800	3.200
Industry specific forces	5.667	4.333	3.000
I4.0 degree of implementation	6.444	5.000	2.556

Source(s): Authors' elaboration

Table 4.
Calibration values

Variables	Presence of I4.0 degree of implementation		Absence of I4.0 degree of implementation	
	Consistency	Coverage	Consistency	Coverage
Technological I and C	0.816	0.812	0.587	0.496
~Technological I and C	0.494	0.585	0.778	0.782
I4.0 integration capabilities	0.805	0.834	0.561	0.494
~I4.0 integration Capabilities	0.511	0.578	0.881	0.780
Organizational agility	0.766	0.762	0.636	0.538
~Organizational agility	0.535	0.634	0.719	0.723
Strategic flexibility	0.786	0.816	0.593	0.523
~Strategic flexibility	0.541	0.610	0.792	0.759
Environmental dynamism	0.732	0.764	0.610	0.541
~ Environmental dynamism	0.561	0.628	0.735	0.700
Industry-specific forces	0.710	0.758	0.589	0.535
~ Industry-specific forces	0.565	0.681	0.734	0.682

Source(s): Authors' elaboration

Table 5.
Analysis of necessary conditions

implementation and an absence of the outcome variable, are well below the critical threshold (maximum consistency value 0.816). This implies that the outcome variable will depend on a specific configuration of two or more casual conditions.

Therefore, we incorporated our six causal conditions into fsQCA truth table analysis to examine configurations of different technological, organizational and environmental variables which could lead to high or low I4.0 degree of implementation. The truth table is the central aspect of fsQCA as it verifies both the sufficient conditions and the configurations that lead to a desired outcome. Following Pappas and Woodside (2021), we constructed the truth table by setting the minimum frequency of cases to 3, since the sample size has more than 300 observations and applied the threshold of 0.85 to determine raw consistency.

The truth table gives three types of solutions: complex, parsimonious and intermediate. Based on several studies that apply the fsQCA methodology, the intermediate solution is superior to the other two types. Finally, we identified the core and peripheral conditions present in the different combinations. According to Fiss (2011), core conditions are those that appear in both intermediate and parsimonious solutions and are crucial and critical factors in achieving the desired outcome. Peripheral conditions, on the other hand, hold a supportive role and only appear in the intermediate solution (Pappas *et al.*, 2016). As identified in Table 6, there are five configurations that lead to high degrees of I4.0 implementation in manufacturing SMEs. Conversely, as suggested in Table 7, there are four configurations that can explain low degrees of I4.0 implementation.

	Solution				
Configuration	**1**	**2**	**3**	**4**	**5**
Technological I and C		●	●	⊗	⊗
I4.0 Integration Capabilities	•	•	•	⊗	⊗
Organizational Agility	●		⊗	●	
Strategic Flexibility	●		⊗		●
Environmental Dynamism	●	⊗		●	●
Industry Specific Forces				●	⊗
Consistency	0.952	0.886	0.891	0.880	0.906
Raw Coverage	0.515	0.464	0.358	0.290	0.248
Unique Coverage	0.150	0.028	0.017	0.020	0.017
Overall solution consistency	*0.856478*				
Overall solution coverage	*0.747074*				

Note(s): Black circles (●) indicate the presence of a condition, and circles with "x" (⊗) indicate its absence. Large circle; core condition, Small circle; peripheral condition; Blank space; "don't care" condition

Source(s): Authors' Elaboration

Table 6.
Configurations leading to a high I4.0 degree of implementation

	Solution			
Configuration	**1**	**2**	**3**	**4**
Technological I and C	⊗	•	•	•
I4.0 Integration Capabilities	⨂			
Organizazional Agility				•
Strategic Flexibility		⨂	⨂	⨂
Environmental Dynamism			•	
Industry Specific Forces		⊗		
Consistency	0.829	0.817	0.790	0.789
Raw Coverage	0.727	0.420	0.409	0.420
Unique Coverage	0.362	0.004	0.010	0.005
Overall solution consistency	*0.761289*			
Overall solution coverage	*0.852993*			

Note(s): Black circles (●) indicate the presence of a condition, and circles with "x" (⊗) indicate its absence. Large circle; core condition, Small circle; peripheral condition; Blank space; "don't care" condition

Source(s): Authors' Elaboration

Table 7.
Configurations leading to a low I4.0 degree of implementation

4.3 Configurational analysis of high I4.0 degree of implementation

The results of the study indicate that the degree of I4.0 implementation in SMEs is influenced by each of the three dimensions of the TOE framework, namely organizational, technological and environmental factors. The study identified five solutions that demonstrate the different trajectories of I4.0 implementation in SMEs depending on the presence of these factors.

Overall, the study highlights the complexity of I4.0 implementation in SMEs and the interplay of organizational, technological and environmental factors in driving technology adoption. It is essential for SMEs to consider all three contexts and prioritize a holistic approach to foster high levels of I4.0 implementation.

In detail, Solution 1 revealed that a combination of organizational agility, flexibility and environmental dynamism is an effective driver for SMEs to implement high degrees of I4.0. This solution places emphasis on the internal organizational and environmental elements, highlighting the importance of strategic sensitivity, resource fluidity and leadership unity in fostering I4.0 implementation. Additionally, the presence of I4.0 integration capabilities is also acknowledged as a peripheral aspect, emphasizing the secondary role of technological factors in this solution (Nyamrunda and Freeman, 2021; Zhou and Wu, 2010).

Solution 2 and 3, on the other hand, demonstrate that the decision to implement I4.0 in SMEs is influenced by technological factors, specifically the availability of adequate technological infrastructure and competence and I4.0 integration capabilities. Solution 2 and 3 underweight the role of external pressures and environmental uncertainty, as well as the one of flexible and agile internal culture as drivers of I4.0 implementation.

Finally, Solutions 4 and 5 indicate the relevance of both internal capabilities and external pressures in fostering I4.0 implementation. These solutions recognize the dynamic environment and industry forces as key drivers affecting high levels of technology implementation and emphasize the importance of proactivity and alignment with external stakeholders. Interestingly, these solutions emphasize organizational and environmental factors rather than technological factors in determining a successful I4.0 implementation.

4.4 Configurational analysis of low I4.0 degree of implementation

From our analysis, the low degree of I4.0 implementation in SMEs is driven by different factors. Four solutions have emerged to explain this phenomenon. Solution 1 posits that SMEs have a low degree of I4.0 implementation when they lack both technological and infrastructural factors as well as innovative skills. This approach highlights that the absence of I4.0 integration capabilities, such as the knowledge and ability to integrate new technologies into existing infrastructures, is the driving condition for low levels of technology implementation. This finding is corroborated by extant research, which suggests that I4.0 does not simply involve knowing how to use specific technologies, but rather, the integration of such technologies into existing systems (Bag *et al.*, 2021).

In addition, the data produced by I4.0 systems are expected to be used for forecasting, improving automation and efficient production processes, however, the absence of internal capabilities and knowledge of technological factors significantly limits the implementation of I4.0. When SMEs fail to grasp the full potential of an innovation due to a lack of capabilities, they will also be reluctant to its implementation. Furthermore, the limitation of financial resources that characterizes SMEs may lead to fewer available resources being invested in infrastructure or competence reconfiguration.

Solutions 2, 3 and 4, on the other hand, are structured around organizational factors. These solutions highlight that the absence of flexibility in SMEs reduces the levels of implementation of I4.0 technologies. The inability to capture external inputs and strategically reallocate resources decreases technology implementation levels, even though appropriate technological infrastructure and competence exists. The literature suggests that developing strategic flexibility in resource management and production processes can create an organizational culture that supports innovation (Zhou and Wu, 2010). Furthermore, strategic flexibility can help firms to reach the full potential of its key resources by overcoming inertia.

In sum, the low degree of I4.0 implementation in SMEs is a multidimensional issue, with a combination of technological and organizational factors contributing to this phenomenon. Solution 1 demonstrates that low levels of I4.0 adoption occur when SMEs do not have sufficient capabilities to capture the true potential of new technologies, and they lack adequate IT infrastructure and competence, while solutions 2, 3 and 4 are entirely driven by the absence of organizational factors resulting in a low implementation of I4.0. It is, therefore, crucial for SMEs to focus on both technological and organizational aspects to improve their I4.0 implementation levels.

5. Theoretical and practical implications

This study aimed to develop a configurational approach based on the TOE framework (technology, organization and environment) to understand the degree of implementation of I4.0 technologies in manufacturing SMEs. The findings of this study indicate that the implementation of I4.0 technologies in SMEs is a complex phenomenon that depends on multiple factors, including technological infrastructure, I4.0 integration capabilities, organizational agility and strategic flexibility, environmental dynamism and industry-specific forces.

Theoretically, this study extends the traditional literature on I4.0 and SMEs by observing how implementation is not only a phenomenon related to perceived usefulness or ease of use of a technology, but also on organizational traits (i.e. more flexible and agile SMEs are more prone to fully exploit I4.0) whether they are in conjunction with hard technological factors and environmental characteristics. This study also extends literature on organizational factors driving I4.0 in SMEs (Agostini and Filippini, 2019; Agostini and Nosella, 2019) by establishing the combined importance of agility and flexibility. Strategic flexibility emerged as fundamental in the understanding of environment and the re-deployment of resources to cope with environmental pressures (Zhou and Wu, 2010). The two organizational factors are fundamental even in the I4.0 context, increasing the knowledge body on their importance in IT literature and in the digital transformation (Messeni Petruzzeli *et al.*, 2021). Additionally, this study contributes to the literature on the implementation of I4.0 technologies in SMEs by highlighting the importance of TOE framework in understanding the implementation process (Ahmad *et al.*, 2020).

Practical implications of this study include the importance of considering the interplay of multiple factors when implementing I4.0 technologies in SMEs, specifically IT infrastructure and competence and I4.0 integration capabilities are the main pushing factors, but organizational traits and environmental push also play a critical role. Another important practical implication of this study is the importance of organizational agility and strategic flexibility in the implementation of I4.0 technologies in SMEs. The study found that agile and flexible SMEs are more likely to fully exploit I4.0 technologies, due to their ability to sense opportunities and re-deploy resources to re-configure the firm. This highlights the importance of investing in organizational agility and strategic flexibility when implementing I4.0 technologies in SMEs. Furthermore, the study highlights that the lack of flexibility is a crucial factor in the failure to implement I4.0 technologies in SMEs, therefore, SMEs managers should invest in the development of innovative internal cultures capable to identify environmental change and react accordingly and invest in continuous updates of their systems to remain competitive, as IT infrastructure is fundamental in the achievement of I4.0 implementation.

6. Conclusions and limitations

This study contributes to the growing body of literature on the I4.0 technologies and SMEs by offering a broader perspective on the interplay between technological factors, organizational factors and environmental factors. Still, this study has a number of limitations. For example, the findings may not be generalizable to SMEs in other countries, and a larger sample size or inclusion of additional organizational variables may have provided greater insight. Further research is recommended to investigate the phenomenon in different contexts and to examine the potential outcomes of high or low degrees of I4.0 implementation, such as its effects on performance, innovativeness and sustainable practices.

In conclusion, we hope this study could serve as a starting point in the attempt to build a wider conceptual framework to analyze the underlying mechanisms to the implementation of I4.0 technologies. However, it is important to note that there is still much to be explored in this field. The implementation of I4.0 technologies has the potential to bring about significant advancements in efficiency, productivity and overall competitiveness for businesses. Further research is necessary to fully understand the complex interactions and implications of these technologies in industrial contexts, and it is crucial for businesses to stay informed on the latest developments in I4.0 to remain competitive in an ever-evolving technological landscape.

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Appendix

Technological Infrastructure and Compentence 1 = Completely Agree – 7 = Completely Disagree	
TI1	Our company have adequate IT infrastructure to implement Industry 4.0 technologies
TI2	Our company have adequate IT infrastructure to operate with Industry 4.0 technologies
TI3	Our company have adequate skills to implement Industry 4.0 technologies
TI4	Our company have adequate skills to operate with Industry 4.0 technologies
I4.0 Integration capabilities 1 = Low/Absent Capabilities – 7 = High Capabilities	
IIC1	In all our plants, located across different geographical regions, the necessary capabilities to apply I4.0 front end technologies and base technologies exist
IIC2	All divisions in our company have the necessary capabilities to apply I4.0 front end technologies and base technologies
IIC3	Our company has the necessary capabilities to apply I4.0 front end technologies and base technologies at functional level
Organization Agility 1 = Completely Agree – 7 = Completely Disagree	
AG1	Our company has the ability to rapidly respond to customers' needs
AG2	Our company has the ability to rapidly adapt production to demand fluctuations
AG3	Our company has the ability to rapidly cope with problems from suppliers
AG4	Our company has rapidly implemented decisions to face market changes
AG5	Our company has continuously search for forms to reinvent or redesign our organization
AG6	Our company sees market changes as opportunities for rapid capitalization
Strategic Flexibility 1 = Completely Agree – 7 = Completely Disagree	
FL1	Our business strategy emphasizes the flexible allocation of marketing resources (including advertising, promotion, and distribution resources) to market a diverse line of products
FL2	Our business strategy emphasizes the flexible allocation of production resources to manufacture a broad range of product variations
FL3	Our business strategy emphasizes the flexibility of product design (such as modular product design) to support a broad range of potential product applications
FL4	Our business strategy pays attention to which products the company intends to offer and which market segment it will target
FL5	Our business strategy pays attention to the resources the company can use in developing, manufacturing, and delivering products to targeted markets
FL6	Our business strategy emphasizes the redeployment of organizational resources effectively to support the firm's intended product strategies
Environmental Dynamism 1 = Completely Agree – 7 = Completely Disagree	
ED1	Environmental changes in market our company operates are intense
ED2	Our company clients regularly ask for new products
ED3	In the market our company operates, changes are taking place continuously
ED4	Frequent and major changes in government regulations occur in the market our business operates
ED5	In the market our business operates, a high rate of innovation is required
Industry Specific Forces 1 = Completely Agree – 7 = Completely Disagree	
ISF1	Competition in our industry is cutthroat
ISF2	Price competition is a hallmark of the industry the business operates
ISF3	It is easy for new players to enter our industry
ISF4	Competitors outside of our industry offer viable substitutes for business' products
ISF5	Our major customers are in a strong bargaining position in respect of the company
ISF6	Our major suppliers have the strength to bargain with the business effectively

(*continued*)

Table A1. Constructs and items

Table A1.

I4.0 degree of Implementation 1 = Completely Agree – 7 = Completely Disagree	
II1	Our company uses technologies such as Sensors, RFID, IoT in our processes
II2	Our company uses software to exchange data with other devices and systems over the internet
II3	Our company promotes automation in our processes
II4	Our company promotes servers and communication to run the software
II5	Our company uses service-oriented architecture
II6	Our company promotes interactions using advanced social and web-based services
II7	Our company processes are observed using sensors for better control
II8	Our company uses technologies to analyze real world action
II9	There are continuous and seamless interactions between processes and humans

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