

Review

Technological Capabilities and Digital Transformation of Industrial SMEs Toward Sustainable Adaptation to Industry 4.0 Environment: A Theory-Building Approach

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Abstract

This study provides a systematic analysis of technological capabilities and their impact on the digital transformation of industrial small and medium-sized enterprises (SMEs) to develop an Industry 4.0 environment. A semi-systematic literature review was conducted, from which the authors identified and selected 117 articles for their relevance and contributions to be further studied, and framed to achieve the research objectives. The authors identified the following variables of analysis: technologies and digitalization, technological capabilities, infrastructure, and strategies. Furthermore, the study identified promoting and hindering factors to the digital transformation of industrial SMEs, along with the technological capabilities that drive it, thereby generating opportunities and challenges for improving their integration into Industry 4.0. As the promoting and inhibiting factors, the following were determined: culture, leadership and entrepreneurial orientation, market orientation, processes and operations, people and business environment. Government support, access to technology, leadership and strategy, and employees stand out as factors that, when limited or absent, restrict SMEs' ability to manage and increase their maturity level to integrate into Industry 4.0. From a resource-based view and dynamic capability theory, this research advances theory by presenting four propositions that integrate the identified technological capabilities and driving factors into a capability-based framework. This framework will serve as the foundation for a capability-based roadmap to guide industrial SMEs toward an Industry 4.0 environment and achieve sustainability outcomes.

Keywords: Industry 4.0; industrial SMEs; digital transformation; technological capabilities; theory building; promoting factors; hindering factors



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1. Introduction

Small and medium-sized enterprises (SMEs) play a crucial role in driving a nation's economy by generating employment and fostering economic growth [1,2]. However, these companies face significant challenges due to recent changes in the manufacturing environment brought about by the current digital age. This era is marked by short product life cycles, market volatility, and an increasing demand for personalized and innovative products [3,4]. Such conditions put pressure on companies to adapt to a highly digitalized

and intelligent manufacturing environment. As a result, the concept of SMEs 4.0 has emerged, referring to SMEs that have adopted Industry 4.0 (I4.0) technologies to improve their production processes and enhance their competitiveness [4,5].

Thus, the term SMEs 4.0 refers to SMEs that use advanced digital technologies to optimize supply chain management, improve energy efficiency, reduce production costs, increase product and service quality, and enhance the customer experience [6]. However, adopting I4.0 constitutes a challenging endeavor for SMEs due to a lack of resources and technical knowledge, while at the same time, it represents an opportunity to improve their market position. The importance of digital transformation and its relationship with flexibility in the I4.0 initiative emphasizes intelligent and autonomous systems, creating new opportunities to add flexibility and agility to automated manufacturing systems, ultimately aiming to revolutionize the supply chain [6]. One of the main limitations of manufacturing SMEs is their lower productivity compared to large firms. This is largely due to their limited access to investment or credit and their reduced capacity to take advantage of economies of scale. Large firms have a significant advantage in terms of access to specialized inputs, trained personnel, and advanced machinery [1,7,8].

Furthermore, industrial SMEs in developed countries show a higher level of technical development and adoption of advanced technologies compared to their counterparts in developing countries [9]. SMEs in these countries, invest more in R&D and adopt cutting-edge technologies more frequently, improving their productivity and competitiveness [10,11]. The technological gap between SMEs in developed and developing countries has widened in recent decades due to the difficulties faced by companies in developing countries in accessing modern technologies and capital for investment [12]. These differences in the level of technological development translate into productivity and competitiveness gaps. For example, the adoption of advanced technologies allows industrial SMEs in developed countries to diversify their production, improve product quality, and access more competitive export markets [11,13].

The ability to adapt to changes in the technological landscape over time is a critical factor for SMEs, as it enables them to leverage new opportunities within their markets and increase their competitiveness. By enhancing their technological adaptability, SMEs can focus on developing their digital skills and capabilities, contributing to their digital ecosystem [4]. However, adopting new technologies requires a willingness to change and a commitment to continuous learning and development, as new technologies and processes continue to emerge. This is overwhelming for SMEs due to their limited resources and capabilities. Hence, a good starting point is to identify these firms' technological capabilities and their impact as potential success factors for their digital transformation [14]. Furthermore, the main drivers and inhibitors of their digital transformation must be identified to foster these enterprises into the I4.0 ecosystem [15].

The increasing complexity encountered by SMEs during their digital transformation has catalyzed substantial academic interest, resulting in a large and diverse body of literature. This literature, being highly eclectic, currently lacks sufficient universally applicable conceptual schemas and typologies, which constrains its utility for broad generalization and coherent theoretical development.

Regarding this background, this work addresses the need for a systematized framework to define the technological capabilities of these firms and their impact on the digital transformation of industrial SMEs oriented towards an I4.0 environment. From a theory-building approach, it presents the state of the art on the technological capabilities of digital transformation in the context of industrial SMEs. Furthermore, a framework of critical variables related to the factors that promote or inhibit the acquisition of technological capabilities was identified to understand the digital transformation process of SMEs and their

decision-making when implementing new technologies. For SMEs operating in developing countries and low-income regions, it is critical to sustain their path towards I4.0. The scarcity of resources, the need to adopt cost-effective and environmentally friendly practices, rising energy demand, and customer demand for sustainable/greener products have prompted SMEs to adopt cleaner, more efficient, and sustainable practices [7,15–18]. Additionally, providing a comprehensive framework for embracing I4.0 has become essential for SMEs to sustain their business in the current environment. By developing technological capabilities and advancing digital transformation, SMEs can reduce resource consumption and minimize their environmental impact as I4.0 environments “promote sustainability through production efficiency and productivity, energy and resource utilization, carbon gas reduction, production risk, and workplace safety management” ([17] p. 326).

Thus, this research offers three main contributions. First, it consolidates fragmented conceptualizations of technological capabilities and provides a comprehensive theoretical analysis of the factors that promote or hinder technological transformation among industrial SMEs. Second, it offers a theory-building framework to organize the connections between these capabilities and the factors that promote or inhibit them, facilitating the assessment of variables that influence industrial SMEs’ adoption of I4.0 environments. Finally, by analyzing these relationships, it becomes possible to propose a capability-based roadmap for SMEs that offers both theoretical and managerial understandings for transitioning to I4.0. These contributions help advance theoretical understanding and provide valuable insights to both practitioners and scholars.

This paper is organized as follows. Section 2 introduces the main concepts framing the theoretical background of this research. Section 3 presents the research methodology conducted for this review. Section 4 reports the review findings while discussing and framing the relationship among the identified variables: technological capabilities and resources, promoting factors of SMEs’ digital transformation, and hindering factors of such transformation. Section 5 presents a conceptual framework for assessing variables for industrial SMEs’ adoption of I4.0 environments. Finally, Section 6 outlines conclusions, limitations of this research, and future studies.

2. Research Background

This section provides the theoretical background of the main concepts driving this research.

2.1. Small and Medium-Sized Enterprises (SMEs)

The acronym SMEs refers to companies that employ fewer than 250 workers and have an annual turnover not exceeding 50 million euros, and/or a total balance sheet of no more than 43 million euros [19,20]. This group of firms constitutes a driving force of gross domestic product (GDP) growth and generates employment [21]. Of the 192 million formal SMEs registered in emerging markets, the East Asia and Pacific region have the most significant number (102 million). At the same time, Latin America has the fewest (17 million) [22].

Industrial SMEs are recognized by their flexibility as a capability that helps them navigate the challenges in their environment [23]. Flexibility is a particularly well-known strength of SMEs, enabling them to cope with their limitations [24]. This flexibility also prompts communication and information sharing, allowing a more agile response to changing market demands and customer needs [1,25].

In addition, these firms are characterized by a flatter organizational structure that allows information to be distributed quickly among their staff. This structure provides SMEs with a competitive advantage in innovation by prompting the development of

creative and rapid solutions to meet customer needs and adapt to changes in the business environment [26].

2.2. Industry 4.0 (I4.0) and SMEs

Industry 4.0 (I4.0) is a term that refers to the fourth industrial revolution, characterized by increased connectivity and the use of digital technologies, as well as smart manufacturing [27]. This includes technologies such as artificial intelligence (AI), the Internet of Things (IoT), advanced robotics, and 3D printing, among others. I4.0 also focuses on the integration of systems and processes to improve efficiency and productivity in industrial manufacturing. Smart manufacturing involves communication and interactions between machines and humans, as well as between machines themselves, to operate a business with the potential to manage processes in a self-controlled and autonomous environment [28].

Table 1 below compares SMEs and large companies, contrasting several aspects and highlighting the gaps between them.

Table 1. Comparison of gaps identified between large companies and SMEs.

Functions	SMEs	Large and Multinational Enterprises
Organizational Environment		
Organizational Structure	Informal and less complex	Formal and complex
Company Strategy	Mostly driven by the leader's (owner's) instinct	Accurate market research and analysis
Decision-making	Limited to leaders/a few knowledge holders	Board of advisors and (internal/external) consultants
Organizational Culture/Leadership Flexibility	Low	High
Access to Resources		
Financial Resources	Low	High
Human Resources Commitment	Multiple domains	Specialized domains
Human Resources Development	High within the industry/Low outside the industry	High-level outside the industry
Industry Knowledge and Experience	Focused on a specific area	Distributed across different areas
Technological Environment		
Use of Advanced Manufacturing Technologies (AMTs)	Low	(Very) High
Software umbrella (including data analysis)	Low (Often customized solutions)	High (with more standardized solutions)
Research and Development (R&D)	Low	High
Nature of product specialization	High	Low
Alliances with Universities/Research Institutions	Low	High
Market Environment		
Customer/Supplier Relations	High (Strong)	Low (not so strong)
Dependence on Collaborative Network	High	Low

Source: Adapted from [19,29].

Table 1 reveals several gaps between SMEs and multinational companies. Regarding organizational structure, large, multinational enterprises tend to have a formal, complex structure, with a board of advisors guiding strategies toward market orientation and flexible leadership. In contrast, SMEs are simpler and more informal, with decision-making driven by their owners or leaders, who depend on practical experience or instincts. Therefore, the degree to which SMEs transition toward I4.0 environments is limited by the knowledge and entrepreneurial mindset of their decision-makers.

With respect to resource access and technological environment, the distinction between these two groups of companies becomes more evident. Large and multinational enterprises have access to financial resources, allowing them to invest in R&D and AMTs, which include technologies such as “3D printers, Computer Numerical Control (CNC) machines, modern enterprise resource planning (ERP) platforms, and MTM (machine-to-machine)/HMI (Human–Machine Interconnection) communications to stay competitive in the hyper-competitive global market” [29]. They also engage in strategic alliances with universities and research institutes and hire and train highly skilled personnel. In contrast, SMEs have limited financial resources, which constrain their access to R&D, AMTs, skilled personnel, and strategic alliances with universities. These gaps are widening between industrial SMEs in developed countries, where these companies show a higher level of technical development and advanced technology adoption than their counterparts in developing countries [9,11].

Furthermore, as the business environment becomes more digital and automated, SMEs are urged to keep up with technological advancements. This has led to the term SMEs 4.0, which describes the use of I4.0 technologies in SMEs. The aim is to enhance the efficiency, productivity, sustainability, and competitiveness of these firms by adopting advanced technological solutions. This term includes process automation, data digitalization, and the deployment of AI systems for decision-making, all of which contribute to their digital transformation [5].

2.3. Digital Transformation of SMEs

Digital transformation is the process of integrating advanced digital technologies across an organization’s operations, including production, operations, marketing, sales, and customer service. This transformation encompasses how the organization interacts with customers, operates internally, and delivers its products and services [30,31]. Digital transformation involves a fundamental shift in how a company uses technology to create value and improve its performance. Digital transformation also involves reorganizing the organization’s processes and structures to improve customer experience and make the most of new technologies to enhance the organization’s efficiency, productivity, social welfare, and competitiveness [32,33]. Digital transformation drives and facilitates new forms of innovation by integrating knowledge management and empowering demand-driven supply chains [34]. Therefore, it is necessary to assess the readiness of SMEs before applying digital transformation to business processes [33,35].

Digitalization goes beyond products; it influences the business organization and its model, as well as the entire value chain [36]. Nowadays, as the business environment is digitalized, companies are required to manage their decision-making process supported by digitalization to gain a competitive advantage [33,37].

2.4. Technological Capability

Technological capabilities refer to the skills, knowledge, and resources that an organization possesses to develop, implement, and utilize advanced, new or emerging technologies in its operations to enhance performance and achieve business objectives. These capabilities include identifying and evaluating emerging technologies (e.g., process automation, cloud computing, and cybersecurity). They also refer to the capacity to integrate these technologies into the organization’s processes, develop custom software and hardware, and maintain and update existing technologies. Moreover, technological capabilities encompass the ability to manage and protect the organization’s data and information, utilize data analytics tools and technologies to enhance the customer experience, and improve process efficiency [38].

Organizations that adopt new technologies will gain a competitive advantage, improving efficiency and productivity. This adaptability is essential in today's digital age, where emerging technologies and trends are constantly evolving. Technological adaptability implies an organization's ability to identify, evaluate, and integrate new technologies into its existing business processes effectively and efficiently. To achieve this adaptability, organizations must have a business culture that fosters experimentation and innovation, as well as a willingness to invest in developing and training their personnel's technical skills. It is also necessary to have a clear, well-defined strategy for implementing new technologies and a leadership team committed to digital transformation and continuous improvement [39].

2.5. Framing the Objective of the Review

This literature review aims to advance theory development in the field of I4.0 and SMEs by exploring the digital transformation that industrial SMEs need to undertake to integrate into I4.0 environments. It focuses on identifying technological capabilities that support this digital transformation for these SMEs. Additionally, it examines the factors that facilitate or hinder this process. The review also explores gaps in the current literature on these topics. Based on this analysis and a theory-building approach, the proposed conceptual framework defines the variables to evaluate for enabling SMEs to integrate into I4.0 environments.

Figure 1 presents the framework underlying this study, illustrating the analysis we followed to identify the determinants of SMEs' digital transformation towards the I4.0 environment.

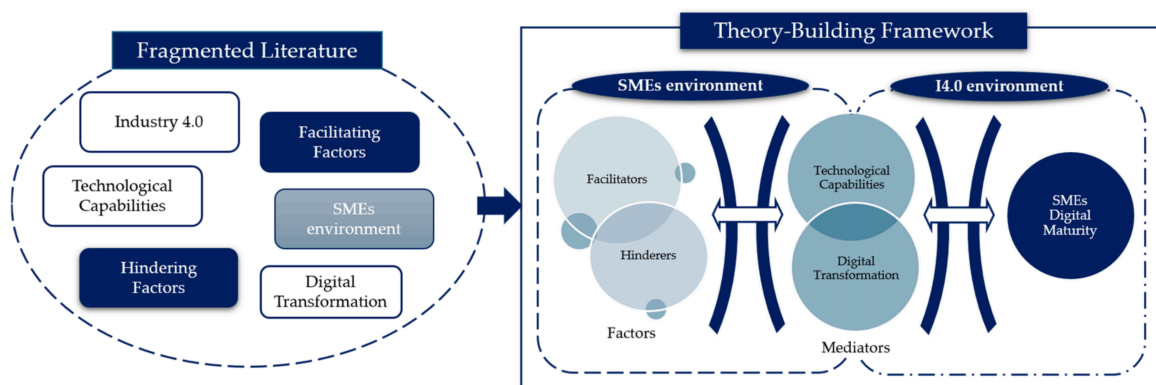


Figure 1. Framework of the research object.

Based on the fragmented literature, we propose a theory-building framework rooted in the Resource-Based View (RBV) and Dynamic Capability Theory (DCT) approaches that outlines a dynamic and sustainable path for SMEs' integration into the I4.0 environment. We examined how both promoting and hindering factors influence SMEs' digital transformation and shape the mediating role of technological capabilities and resources in improving their digital transformation processes.

3. Research Methodology

This research adopts the conceptual framework approach defined by Meredith [40] to systematize and conceptualize the current body of knowledge on the digital transformation of SMEs to adopt an I4.0 environment. Meredith's approach blends multiple sources, contrasts different factors, synthesizes common elements from previous work, and incorporates a maturity-based perspective on technological tools. In addition, a complete theory involves four features: definitions, domains, relationships, and predicative claims [41].

This work provides explicit definitions and structured relationships among technological capabilities, digital transformation, and promoting and hindering factors to achieve an I4.0 environment, laying the foundation for further empirical predictions.

Furthermore, to achieve the research objectives from a theory-building perspective [40], a semi-systematic literature review was conducted as a conceptual approach to establish a theoretical understanding of SMEs' digital transformation. Because of the scope and complexity of this topic, it is necessary to identify and understand all relevant research and synthesize their implications using meta-narratives rather than measuring effect sizes, as would be done in a purely systematic literature review. Additionally, this type of review employs a repeatable analytical method to collect and analyze data published in peer-reviewed scientific journals [42]. This semi-structured review combines comprehensive search strategies and critical analysis [43–45].

This methodology has been widely used to identify the state of the art in different research areas in the fields of innovation [46,47], management [48], industrial engineering [49], Industry 4.0 [50], SME management [51,52], among others.

To achieve the objectives outlined in this research, the three key stages proposed by Tranfield and Denyer [43,44] were used for conducting this semi-systematic literature review: (1) plan the search by defining the scope of the review, (2) execute the review applying inclusion and exclusion criteria, and (3) report the results. Each stage supported the process of determining the relevance of the manuscripts to inform this literature review. It is critical to establish transparent selection criteria, explicit coding procedures, and stated justification of the scope to enhance the rigor and replicability of methodological reviews [44,45]. This process was carried out between January 2024 and April 2025.

Figure 2 illustrates the methodology developed for this study.

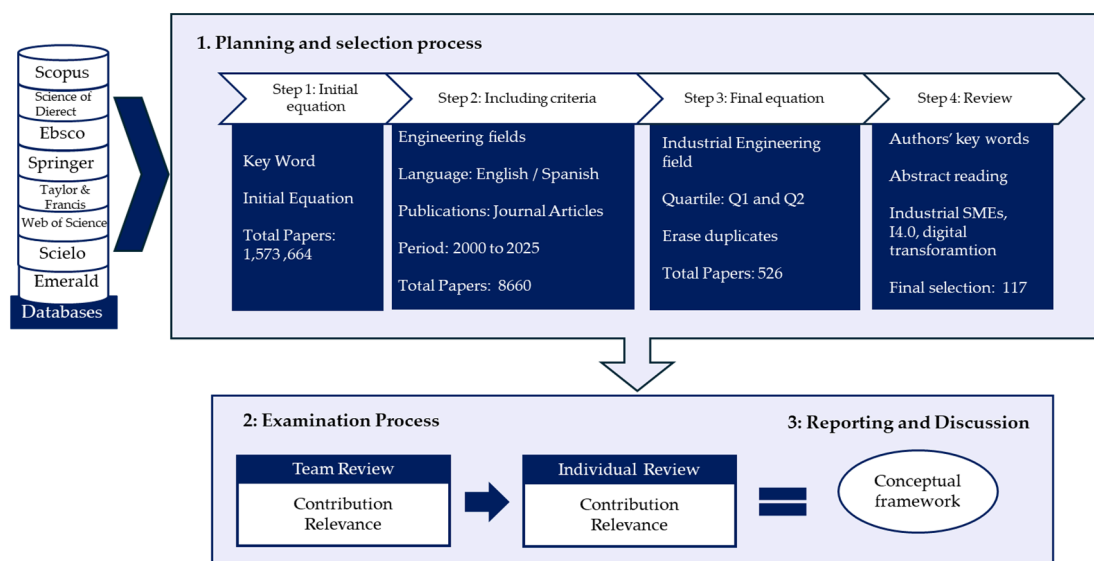


Figure 2. Methodological stages applied to the semi-systematic literature review.

Figure 2 depicts the three previously identified stages. Stage 1: Search planning, where the initial equations and criteria for document selection were designed to align with the scope of this research. Stage 2: Plan execution, where the selection criteria were applied to identify the reviewed manuscripts, ensuring that they met the initial criteria and were relevant to the research topic. Stage 3: Finally, each selected paper was thoroughly analyzed, and the results were discussed and systematized.

The remaining section describes in detail each of the processes followed for this review, which were recorded in a public dataset [53].

3.1. Stages 1 and 2: Planning and Selection

After defining the scope of this review, the research team started by selecting the databases for the search based on their relevance in the field of study: Emerald Insight, Scopus, Web of Science, Taylor & Francis, SciELO, Springer, ProQuest, EBSCOhost, and ScienceDirect, in which the keyword search was carried out (see [53]).

Since the objective of this study is to identify how technological capabilities impact the digital transformation of industrial SMEs to develop an Industry 4.0 environment, the team included the following keywords in the search equations: “Industry 4.0”, “SMEs”, “manufacturing SMEs”, “technological transformation”, “technological capabilities”, “digitalization”, “evaluation model”, “digital transformation” and “adaptation/inclusion of new technologies”. This initial search returned 1,573,664 documents.

For the second step, an improved search query was developed including only articles published in English and Spanish in peer-reviewed journals from 2000 to April 2025. This second step yielded 8660 articles.

In step 3, the team applied filters to limit the search to documents published in the fields of engineering and industrial engineering and Q1 and Q2 scientific journals [54]. Also, duplicate articles were removed. This search resulted in 526 manuscripts. Finally, in step four, the titles, keywords, and abstracts of the documents were reviewed to determine their relevance to the research topic: industrial SMEs, digital transformation, and I4.0, limiting the final selection to 117 articles.

Figure 3 shows the distribution of the 117 selected articles that correspond to the period between 2000 and 2025.

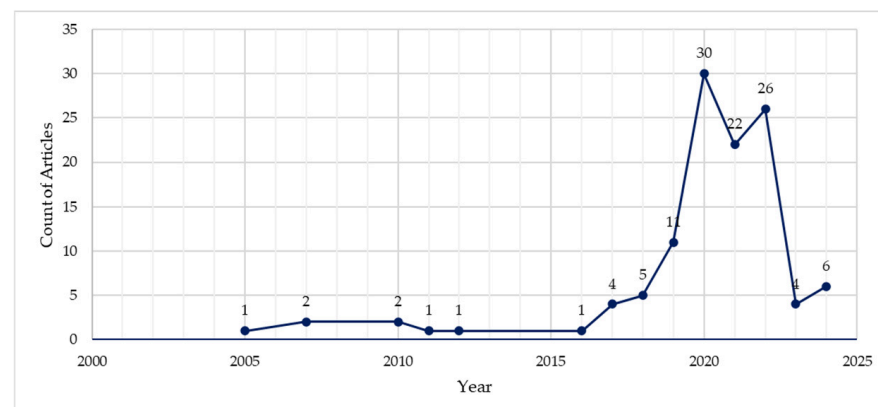


Figure 3. Chronological distribution of selected articles.

As observed in Figure 3, the number of publications increased from 2017 onwards, with 2022 recording the highest count.

Figure 4 shows the regional distribution of participation in selected studies focusing on industrial SMEs to highlight areas of dominance and gaps.

Regarding the selected studies, mainly focused on industrial SMEs’ adoption of I4.0 environments, Europe leads with 57 studies, with Italy having the most in the region at 13 publications, followed by Germany with 6, and France with 5. The European Parliament recognizes SMEs as the backbone of the European economy, as reflected in the number of studies in which European SMEs participated [55].

Next, Asian countries participated 25 times, with India reporting 6, Malaysia 5, and Singapore 3. Third, South America had 10 participations, led by Brazil (4), followed by Colombia and Ecuador with 2 participations each. In fourth place, North American countries participated 8 times, being led by the United States of America with 3 participations and followed by Mexico with 2 studies. Finally, Africa (Kenya) and Oceania (Australia)

each participated in 1 study. As observed, the geographic asymmetry in studies of SMEs' digital transformation points to diverse development and technology-adoption contexts across regions.

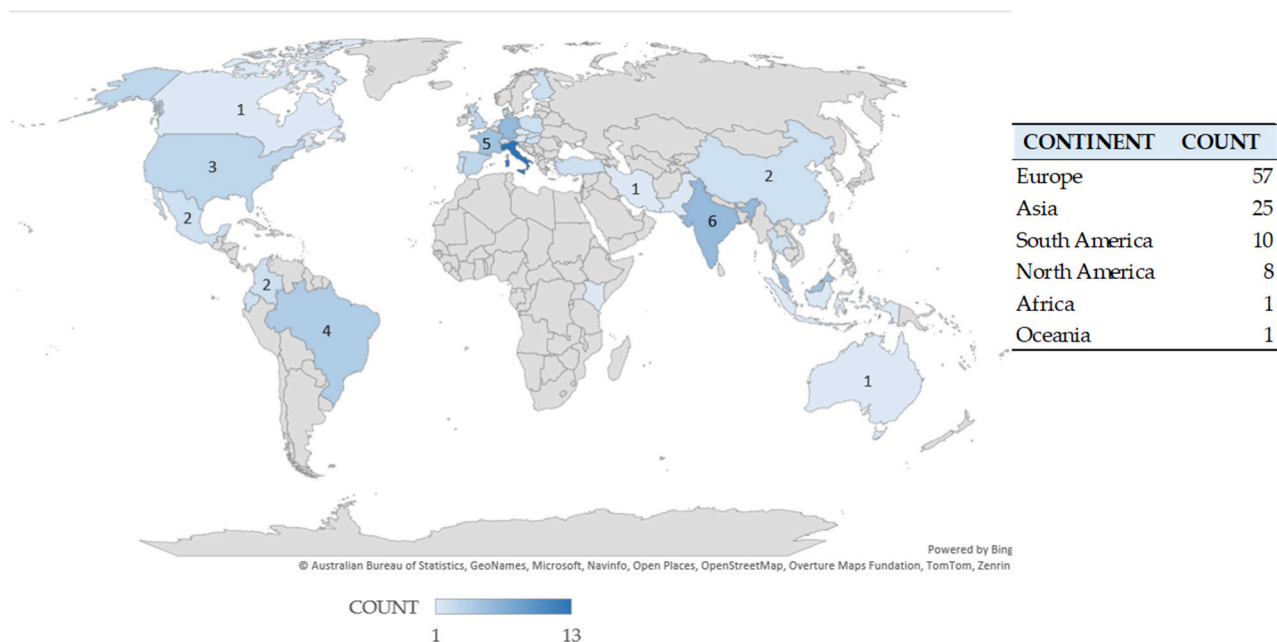


Figure 4. Number of participations in the selected SME studies by region. Powered by Bing Technology.

The World Trade Organization (WTO) and the World Bank, along with other institutions, have conducted multiple studies to evaluate and oversee the digital transformation of economic actors across different countries and regions. The aim is to identify gaps and offer support and guidance to those nations and actors that are lagging behind. Among the key players constantly under scrutiny are SMEs, due to their ability to create jobs and boost GDP growth, thereby stimulating economic growth and development in any nation, regardless of population, income, or territory [56–58].

The WTO has highlighted the essential need for digital transformation among SMEs to lower operational and trade costs and to engage more effectively in global supply chains. Additionally, regional readiness greatly influences how quickly SMEs can adopt I4.0 environments [57]. However, this readiness varies widely across regions due to conflicting regulatory landscapes, differing levels of digital tool adoption, and infrastructure gaps [59,60]. Furthermore, the World Bank has found that high-income economies are deepening and strengthening their integration of e-commerce and cloud technologies, while developing markets lag, relying mostly on social media platforms for sales [58,61]. Therefore, SMEs' digital transformation speed depends on firm size and the nation's digital infrastructure.

Below is a brief overview of the regional analysis on the digital transformation of SMEs, highlighting different regional trends:

- **Africa:** Many lower-income countries report high percentages of SMEs lacking reliable internet due to infrastructure gaps, outdated systems, and challenges with cross-border digital payments. To bridge the gap with more digitally advanced regions, the World Bank is focusing on large-scale regional investments to support digital entrepreneurship, expand fiber-optic networks, and lower internet costs, thereby boosting MSME e-commerce capacity [62–64].
- **Asia & The Pacific:** This region leads SMEs' digital transformation in developing economies. The share of firms investing in I4.0 solutions quadrupled from 13% to 54%

between 2020 and 2022 [58,65]. SME digitization is mainly driven by digital identity, mobile internet, and mobile financial services, rather than advanced technologies. Hence, SMEs' investments mainly focus on digital payment methods, e-commerce adoption, and cloud-based management tools. However, the gaps between hyper-connected nations and emerging economies remain wide [59]. Therefore, the region needs innovative national policies, such as Digital Kazakhstan's spectrum fee discounts and South Korea's 5G tax reductions, to help SMEs leverage e-commerce, AI platforms, and digital payments [66].

- **Latin America & The Caribbean:** During the pandemic lockdowns, SMEs in this region were forced to adopt e-commerce and digital delivery solutions, especially for retail and food service SMEs. However, gaps in digital literacy and uneven access to high-speed internet still exist. Additionally, wider adoption of advanced digital solutions is limited by regulatory gaps [58,67]. Therefore, regional efforts should focus on closing infrastructure gaps and updating regulatory frameworks to meet international standards [68]. Organizations like ECLAC are promoting capacity-building models (often inspired by South Korea) to help SMEs modernize [69], while the Informal Working Group on MSMEs at the WTO actively shares best practices to support smaller Latin American businesses in accessing supply-chain financing [56]. The World Bank emphasizes improving access to finance and reducing logistical bottlenecks to expand digital supply chains [61].
- **Europe:** This region has a large infrastructure but slow adoption. Despite a high baseline internet penetration (over 84%), many regional SMEs remain at a basic level of digital intensity (basic websites, e-mail) rather than undergoing deep operational transformation [58,70]. Thus, European countries should provide an environment that enables navigation of complex cross-border data protection laws and ensures that traditional businesses keep pace with rapid innovation and technological developments [71]. International Trade Center (ITC) data indicate that many European SMEs are highly ready, but smaller firms still face financial hurdles [66]. Hence, the region should boost technological skills and close the gap between large firms and smaller enterprises.
- **North America (US & Canada):** This region exhibits high digital adoption and well-established legal frameworks [57]. These countries significantly benefit from the WTO Information Technology Agreement, but SMEs still face challenges in navigating complex and sometimes fragmented digital regulations [57]. Additionally, there is a disproportionate level of digital adoption between urban and rural SMEs. Moving forward, efforts should focus on advancing SMEs' integration of AI tools, big data analytics, cross-border digital payments, and paperless trade documentation [56,58,66,72].

3.2. Stage 3: Examination Process

The authors independently analyzed each of the 117 articles to determine their relevance and contribution to this study's research objectives. Subsequently, the team discussed the findings to combine and integrate them and to define the selection of variables included in this study.

For this process, the team used collaborative platforms Rayyan [73], Carrot2 [74], and Mendeley Reference Manager [75] to facilitate reading, processing, clustering, sharing, and discussing information. In addition, an Excel spreadsheet (published for public access in the dataset [53]) was designed to collect, filter, and synthesize the characteristics and scientific data of the articles included in the study. The application of these tools and processes enabled the assessment of "fit-for-purpose" for each publication [42,44,45]. The

information was categorized by authors, article title, journal name, study type, article methodology, country, keywords, and the study's contributions to the research.

4. Presentation and Discussion of Results

4.1. Carrot2 Bibliographic Clustering Analysis

The open-source clustering tool Carrot2 (Carrot2 search results clustering engine) was used, as part of the bibliographic analysis, to identify recurring themes among the analyzed documents and to provide an initial stage for clustering and identifying the main framework variables.

Figure 5 shows the 22 original thematic groups identified among the papers [53].

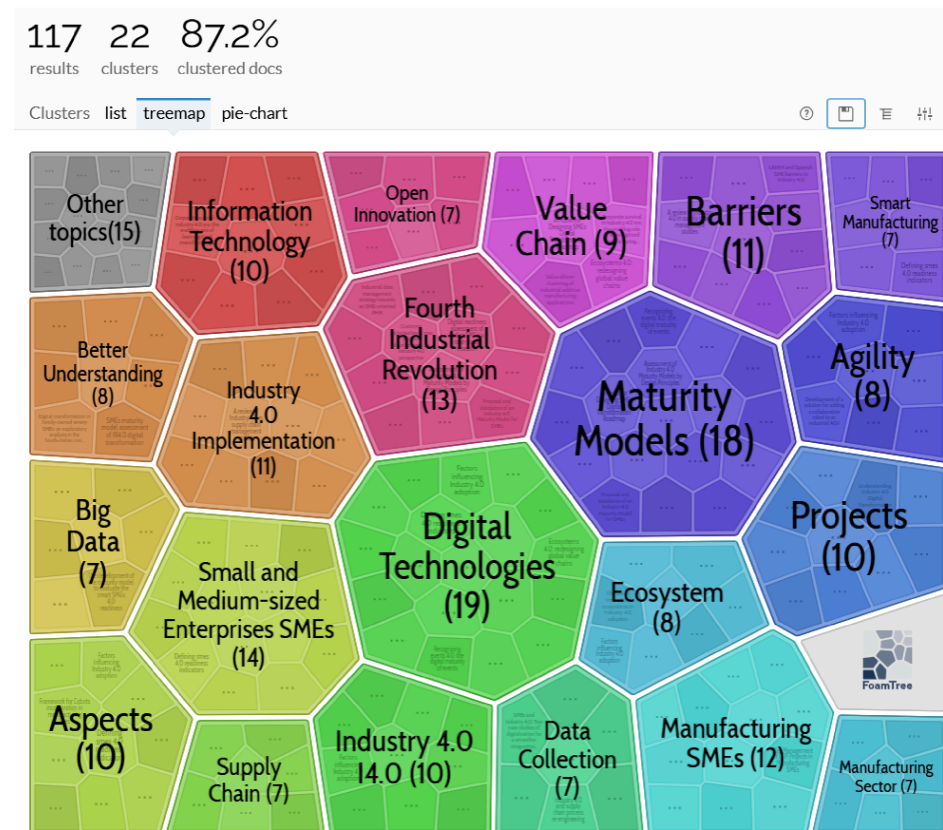


Figure 5. Carrot2 bibliographic clustering. Powered by Carrot2.

From this original grouping, the papers classified in the categories “better understanding”, “others,” and “aspects” were readjusted and reassigned to a more specific thematic group. This analysis resulted in the clusters “Digital Transformation,” “Readiness Assessment,” and “Influencing Factors.” Furthermore, the documents categorized as “Manufacturing SMEs” and “Small and Medium-sized Enterprises SMEs” were combined, as well as those classified as “Industry 4.0” and “Fourth Industrial Revolution”.

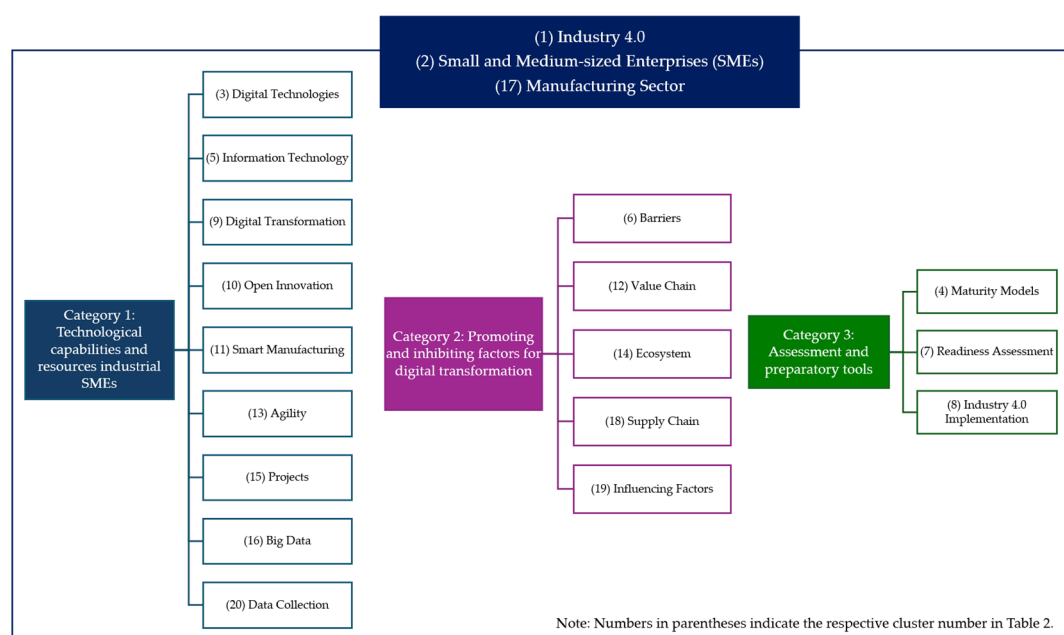
Table 2 lists the 20 clusters and the bibliographic references included in each grouping.

From the 20 clusters listed in Table 3, we identified three major categories for the analysis. The first category grouped nine clusters: (1) Digital Technologies, (2) Information Technology, (3) Digital Transformation, (4) Open Innovation, (5) Smart Manufacturing, (6) Agility, (7) Projects, (8) Big Data, and (9) Data Collection. The basis for this grouping is their insight into the technological capabilities and resources of industrial SMEs for adopting I4.0.

Table 2. Adjusted clustering of bibliographic references based on Carrot2 initial results.

Cluster	Topic	References	Count of Documents
1	Industry 4.0	[4,17,31,39,76–96]	25
2	Small and Medium-sized Enterprises (SMEs)	[2,5,15,19,76,80,84,89,90,97–112]	25
3	Digital Technologies	[4,5,27,76,83,91,92,101,103,104,111,113–122]	21
4	Maturity Models	[19,27,31,35,77,81,83,90,91,96,97,102,123–128]	18
5	Information Technology	[2,29,93,95,129–138]	14
6	Barriers	[2,7,14,19,38,87,88,104,113,139–141]	12
7	Readiness Assessment	[2,19,38,88,89,127,142–147]	12
8	Industry 4.0 Implementation	[14,28,30,81,107,109,124,139,143,148,149]	11
9	Digital Transformation	[27,31,33,35,83,97,100,104,113,150]	10
10	Open Innovation	[51,108,110,111,138,151–154]	9
11	Smart Manufacturing	[5,19,28,92,102,123,155–157]	9
12	Value Chain	[29,35,38,97,101,114,116,128,158]	9
13	Agility	[4,6,27,83,89,158–160]	8
14	Ecosystem	[4,32,51,82,116,155,161,162]	8
15	Projects	[18,19,39,112,121,163–165]	8
16	Big Data	[90,94,127,130,135,166,167]	7
17	Manufacturing Sector	[90,95,104,150,163,168,169]	7
18	Supply Chain	[14,27,86,108,147,166,170]	7
19	Influencing factors	[2,4,5,38,149,171]	6
20	Data Collection	[17,95,121,128]	4

The second major category includes six clusters focused on understanding the business environment of industrial SMEs as well as the factors that promote and inhibit digital transformation: (1) Barriers, (2) Value Chain, (3) Ecosystem, (4) Supply Chain, and (5) Influencing Factors. Finally, the third main category encompasses four clusters related to assessment and preparation tools for industrial SMEs to integrate into I4.0: (1) Maturity Models, (2) Readiness Assessment, and (4) Industry 4.0 Implementation. These three categories were analyzed within the frame of manufacturing SMEs and I4.0 as shown in Figure 6.

**Figure 6.** Identified categories for the analysis of literature within the frame of SMEs and I4.0.

Next, we will discuss the technological capabilities and resources, as well as the factors that promote and inhibit digital transformation in industrial SMEs, based on the best knowledge obtained from the categories above.

4.2. *Technological Capabilities and Resources*

The most competitive companies are those that best utilize technology and are most effective at developing and launching innovations. Thus, countries will become more advanced and developed to the extent that they create business environments that enable their companies to innovate faster than rivals elsewhere [152].

Wernerfelt (1984) [172] and Barney (1991) [173] framed the concept of capabilities within the RBV of the firm. The RBV argues that the collection of available resources shapes organizations and enables superior long-term performance and competitive advantage when the resource arrangement is rare, imperfect, valuable, and non-substitutable [174–176]. The RBV includes capabilities and assets as resources [177]. Capabilities are defined as the ability to perform tasks to achieve specific outcomes; assets refer to anything, intangible and/or tangible, that an organization uses [178].

From an extended RBV perspective, the DCT distinguishes operational and dynamic capabilities [178,179]. Effective dynamic capabilities build, synchronize, and reconfigure operational capabilities, enabling temporary competitive advantages and allowing the firm to stay ahead of competitive forces in turbulent environments [180,181]. Operational capabilities are defined as the ability to “make a daily living” [182] (p. 242). Capabilities can be framed based on similarities in fundamental features and particular factors within a given domain [183]. Previous research has presented a theoretical framework for firms’ innovation to determine their individual, organizational, process, and technological capabilities and to support firms in identifying the capabilities they lack to successfully convey an idea to market [184]. Rosemann and Vom Brocke (2015) [183] featured six factors (i.e., people, methods, IT, governance, strategic alignment, and culture) and corresponding capability areas.

Technological capabilities encompass the identification, management, and evaluation of emerging technologies. It also involves integrating technologies into organizational processes; developing customized software and hardware for process automation with data management; and maintaining and updating existing technologies [38]. Moreover, these capacities play a key role in the innovation process of an organization, particularly in the “inside-out process” [185,186]. This process refers to the cross-industry innovation that involves the exchange of new technologies and own ideas in new markets [138].

Taking the cluster analysis from Carrot 2 clustering as the starting point, four categories of SMEs’ technological capabilities are identified: (a) digital transformation, (b) data infrastructure, (c) cyber-physical infrastructure, and (d) intrinsic capabilities.

Figure 7 presents a sample of the recurring aspects in the analyzed literature regarding technological capabilities (see dataset [53]).

The initial group identified is digital transformation, which refers to the process of advancing along the road to strategically incorporate emerging technologies to promote sustainable operations across all fronts: productivity, economic, social, and environmental. Hence, this process depends on SMEs’ technological capacity to drive this transformation.

The first step towards digital transformation is “digitization”. It refers to the conversion of analog information into digital form [156]. Furthermore, “digitalization” refers to the “process” of induced change across industries. This process has facilitated the development of several phenomena, including AI, IoT, Industrial Internet of Things (IIoT), Big Data (BD), and Blockchain. Therefore, digitization (the conversion), digitalization (the process), and digital transformation (the effect) drive societal change [156].

Category	Technological capabilities emerging topics	Schönitz et al. (2021)	Depaoli et al. (2020)	Chan et al. (2019)	Murugaiyan and Ramasamy (2021)	Brodeur et al. (2022)	Liebrecht et al. (2021)	Spallini et al. (2022)	Dutta et al. (2020)	Garbellano and Da Veiga (2019)	Schmidt et al. (2021)	Khin and Kee (2022)	Facchini et al. (2022)	Appio et al. (2024)	Genest and Gamache (2020)	Ávila-Bobórquez and Gil-Herrera (2022)	Buenrostro Mercado (2022)
Digital Transformation	Digitization, Digital Transformation	x	x			x		x		x	x		x	x	x	x	x
Digital Transformation	Technological Transformation (TT) projects	x	x		x	x		x		x	x	x	x	x	x	x	x
Data infrastructure	Information and Communication Technologies (ICTs)	x	x					x			x				x	x	x
Data infrastructure	Big data and data analytics	x					x	x			x				x	x	x
Data infrastructure	Cloud computing	x	x	x			x	x	x	x					x	x	x
Data infrastructure	Artificial Intelligence (AI) - Machine Learning (ML)														x	x	x
Data infrastructure	Cibersecurity / Blockchain														x	x	x
Cyber-Physical infrastructure	Human-Machine Interconnection (HMI) / Advanced Manufacturing Technologies (AMTs)	x			x		x	x	x						x	x	x
Cyber-Physical infrastructure	Intelligent Sensors Technology (IST)/Simulation	x			x			x		x			x		x	x	x
Cyber-Physical infrastructure	Collaborative Robot (Cobots)	x													x	x	x
Intrinsic capabilities	Human skills & capabilities	x		x			x	x		x	x	x	x	x			
Intrinsic capabilities	Strategic Alignment	x	x			x	x	x		x	x	x	x			x	x
Intrinsic capabilities	Agility - Flexibility		x	x					x	x	x	x	x	x	x	x	x
Intrinsic capabilities	Innovation/ R&D			x				x		x	x	x	x	x		x	

Figure 7. Sample of the literature examined for the categorization of technological capabilities of SMEs to adopt I.4. Sources: [4,27,28,76,83,89,90,100,102,104,111,115,116,120,155,159].

Digital transformation requires a shift in mindset and the development of a culture that embraces this change, including its benefits and challenges, beyond simply implementing technology or digitizing processes and services [156,187]. Thus arises the concept of technological integration, which expresses the degree to which inter-organizational digital infrastructures shape and guide an organization's internal and external collaboration processes during its digital transformation [135].

A critical part of this digital transformation is the technological capabilities related to data infrastructure (the second group identified), which is defined as the use, transmission, and management of data using tools such as AI, information and communication technologies (ICTs), machine learning (ML), data analytics, cloud computing, cybersecurity, and blockchain.

ICTs encompass telecommunications technologies such as the Internet, mobile telephony, and broadband networks that are increasingly pervasive in industrial environments, enabling information exchange among systems and devices [188,189]. Nowadays, the business environment evolves rapidly, mainly due to the worldwide adoption of ICTs. These technologies ease and enable “a broad range of business activities related to the storage, processing, distribution, transmission, and reproduction of information” [189]. Moreover, information technologies significantly impact marketing, supporting the establishment and management of customer relationships and creating value for each organization [103]. However, many manufacturing SMEs that rely on outdated equipment, processes, and technology, along with a lack of ICT integration, find it challenging to transition to I4.0, particularly in developing countries [95].

Pech and Vrchota [124] conducted a stratified survey among Czech SMEs to identify the level of Industry 4.0 implementation. Most companies acknowledged benefiting from generic information technologies and digitization, though they showed only a moderate rate of Industry 4.0 technology implementation. However, due to various resource limitations and a lack of understanding of ICT-related opportunities, SMEs face greater difficulties in adopting new technologies.

Emerging technologies, particularly in big data analysis, have transformed companies' digital landscapes. Big data refers to the set of emerging tools, methods, and artifacts

used to collect and analyze significant volumes of data at high speed and with high efficiency, through data cleansing, data scrubbing, filtering, correlation identification, and reporting insights that would not be possible with previous data technologies [95]. To ensure a continuous, permanent flow of data between organizations, advanced information technologies, particularly those related to big data, facilitate the transfer of large volumes of data and enhance transparency across organizations. Ref. [135] highlighted the relevance of a smooth, rich flow of real-time data across organizational boundaries, as it provides transparency and enables greater automation of routines across organizations. Based on an extensive review of literature and on observations from research in an industrial setting, the authors theorized how increasing technological embeddedness created by big data technologies affects the development of inter-organizational trust, mutual adaptation, and the temporal structuring of collaboration. However, SMEs depend on top management support to mediate organizational and technological factors in the adoption of big data analytics [190]. Hence, the extent of decision-makers' knowledge of the benefits and challenges of big data will shape its implementation in SMEs.

Generative AI and ML have emerged over the last five years as a disruptive technology encompassing computational techniques and artefacts that generate novel and meaningful content through a learning process with datasets, spanning audio, images, and text [191]. Hence, AI has transformed industrial and businesses environments by (1) supporting the standardization of operations and enhancing the efficiency, and (2) enabling customization and adaptation which results in broader flexibility of an enterprise [192].

As new technologies arise, securing access to the information and data being exchanged becomes necessary. Hence, blockchain is a transparent and immutable technology that enables trustworthy, decentralized, and secure transactions and swift, private or public solutions, thereby redefining trust [193]. This technology is commonly used for cryptocurrencies operating in a fully autonomous IoT environment without human intervention. The application of blockchain is not limited to financial services, and it can be used for any digitized transfer of information [136,194,195]. For example, IBM and Maersk joined efforts to ease paperwork processing to avoid mishandling, frauds and excessive cost in the management of bill of lading [196]. In the same venue, cybersecurity is a critical element of I4.0, given the risk of attack during data exchange operations. Within the I4.0 environment, "things" are connected via the internet or other telecommunications technologies to create a fully interconnected industrial network across the supply chain. Hence, it is necessary to have reliable, secure, and safe communications so that operations, actions, or decisions are grounded in trustworthy, properly licensed information [136].

Cyber-physical infrastructure emerged as the third group. A cyber-physical infrastructure is required to support companies' operations, exchange data, and accelerate I4.0 [156]. Furthermore, I4.0 promotes the development of smart manufacturing environments by converging new technologies, production, and ICTs in digital and physical domains, making this industrial revolution unique. I4.0 also implies the complete digital transformation of value chains, aiming to integrate data exchange technologies, intelligent software, sensors, and machinery to intelligently monitor, control, plan, and forecast, leading to value creation across the chain [197]. Regarding the cyber-physical infrastructure, three main groups are identified from this systematic review: (a) Intelligent Sensors Technologies (ISTs)/Simulation, (b) Collaborative Robot (Cobots), and (c) HMI/AMTs.

HMI enables a physical and cyber system where humans and machines to operate within a cooperative and learning environment [95]. Advancements in augmented and virtual reality have also impacted the industrial environment [7]. Augmented reality involves a set of effective and innovative HMI techniques, where real objects interact with virtual objects embedded in an interface with the real world. Virtual reality consists of

the usage of computer technology to generate objects with spatial form in an interactive and three-dimensional world. This alternative reality allows users to simulate reality by controlling virtual objects in real time [95,198].

From a five-year case study, ref. [29] found that manufacturers worldwide heavily invest in emerging AMTs (e.g., MTM/HMI communications, ERP platforms, CNC machines, additive manufacturing) “to stay competitive in the hyper-competitive global market”. Further, ref. [199] conducted an international survey in six Central European regions to identify SMEs’ propensity to adopt I4.0 technologies. In their research, the authors identified AMTs as the starting point for SMEs’ adoption of I4.0 technologies. Furthermore, the authors recognized social capital as a variable strongly related to the capacity to absorb new I4.0 technologies. Ref. [158] conducted a multi-case study across the industrial and medical sectors to assess the adoption of AMTs in central European and Swiss regions. From a value chain perspective, the authors analyzed the benefits of AMTs to the processes of new product development and order fulfillment. Their findings suggested that “understanding the additive manufacturing process chain and the design experience are key to explaining the heterogeneous industrial maturity” (p. 366). Finally, ref. [149] identified the most common technology clusters adopted by factories of the future. These methods and technologies include hybrid manufacturing and 3D printing, smart and adaptive manufacturing equipment, cobots, and MTM communications, as well as high-tech production processes integrated with simulation, cloud computing, virtual reality, IoT, big data and analytics, and ML.

Technological capabilities widely support repetitive functions and tasks, revolutionizing operations across the supply chain. The order-picking task is one of these repetitive, heavy functions, including collecting several items distributed across the warehouse’s storage area and taking them to the preparation stations. Hence, various robotic order-picking systems have been proposed, including automated guided vehicles (AGVs), collaborative robots (cobots), and robotic hands. For example, ref. [6] proposed a simplified model to support this task by deploying cobots and AGVs in the warehouse.

Finally, intrinsic capabilities arose as the fourth group of technological capabilities. The digital transformation of a company involves adopting new and emerging technologies to drive industrial change toward increased productivity, sustainability, and competitiveness [17,83]. Therefore, to achieve a successful digital transformation, firms must leverage their managerial and intrinsic capabilities to support decision-making while integrating new technologies into manufacturing and organizational processes. Human skills and capabilities are a crucial element for digital transformation. As factories adopt new technologies, humans need a basic understanding of interconnected systems like ICTs, HMI, MTM, AI, and data analysis, along with interdisciplinary knowledge to succeed and advance I4.0 environments [18,30,102,200,201]. Similarly, an SME requires a strategic, aligned vision across the organization and with its business partners to decide whether to invest in new technology [4,28,102]. Moreover, from a DCT perspective, the organization should be flexible and agile enough to adapt to new technology at the lowest possible cost [27,113]. When well implemented, these technologies provide flexibility further to support the achievement of a sustainable competitive advantage.

Figure 8 presents the distribution of the documents included in this study regarding the technological capacities identified in this work.

Figure 8 shows that 62.2% of the documents focus directly on digital transformation and the study of technological capabilities in SMEs to incorporate new technologies and adapt to Industry 4.0. Furthermore, 58.1% of the documents include the role of ICTs in their analysis, highlighting their importance within companies for data use, management, and handling.

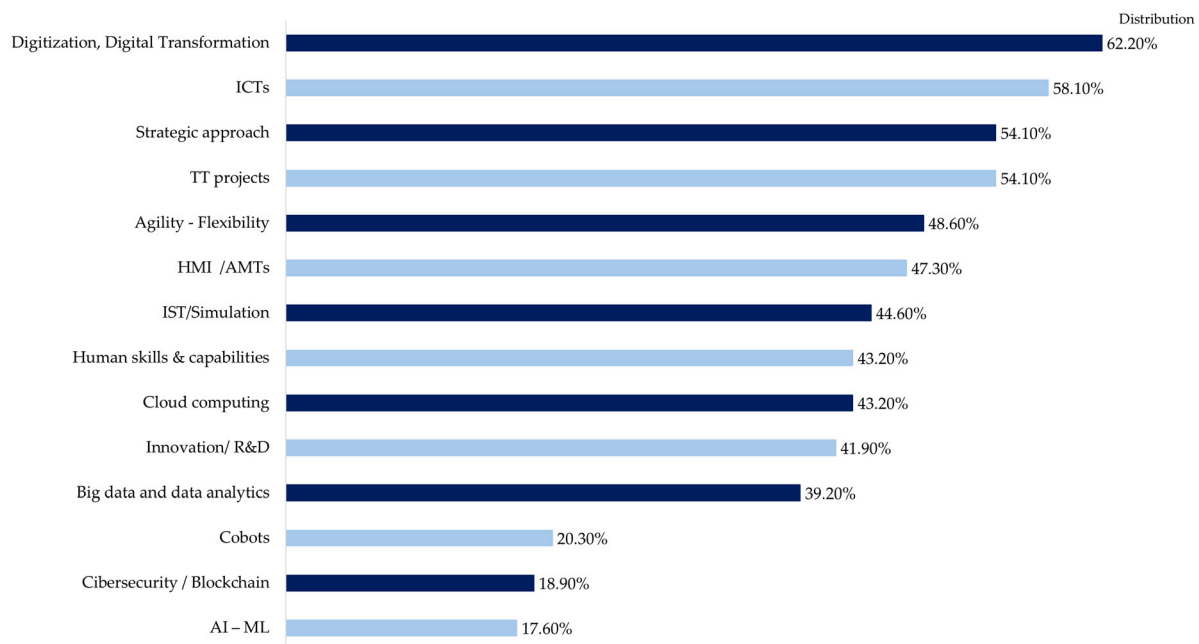


Figure 8. Distribution of technological capacity from the SMEs identified in the literature review.

Regarding alignment with business needs and technological transformation project, the literature review shows a 54.1% representation, highlighting the role of the organization's strategic orientation when designing the process of incorporating and developing technological capabilities. Furthermore, agility and flexibility, at 48.6%, stand out as intrinsic dynamic capabilities, enabling organizations to adapt to technological changes and leverage available resources.

As part of the physical infrastructure for technological capabilities, HMIs and AMTs stand out, accounting for 47.3%. Furthermore, the study on ISTs, simulation, augmented reality, and virtualization accounts for 44.6% of the documents, while cloud computing represents 43.2%, with big data and data analytics at 39.2%. Both represent data infrastructure as resources for companies' technological capabilities.

Furthermore, noteworthy are the human capabilities and skills possessed by 43.2%, as well as R&D with 41.9%, which are referenced in the literature review as intrinsic factors for identifying and evaluating emerging capabilities.

Finally, cobots at 20.3%, cybersecurity/blockchain at 18.9%, and artificial intelligence with machine learning at 17.6% are focused on data infrastructure supporting the generation of technological capabilities.

Figure 9 presents a stratified analysis of research trends related to the technological capabilities identified in this study.

The stratified analysis reveals a temporal evolution of technological capabilities underpinning digital transformation in SMEs, structured across four periods (2005–2010, 2011–2015, 2016–2020, and 2021–2025).

The period between 2005 and 2015 is characterized by fragmented and limited research across the domains under study. The attention is focused on ICTs and alignment with business needs. Other capabilities (e.g., AI/ML, big data analytics, cloud computing, and cyber-physical systems) remain largely underexplored. This suggests that research and SMEs were focusing on incremental improvements and recognizing the role of digital technologies as enablers of organizational efficiency.

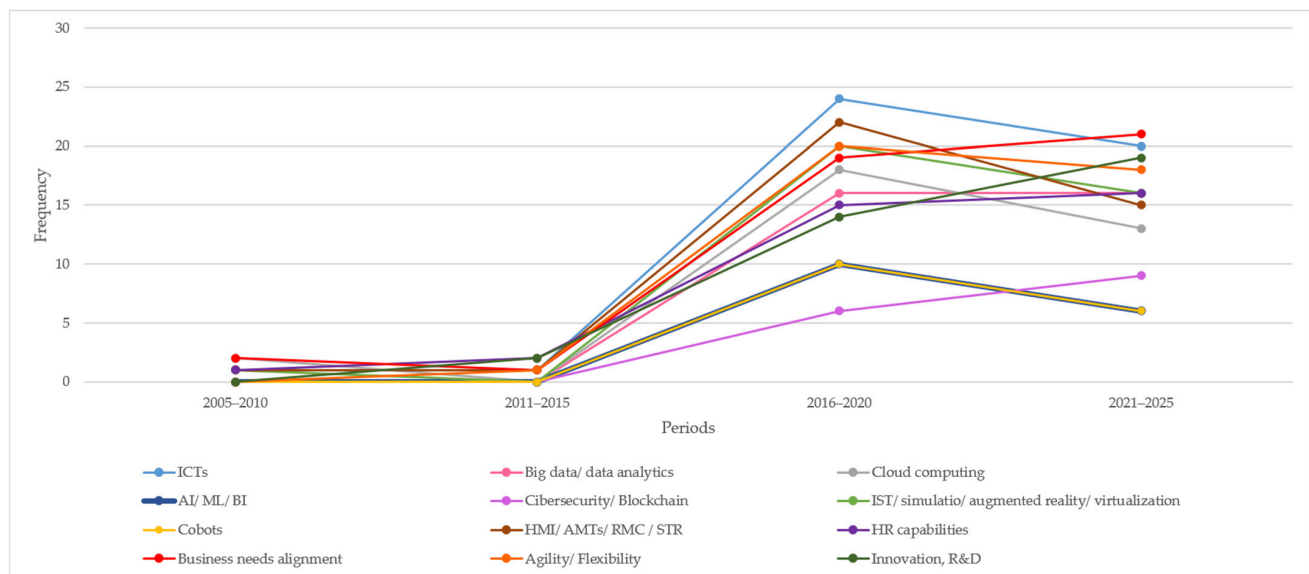


Figure 9. Stratified trends of SMEs' technological capabilities identified in the literature review.

A clear inflection point occurs in the 2016–2020 period, during which all streams of technological capabilities saw significant growth in research attention. ICTs become the most prominent stream, reflecting their fundamental role in enabling digital transformation. HMI/AMT/RMC/STR gain prominence alongside AI/ML/BI, big data analytics, and cloud computing, indicating the spread of I4.0 paradigms into SME research. At the same time, organizational capabilities (agility, flexibility, HR capabilities, and innovation) experienced parallel growth, highlighting the co-evolution of technological and organizational aspects.

In the most recent period (2021–2025), trends show consolidation and differentiation as business needs align with big data and data analytics, which continue to grow and become the main focus of SMEs' digital transformation research. ICTs and Cloud computing continue to expand, albeit at a stable pace, indicating their transition from emerging technologies to fundamental infrastructure capabilities. HR capabilities, cybersecurity/blockchain, and innovation/R&D demonstrate ongoing growth, reflecting a rising awareness of human capital in digital ecosystems and the risks associated with governance failures.

With this in view, the figure shows that research on SME digital transformation has shifted from a technology-focused and fragmented area to a capability-driven, integrated, and sustainability-focused field. This shift highlights the importance of moving beyond isolated technological investments toward building systemic capabilities.

4.3. Promoting Factors of SMEs' Digital Transformation

New technologies are a fundamental aspect of smart manufacturing and Industry 4.0. Furthermore, the adoption of AMTs enhances various strategic areas of manufacturing, including quality and human resources (HR) policies [19]. In this context, SMEs need to understand the concept of I4.0 to identify and assess their needs and develop the capabilities required to address the challenges of digital transformation [97]. However, despite rapid technological advances, SMEs still face difficulties in initiating and adopting digital transformation due to resource constraints, a shortage of skilled workers, and a lack of understanding of I4.0 opportunities [189].

Thus, this literature review presents a framework of key areas and variables related to factors that promote or hinder the acquisition of technological capabilities. It aims to improve understanding of the digital transformation process in SMEs and their

decision-making when adopting new technologies. Therefore, we analyzed the clusters in Category 2, “Promoting and inhibiting factors for digital transformation”, shown in Figure 5.

Figure 10 shows the details of the distribution of the identified specific promoting factors to SMEs’ digital transformation in the analyzed documents.

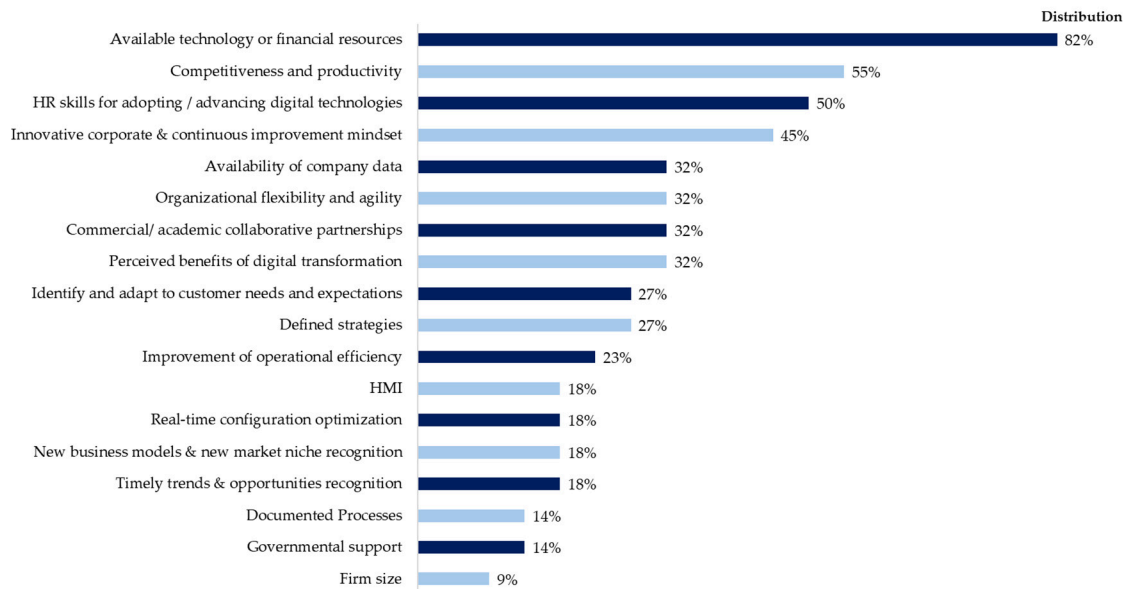


Figure 10. Distribution of the promoting factors for SME adaptation to I4.0 identified in the literature review.

The primary promoting factor depicted in Figure 10, technological availability and access to financial resources for operations and investment (innovation, employee training, technologies, etc.), appears with a relative frequency of 82% in the reviewed documents. Next are the factors of competitiveness and productivity, which register at 56%. The skills required to adopt new technologies account for 50%, while corporate innovation culture and a continuous improvement mindset account for 45%. These four factors emerge as the most prominent drivers.

On the other hand, data availability, business flexibility and agility, and collaboration with business and academic partners in sharing knowledge and resources, along with the perceived benefits of digital transformation, each account for 32%. The ability to identify and adapt to customers’ needs and expectations, as well as to define new strategies, each represents 27%. The need to improve operational efficiency stands at 23%. Furthermore, each representing 18% of the total are: HMI, recognition of new business models and new market niches, real-time configuration optimization based on current requirements, and timely recognition of trends and opportunities. Finally, the last three factors identified are: documented processes (14%), government support (14%), and firm size (9%).

These factors promote the maturity of industrial SMEs in adapting to Industry 4.0 environments, providing insights into their preparedness to advance in the digital transformation process.

Figure 11 presents a stratified trend of SMEs’ promoting factors for digital transformation identified in the literature review.

During the initial period (2005–2010), all promoting factors received minimal research attention, with operations/technologies and culture showing slightly higher frequencies, indicating that early on, digitalization was seen as an operational improvement.

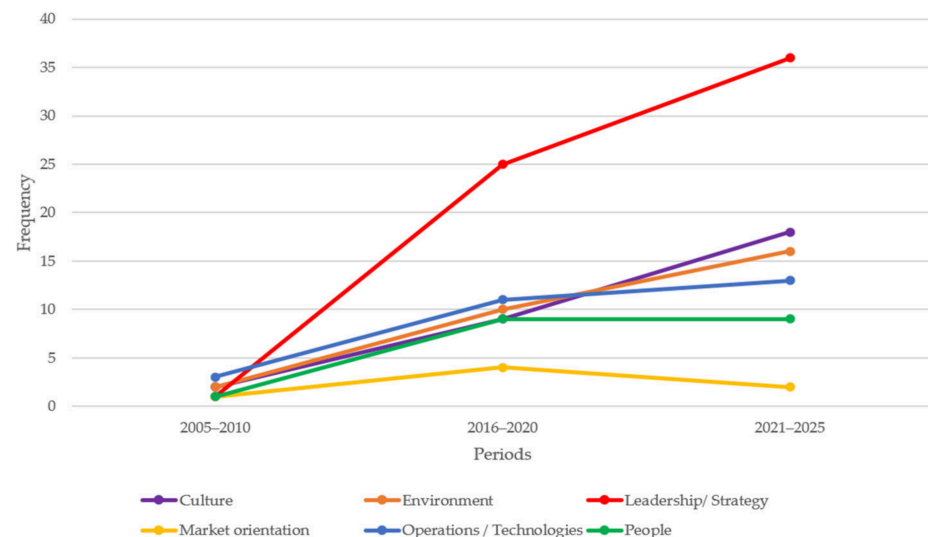


Figure 11. Stratified trends of SMEs' promoting factors for digital transformation identified in the literature review.

A significant rise across all factors is observed during the 2016–2020 period, marking a turning point in the reviewed literature, where leadership/strategy becomes the most prominent factor, reflecting a growing recognition that digital transformation requires a top-level strategic vision and direction. Furthermore, operations/technologies, environment, culture, and people show strong growth, revealing a broader understanding of transformation as a multidimensional process. Therefore, SMEs' digital transformation toward I4.0 environments necessitates coordination across organizational, technological, and environmental dimensions.

Finally, the period from 2021 to 2025 shows consolidation and differentiation trends, with leadership/strategy remaining the most dominant and influential factor. This highlights the vital importance of leadership, vision, strategic alignment, and governance in driving digital transformation success. Regarding culture, environment, and operations/technologies, ongoing growth highlights their roles as key supporting factors. This development indicates that leadership and organizational alignment are crucial for supporting technological capabilities. Moreover, the increasing importance of culture, environment, and operations/technologies highlights that digital transformation is a context-dependent process that needs alignment between internal structures and external conditions. It is notable that market orientation has decreased in recent times, indicating a shift away from a solely external demand-driven approach toward a more internally driven strategic process.

Based on this analysis, the following areas emerged as factors supporting the digital transformation of SMEs in adopting I4.0 tools: culture, leadership, operations and technologies, people, market orientation and environment, which can positively influence the decision to adopt I4.0. Figure 12 illustrates the areas that industrial SMEs need to leverage to progress toward I4.0.

Figure 12 presents five identified areas of opportunity for SMEs to develop technological capabilities and, as a result, advance the digital transformation process: culture, environment, leadership strategy, operations/processes, and people.

Culture encompasses both entrepreneurial and collaborative orientations, in which the former refers to decision-makers' attitudes toward risk-taking, proactiveness, and innovativeness, while the latter encompasses decision-makers' and workers' approaches to internal and external collaborations [4,38,113,197]. Linked to the organization's culture, leadership involves the strategic approach adopted by SMEs to achieve productivity, efficiency, social, and environmental goals [17,143,171]. Additionally, as decision-makers and

the organization gain knowledge through interactions with different actors in their environment, this influences the decision-making process by strengthening their commitment to implementing and advancing strategic decisions for SMEs. Finally, the leadership role of manufacturing SMEs toward I4.0 depends on access to financial, human, and technological resources [5,116]. When SMEs acquire sufficient knowledge, it can serve as leverage to access external resources, helping them overcome resource constraints [7,141].

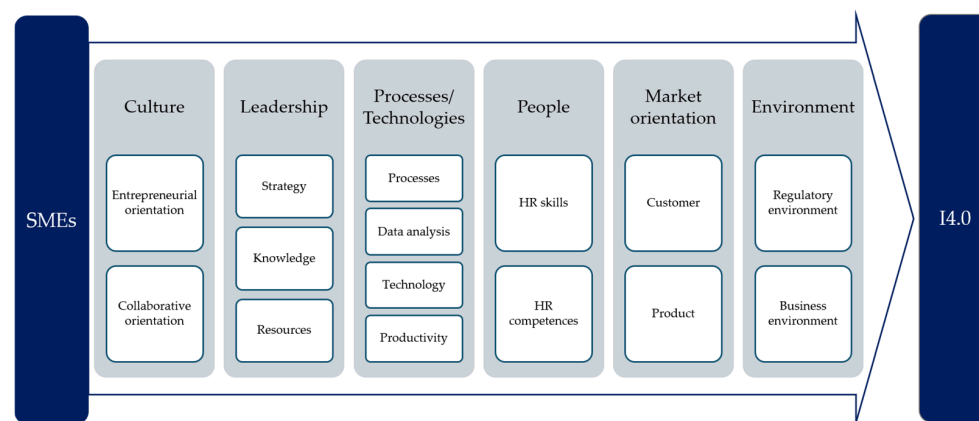


Figure 12. Areas of promoting factors for SMEs in the adoption of I4.0 identified in the literature.

Processes and technologies include documented, digitized, or automated processes that combine technologies and human activities to achieve a specific goal while ensuring consistency [2,83,113]. Additionally, data analysis to support processes and decision-making [7,124,149]. Furthermore, technology refers to the use and performance of tools used to carry out processes [5,141]. Ideally, the latest and most advanced technology provides the greatest impact by enabling high levels of automation. Finally, productivity and efficiency resulting from operations and technology management [2,104].

People encompasses HR skills and competencies reflected in employees' experience in adopting and utilizing advanced digital technologies, as well as access to relevant resources [3,19,87].

Market orientation became a crucial factor for SMEs adopting a customer- and product-focused approach by recognizing customer needs and expectations and adjusting through developing new products [5,14,143]. The environment includes the regulatory framework, mainly shaped by the government, and the business environment, which provides flexibility for forming alliances and influences the value chain. Therefore, SMEs' digital transformation will rely on how much they operate within a supportive regulatory and business environment [2,139].

4.4. Hindering Factors of SMEs' Digital Transformation

SMEs face difficulties in initiating or sustaining their digital transformation process.

Figure 13 presents the inhibiting factors identified in the review that hinder the digital transformation of industrial SMEs.

Among the most relevant factors inhibiting the digital transformation of industrial SMEs are resistance to change and the lack of an innovative corporate culture (86%), lack of knowledge and understanding of digital transformation as well as lack of financial and technological resources (73%), lack of necessary skills and competencies (55%), lack of a clear vision and leadership from senior management (27%), lack of availability of technology and infrastructure, adding the lack of collaboration with technology partners and providers as well as reluctance to adopt I4.0 technologies (18%), lack of government support through policies and laws (5%), and finally, generational factors (5%).

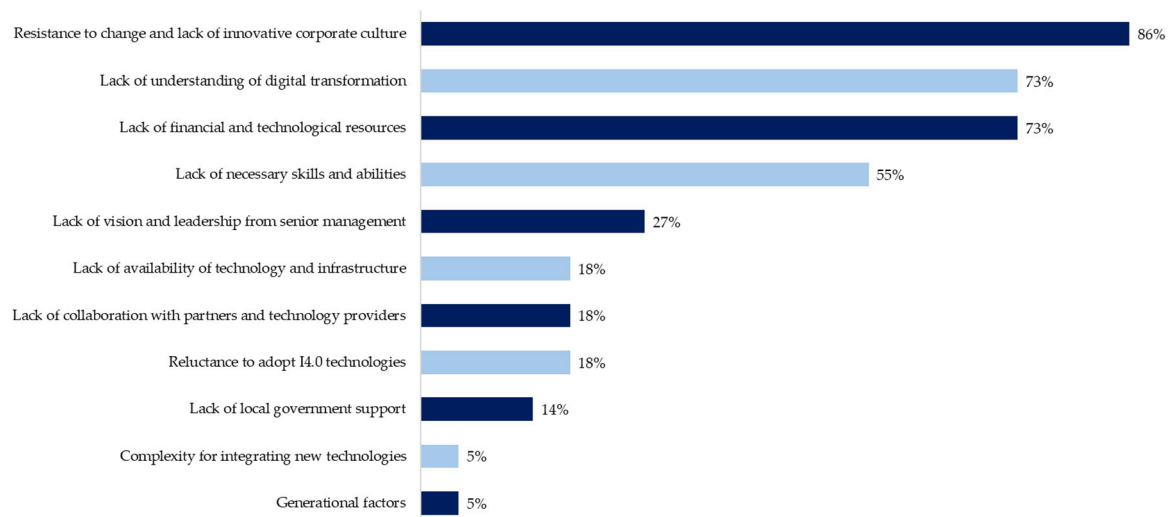


Figure 13. Distribution of the inhibiting factors for SME adaptation to I4.0 identified in the literature review.

Figure 14 shows a layered analysis of research trends related to the obstacles to SMEs' digital transformation identified in this study.

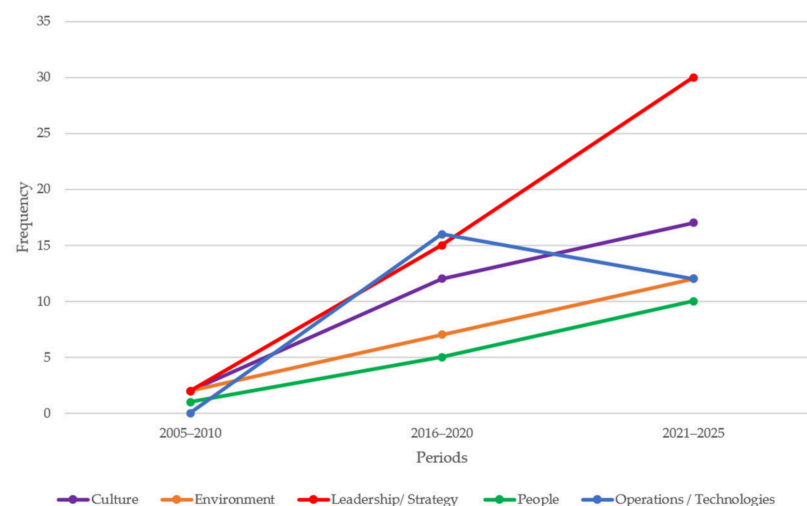


Figure 14. Stratified trends of SMEs' hindering factors for digital transformation identified in the literature review.

Between 2005 and 2010, the study of barriers appears relatively underexplored in the literature, indicating that early research on SMEs' digital transformation focused more on adopting digital technologies and exploring potential opportunities rather than systematically examining barriers and challenges.

From 2016 to 2020, there was a significant increase across all categories, showing a maturing research agenda that clearly recognizes transformation challenges. Operations and technologies became major obstacles, highlighting integration issues, the complexity of new technologies, and infrastructure limitations. Additionally, leadership and strategy rose considerably, indicating weak strategic alignment and a lack of vision among decision-makers. Culture also experienced significant growth, emphasizing resistance to change and organizational inertia. Regarding environment and people, these areas develop more slowly, underscoring skills shortages and external uncertainty. Therefore, this layering reflects a shift toward understanding digital transformation as a complex socio-technical process.

In the most recent period, the trend has shifted in both composition and magnitude. Leadership/strategy increases significantly, becoming the main barrier. This indicates a strong consensus that strategic misalignment and leadership capability gaps are the key constraints to digital transformation success. Furthermore, culture continues to evolve, underlining the importance of an organizational mindset. People-related obstacles, such as competencies and skills, also steadily increase, highlighting ongoing digital skills gaps and talent shortages in SMEs. Regarding the environment (e.g., market uncertainty, governmental regulations), growth remains moderate, indicating that external constraints are significant but that firms are learning how to navigate them.

Thus, barriers to SME digital transformation have shifted from minor, technology-focused to mainly strategic and organizational. This highlights the critical role of leadership, culture, and human skills as the key challenges in today's digital transformation efforts.

SMEs need to identify and improve their weaknesses and develop the skills required to overcome digital transformation challenges. Therefore, based on the previous analysis, Figure 15 below shows the areas industrial SMEs must address as potential barriers identified in this review that limit their adoption of I4.0.

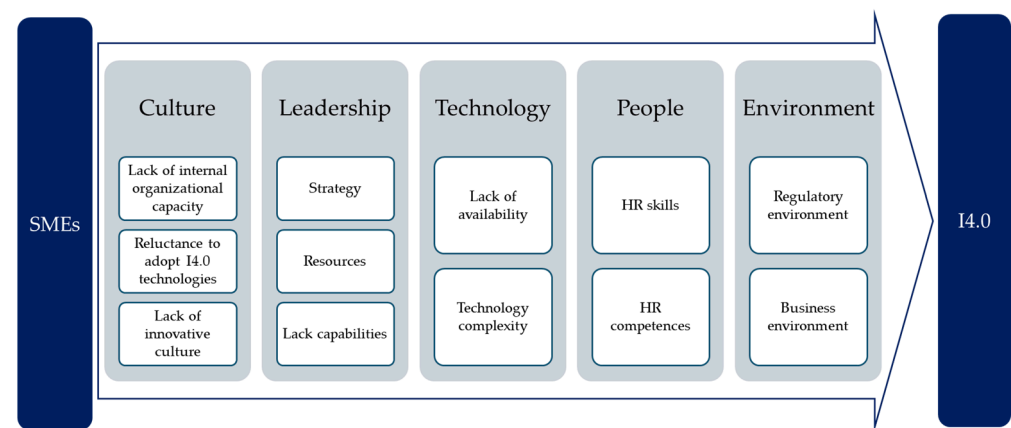


Figure 15. Areas of hindering factors for SMEs in the adoption of I4.0 identified in the literature.

Five key hindering areas are identified: culture, leadership, technology, people, and environment.

Regarding culture, it involves a lack of SMEs' internal organizational capacity, which then results in poor collaboration with partners and technology providers, resistance to adopting Industry 4.0 technologies, and a deficiency in an innovative culture [30,38,105,140]. A lack of vision and leadership from senior management negatively affects SMEs' digital transformation [5,105,171]. This deficiency leads to poor strategy design and implementation, which is also influenced by limited access to financial and technological resources [116,140,141]. Moreover, the limited availability of technology and infrastructure, along with the challenges of integrating new technologies, serve as significant barriers to SMEs' progress toward I4.0 [4,141,199]. As a hindering factor, people refer to HR capacity gaps and limitations for attracting skilled employees in operating and managing existing and new technologies [113,141,149].

Finally, the environment encompasses the regulatory setting, primarily the absence of governmental support through policies and laws, along with the disruptions, volatility, and uncertainty of the business environment in which the SME operates [87,141].

I4.0, characterized by a high level of technological complexity, a high dynamism in the different approaches, and the lack of transparency of existing methods, poses challenges for industrial SMEs, as they often lack the necessary resources, whether capacity, technical knowledge, or capital [28] (p. 6). Thus, SMEs' digital transformation is driven by factors

such as resource availability, an innovative corporate culture, collaboration with business partners, and government support. In contrast, the absence or limited availability of these factors can inhibit digital transformation in SMEs. Therefore, SMEs need to develop strategies that leverage enabling factors while addressing the challenges they face in adopting I4.0. It is important to recognize that these factors can vary across companies and contexts. Additionally, it is worth noting that enabling and inhibiting factors can overlap, as seen with organizational culture, government support, technology, people, and leadership.

The main findings regarding the overlapping listed promoting and inhibiting factors are discussed in Table 3.

Table 3. Overlapping promoting and inhibiting factors for industrial SMEs' digital transformation.

Area	Factors Promoting Digital Transformation	Authors	Factors Inhibiting Digital Transformation	Authors
Leadership	Availability of financial and technological resources to invest in digital transformation (innovation, employment, training, technology, etc.).	[5,7,38,105,116,124,139,140,143]	The high costs of investing in technology, the uncertainty of its returns, and the lack of financial and technological resources to fund digital transformation.	[2,4,5,7,28,30,38,83,87,88,104,105,113,116,124,139–141,143,149,171,202,203]
Culture/Processes	Innovative corporate culture and a continuous improvement mindset. A clear vision and a well-defined strategy for digital transformation. Competitiveness and productivity orientation.	[7,30,38,83,105,113,143,149,171,199,204] [105,143,171]	The lack of an innovative business culture. Lack of vision and leadership from senior management.	[7,38,87,113,149] [105,143,171]
Leadership	The perceived benefits include increased productivity, greater efficiency, greater flexibility, and cost savings. It facilitates better decision-making and greater business agility.	[2,4,5,7,87,104,113,116,139–141,171,199]	Lack of knowledge and understanding of advanced digital technologies and their potential impact on the organization.	[2,4,5,7,14,30,38,83,87,104,105,113,116,124,139–141,143,171,199,202]
Technology	Real-time configuration optimization based on current requirements	[2,19,113,124,205]	Lack of availability of technology and complexity of the technological infrastructure	[3,4,88,104,141]
People	Access to HR skills is needed to adopt and use advanced digital technologies. Digital skills training programs for HR.	[2,4,5,14,19,38,83,87,143,149,190,199]	The lack of skills and abilities is needed to adopt and use advanced digital technologies.	[2,4,5,7,14,19,30,38,83,87,104,105,113,116,124,139,141,143,149,171,190,199]
People	The organization's ability to develop the skills necessary to adopt and use advanced digital technologies. Timely recognition of trends and opportunities, new business models, and new market niche recognition, including the identification of customer needs and expectations, and the capability to adapt to them.	[2,4,5,7,14,19,30,38,83,87,88,104,105,113,116,124,139–141,143,149,171]	The lack of suitable personnel to manage the digital transformation project.	[4,88,149,169,199]
Leadership	Product development and adaptation. Real-time configuration optimization based on current requirements. Collaboration with commercial and academic partners to obtain support in the adoption of advanced digital technologies.	[5,14,87,88]	Resistance to change and the lack of an innovative corporate culture.	[2,4,5,7,14,19,30,83,87,88,104,105,113,116,124,139,141,143,149,171]
Market orientation	Product development and adaptation. Real-time configuration optimization based on current requirements. Collaboration with commercial and academic partners to obtain support in the adoption of advanced digital technologies.	[2,19,95,113,124]	Complexity of integrating new technologies.	[28,88]
Culture	Government support policies and laws that promote digitization and digital inclusion.	[2,5,7,14,87,88,104,105,113,116,139–141,149,171]	Lack of collaboration with partners and technology suppliers. The lack of suppliers' experience with I4.0 technology and services.	[87,105,143,149]
Environment (governmental support)	Government support policies and laws that promote digitization and digital inclusion.	[2,38,139]	The lack of government support through policies and laws that promote digitization and digital inclusion.	[14,38,87]

In the context of adopting new technologies, the enabling factors identified can be external to companies, such as government support for financing, training, and technological advice, or internal or organizational, such as technological skills, a skilled workforce, and infrastructure.

All businesses rely heavily on access to investment and its profitability. SMEs are often sole proprietorships and face various risks, such as lacking collateral and dealing with information asymmetries between small businesses and investors. Consequently, SMEs must confront the lack of financial and human resources to invest in advanced technologies that facilitate their digital transformation [19]. Added to this is the high cost of investment. A high percentage of German SMEs (41%) have not successfully implemented I4.0, primarily due to significant investment costs and uncertainty surrounding the vision and the benefits that can be gained from 4.0 [30] (p. 1). Therefore, it is important to

recognize that a realistic financial assessment is necessary before investing, but it is difficult to obtain due to the expected return period (around 5 years) and the uncertainty during that time, caused by the changing and complex nature of the business environment, which makes it hard to predict the financial outcomes.

Limited knowledge and experience with advanced technologies, as well as resistance to change from business leaders and employees, are critical factors that limit digital transformation [19]. Ref. [99] examined the level of preparedness for digital transformation across multinational corporations and SMEs through a series of structured, in-depth interviews with 195 senior leaders from MNCs and SMEs. The results identified that, although managers recognize the urgency of the challenges presented by digital transformation, deficiencies in organizational culture are the main obstacle to achieving business success in this era. Furthermore, the study highlighted the need for organizations to have the right people to manage the digital transformation project. On the other hand, the organizational structure of SMEs is less complicated and formal, which means that IT integration requires solutions adapted to the specific problems SMEs face [19].

Collaborative strategies with business and academic partners are crucial to an organization's success. However, SMEs often lack alliances, strategies, and collaboration with other companies and organizations to share knowledge and resources. Ref. [19] argues that "SMEs lack the culture and strategy of innovation necessary to succeed". This limits them to creating and sharing knowledge within their own context and specific domain, which, in turn, narrows their view of the wider business environment. This negatively affects their ability to identify new business opportunities or respond to them.

Moreover, the "lack of technological infrastructure" represented the most pressing challenge hindering SMEs' I4.0 adoption. This lack includes the limited autonomy of many systems, insufficient bandwidth, and limitations in developing, modeling, and analyzing complex systems. It also refers to the limited capacity to improve the quality and integrity of recorded data, to adjust current production routes to accommodate dynamic reconfiguration for individualized and customized products, and to ensure cybersecurity and data privacy [4,33].

In general, a holistic and collaborative approach is required to promote digital transformation in SMEs, addressing both technical and cultural and organizational challenges. While SMEs face financial constraints and their R&D is not very advanced, their hard work results in highly specialized products that can differentiate them from competitors [19]. This underscores the need to identify the best areas for assessment and investment in technological transformation and optimal government support [33]. The areas of evaluation include the effectiveness and efficiency of digital technologies in improving productivity and reducing costs and carbon emissions, employee and customer satisfaction with digital technologies, and the company's ability to adapt and evolve in response to changes in the business environment [17,30].

Regarding the social context, the following variables stand out for evaluation:

1. **Organizational culture:** SMEs' organizational culture can affect their ability to adopt and use advanced technologies. For example, a culture that encourages innovation, is flexible enough to adapt to a changing environment, and promotes continuous learning may be more supportive of digital transformation than one that emphasizes stability and short-term efficiency.
2. **Skills and competencies:** Employee skills and competencies are essential for the adoption and effective use of advanced technologies. SMEs may need to invest in training and development of technical and digital skills to ensure their employees are prepared for digital transformation.

3. Collaboration and networking: These are important for the adoption of advanced technologies. SMEs may need to work with other ecosystem players, such as suppliers, customers, and universities, to access knowledge and resources to adopt and leverage advanced technologies.
4. Regulation and public policies: They influence the adoption and use of advanced technologies by SMEs. Policies that encourage innovation and the adoption of advanced technologies can benefit SMEs, while those that limit investment in such technologies or favor large companies can be detrimental to them.
5. Customer needs and environmental sustainability: As customers demand new products that are high quality, affordable, safe, and environmentally responsible, I4.0 offers SMEs the chance to meet these needs by strategically adopting new technologies. These technologies can help cut waste, energy consumption, and carbon emissions, as well as develop new materials and methods to reduce the use of harmful materials.

5. Theory-Building Model

5.1. Integrating the Baseline Concepts

SMEs encounter difficulties when beginning their digital transformation. They need to recognize the importance of a strategic approach to I4.0, plan their requirements, and leverage available resources to develop the right capabilities to overcome challenges in digital transformation. Based on the literature review, we built a theoretical framework identifying the critical areas for SME evaluation to enhance their digital transformation.

Figure 16 illustrates the conceptual baseline that incorporates factors for industrial SMEs, along with the technological capabilities supporting their digital transformation toward I4.0.

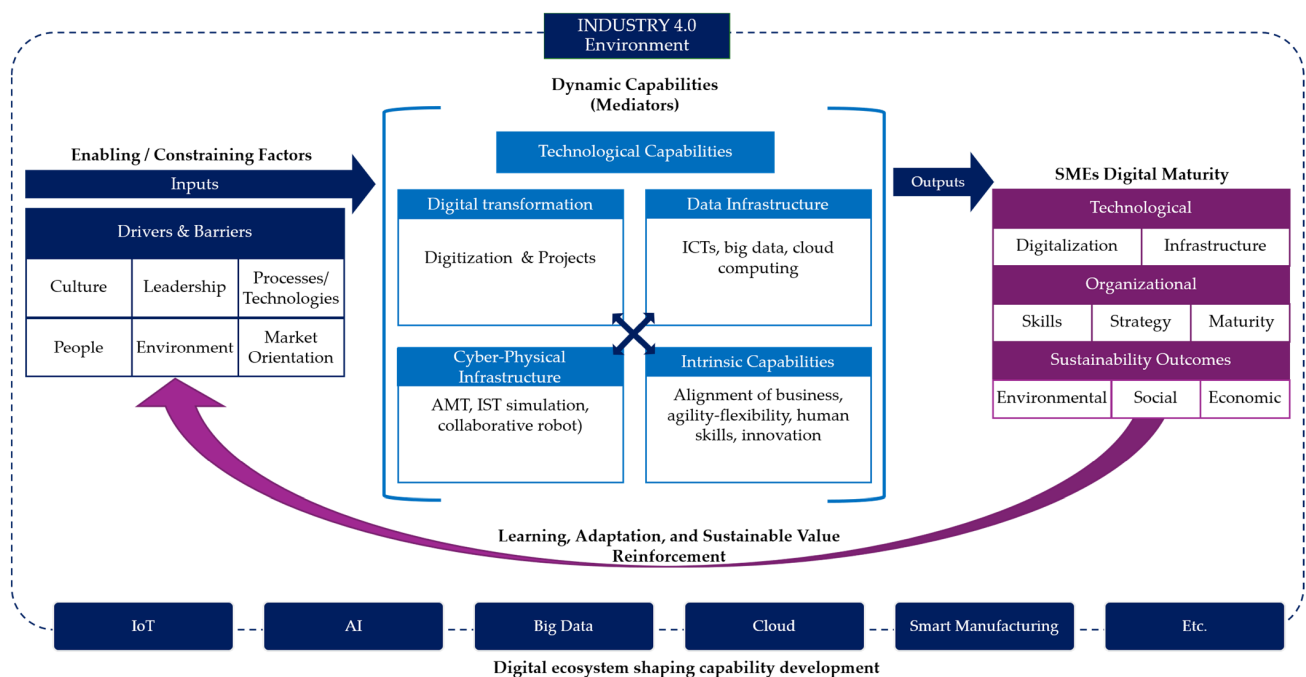


Figure 16. Conceptual baseline of SME digital transformation toward I4.0 maturity.

This baseline illustrates how organizational and environmental factors, as inputs to the system, influence the development of technological capabilities (digital transformation, data infrastructure, cyber-physical systems, and inherent organizational capabilities). These, in turn, determine SMEs' digital maturity. Digital maturity is conceptualized as a multidimensional construct encompassing technological, organizational, and sustainability

outcomes. The model is embedded within the I4.0 environment, highlighting the contextual and systemic nature of digital transformation processes. Building on earlier linear models, the framework introduces an explicit sustainability feedback loop where achieved maturity influences organizational learning, capability reconfiguration, and strategic alignment. This recursive mechanism highlights the ongoing, repetitive process of digital transformation in I4.0 contexts, where constant adaptation is necessary to maintain competitive and sustainable performance.

I4.0 introduces new, advanced technologies by integrating them with existing systems in operations and organization. Therefore, SMEs need to strategically evaluate the technology and digitalization aspects of adopting specific technologies (trending, new, or emerging) to foster positive changes in business management, improve flexibility and speed, and increase productivity, efficiency, quality, competitiveness, and sustainability practices [4,17,101]. This represents a crucial trade-off decision across the short-, medium- and long-term, considering the limited financial resources SMEs can allocate. Any technological approach chosen by these organizations should support the development of a productive business environment, thereby further promoting dynamic capabilities within SMEs [183,206].

Furthermore, HR plays a vital role in the digital transformation of industrial SMEs and their integration into I4.0 environments [30,111]. A company's workforce's digital skills and training significantly impact its ability to adopt and implement new technologies effectively [102,103]. This resource also refers to the relationships and networks a company maintains with other entities and individuals that directly influences its ability to adopt advanced technologies [111]. Therefore, as SMEs plan their technological future, they must determine the necessary HR skills and capabilities, as well as the availability and costs associated with them, to support a sustainable digital transformation [207].

Moving forward, infrastructure is a vital enabler of digital transformation for industrial SMEs, supplying the physical and digital tools needed to implement I4.0 technology solutions. It impacts the performance and reliability of modern equipment, digital platforms, and integrated systems, as well as the ability to create a secure, comfortable, and accessible environment for HR to manage these technologies [114,155]. Therefore, SMEs should define their infrastructure investment requirements not only to enhance technological and digital adoption but also to optimize internal resources and foster external partnerships.

SMEs' digital maturity reflects their ability to identify and capitalize on the benefits of digital transformation. This maturity includes collaborating with business and academic partners by sharing resources and knowledge. It also involves accessing the financial and operational resources needed to invest in technology, along with a focus on innovation and continuous improvement [7,19]. Additionally, maturity models serve as tools for conceptualizing and measuring the maturity of an organization or process to achieve specific goals [80,124]. Therefore, SMEs need a way to assess their level of maturity. As a result, maturity assessment models are developed as tools to understand a company's digital readiness [208]. Ref. [209] states that these models aim to identify the starting point and support the initial development of strategies and processes for adopting I4.0 practices.

While maintaining a customer- and internationalization-focused approach, SMEs need to develop strategies and policies to capitalize on opportunities and tackle challenges in their business environments, leveraging their technological capabilities [76,166]. In this context, industrial SMEs must manage knowledge and information effectively to craft strategic solutions that overcome limited access to financial and technological resources. For example, they can gather insights from supply chain partners on how to secure government support or bank credit for digitalization projects. Following this approach, SMEs can identify organizational and environmental opportunities and challenges related to the potential

effects of implementing specific technologies on productivity, efficiency, competitiveness, sustainability, and flexibility.

SMEs should approach their digital journey and technological capabilities with a focus on sustainability to achieve economic, social, and environmental outcomes. This implies promoting environmentally friendly practices, ensuring responsible resource use, reducing waste, and developing new materials and methods to lower the use of harmful substances.

Finally, a reinforcement loop is vital for learning, adapting, and maintaining value creation. This loop supports ongoing improvement, organizational learning, strategy refinement, and capability development. Therefore, this conceptual baseline emphasizes the importance of integrating I4.0 and sustainability as a continuous, systematic process that involves regular assessment and improvement cycles.

5.2. Theoretical Propositions for SMEs' Sustainable Digital Transformation

Building on the systematic literature review and the conceptual baseline, this section develops four theoretical propositions that integrate the identified technological capabilities and both promoting and inhibiting factors into a capability-based framework. Here, we advance the argument that the organizational, human, technological, and environmental dimensions, previously categorized in Section 4, interact and integrate to shape the development of technological capabilities. Moreover, these propositions underpin the staged roadmap for digital transformation outlined in Section 6. Drawing on the RBV and DCT, the propositions conceptualize digital transformation as a multifaceted, path-dependent process to build capabilities, influenced by organizational, human, technological, and environmental factors to achieve sustainability-oriented outcomes.

Figure 17 illustrates the path for developing the four theoretical propositions and the staged roadmap.

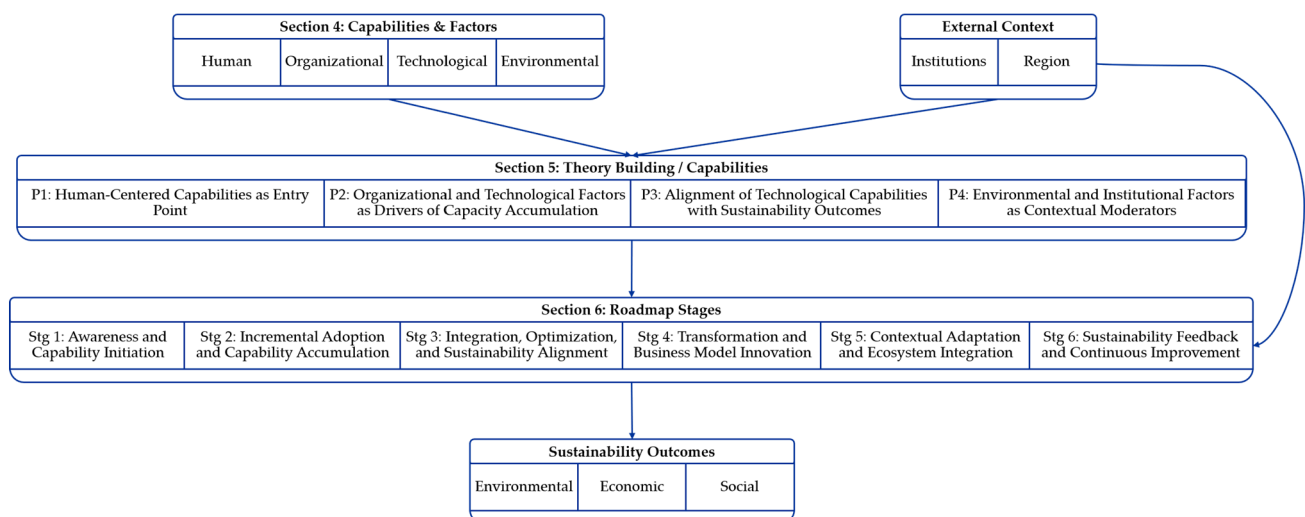


Figure 17. Development of the theoretical propositions.

5.2.1. Human-Centered Capabilities as the Foundation of Digital Transformation

SMEs' digital transformation should be analyzed as a path-dependent process that gradually develops, reconfigures, and deploys capabilities to integrate sustainably into I4.0 environments.

As discussed in Section 4, organizational leadership commitment, strategic orientation, human capital, and organizational culture are identified as the main capabilities and driving factors of digital transformation [108,111,113]. In contrast, resistance to change, a lack of an

innovative corporate culture, insufficient digital skills, and limited managerial vision stand out as key obstacles [7,87,132,141].

These findings show that the initial phase of the digital transformation roadmap largely depends on developing human-centered capabilities. In resource-constrained environments, SMEs lean heavily on their workforce's skills, flexibility, and the strategic vision of their management teams [4,7,17]. From a DCT perspective, human-centered capabilities enable firms to identify digital opportunities, leverage them through strategic decision-making, and reconfigure internal processes accordingly [98,183].

Furthermore, leadership is crucial for cultivating a digital culture, overcoming resistance to change, and aligning technological efforts with the organization's overall goals and vision, including sustainability [15,17,38]. Additionally, leadership commitment fosters an innovative culture that supports experimentation and learning—both essential in the early stages of the roadmap, like digital awareness and initial adoption [98,116].

Additionally, the literature highlights the importance of adopting I4.0 tools that align with business needs, since technological infrastructure alone does not ensure successful digital transformation [33,114]. This also suggests that technology is a latent asset until activated by specific workforce skills, where these skills are the mechanism through which technology (e.g., hardware) and infrastructure become valuable. Therefore, the link between business success, digital infrastructure investment, and I4.0 maturity is a key decision area for industrial SMEs. Additionally, this relationship is positively influenced by human-centered capabilities (e.g., HMI and specialized training) [30].

Additionally, these human-centered capabilities shape how sustainability considerations are integrated from the beginning. Firms that incorporate sustainability into their leadership vision and employee skills are more likely to pursue digital initiatives that use digital technologies to enhance resource efficiency, environmental performance, and social value creation [15,94]. On this basis, Proposition 1 is submitted:

Proposition 1 (P1). *Human-centered capabilities (particularly digital skills, leadership commitment, and organizational culture) constitute the primary drivers of sustainable digital transformation in SMEs by enabling opportunity recognition, strategic alignment, and embedding sustainability objectives.*

5.2.2. Organizational and Technological Factors as Capability Accumulation in Digital Transformation

The evidence presented in Section 4 suggests that SMEs' digital transformation is not a linear process but a cumulative and path-dependent trajectory. The analysis highlights various organizational and technological factors driving this transformation, including data management capabilities, resource availability, process integration, and IT infrastructure [19,114,158,165]. On the other hand, barriers like financial constraints, technological complexity, and lack of integration hinder progress [38]. These factors collectively influence how SMEs progress beyond initial adoption to more advanced stages of transformation, like process digitization and business model innovation [7,33].

SMEs build on accumulated knowledge, existing organizational capabilities, and previous investments in technology, gradually improving their absorptive capacity and ability to adopt more advanced technologies [51,110]. This foundation influences the speed and path of transformation. Furthermore, digital transformation in industrial SMEs follows a path-dependent process, in which intrinsic capabilities (e.g., R&D and innovation culture) are prerequisites for the effective adoption of external I4.0 technologies [98,158,159]. For example, without an internal innovation mindset (intrinsic capability), simply purchasing cloud or IoT services (emergent) will not integrate effectively into the production process.

Firms with a history of incremental digital adoption are better equipped to integrate advanced technologies, as they have the absorptive capacity needed to absorb and exploit new knowledge [111,114].

From the RBV perspective, these accumulated resources and capabilities create a unique asset base that is hard to imitate. At the same time, DCT highlights the importance of ongoing learning and capability renewal, indicating that digital transformation is a continuous process rather than a single event.

Path dependency also implies that late adopters may face structural disadvantages, particularly in rapidly evolving technological environments. However, strategic partnerships and external knowledge acquisition can partially mitigate these constraints [111,143]. Therefore, organizational and technological factors serve as both enablers and constraints at the intermediate stages of the roadmap, shaping the pace and depth of capability development. This raises Proposition 2:

Proposition 2 (P2). *The development of technological capabilities in SMEs is path-dependent, meaning that previous accumulated knowledge, organizational capabilities, and investments in infrastructure and digital tools shape the firm's ability to adopt and scale advanced digital technologies for integration and innovation, leading to sustainable transformation.*

5.2.3. Alignment of Technological Capabilities with Sustainability Outcomes in Advanced Stages

A key contribution of this study is linking digital transformation to sustainability outcomes. The literature shows that technological capabilities (data infrastructure, cyber-physical infrastructure, and intrinsic capabilities) enable SMEs to optimize resource use, reduce waste, foster innovation, and boost operational efficiency [15,98]. These improvements translate into environmental benefits (e.g., energy efficiency, reduced emissions), economic gains (e.g., cost reductions, productivity gains), and social value (e.g., improved working conditions, customer engagement) [17]. Particularly, integrating digital technologies across supply chain management, logistics, and production processes supports the transition toward greener, more resilient business models [83,143,210].

However, achieving these benefits depends on the strategic alignment between digital initiatives and sustainability objectives [17,38]. Promoting factors (e.g., strategic alignment and an innovation orientation) enable SMEs to leverage digital technologies for sustainability, while inhibiting factors (e.g., a lack of sustainability awareness or short-term focus) limit this potential. Thus, technological capabilities should not be viewed as neutral tools, but as strategic enablers that can either reinforce or hinder sustainability depending on their configuration and deployment [17,114].

As SMEs progress toward full digital integration and business model transformation, the alignment between technological capabilities and sustainability goals become crucial. At advanced stages of digital maturity, companies can implement solutions that optimize resource use, minimize environmental impact, and increase social value. Therefore, this proposition further elaborates the analysis by explicitly linking driving factors to sustainability outcomes, positioning technological capabilities as mediators between digital transformation and sustainable performance. Thus, Proposition 3 states as follows:

Proposition 3 (P3). *Technological capabilities that are strategically aligned with sustainability objectives allow SMEs to improve environmental performance, resource efficiency, and social value creation, thereby progressing the digital transformation roadmap to more advanced stages.*

5.2.4. Environmental and Institutional Factors as Contextual Moderators of the SMEs' Digital Transformation Roadmap

The findings also underscore the importance of the external environment in shaping SMEs' digital transformation processes. Institutional and environmental factors (e.g., regulatory frameworks, access to financing, digital infrastructure, and innovation ecosystems) can either facilitate or hinder the development of capabilities faced by SMEs at all stages of the roadmap [2,38,76,98]. Also, these factors vary significantly across regions [107,116,141].

In developed economies, SMEs generally benefit from stronger institutional support, advanced infrastructure, and broader access to digital ecosystems [114]. In contrast, SMEs in developing regions often face barriers such as regulatory uncertainty, resource shortages, and limited connectivity [141]. These contextual differences influence both the adoption of digital technologies and their capacity to generate sustainability outcomes [38,114].

With this in view, the roadmap (Section 6) implicitly assumes a passage from basic to advanced stages of transformation; however, the feasibility and speed of this progression depend on regional and institutional contexts. SMEs operating in resource-rich environments with strong institutional support are more likely to advance rapidly, whereas those in constrained contexts might face delays or require alternative strategies [125]. As the efficacy of I4.0 maturity models is moderated by the regional and institutional environments, SMEs in developing economies require higher levels of collaborative capabilities (partnerships and ecosystems) to compensate for weaker national digital infrastructure [149].

From a DCT and RBV perspectives, the ability to recognize and seize opportunities is inherently context-dependent, as it hinges on the institutional environment in which they operate. Therefore, environmental factors should be understood as moderators that influence the effectiveness of internal capabilities and the overall path of transformation. Therefore, Proposition 4 is as follows:

Proposition 4 (P4). *The institutional and regional environment influences the development and effectiveness of technological capabilities in SMEs, impacting both the speed of digital technology adoption and their contribution to sustainability outcomes of SME transformation.*

6. A Capability-Based Roadmap for Sustainable Digital Transformation in SMEs

This section articulates the four theoretical propositions as a capability-based roadmap that outlines how SMEs can systematically advance through digital transformation while achieving sustainability-oriented outcomes. The roadmap operationalizes Propositions 1–4 into a phased, dynamic process, in which each stage depends on specific capabilities and is influenced by both internal and external factors; thereby bridging the gap between theoretical insights and managerial practice.

Figure 18 illustrates the development of the capability-based roadmap.

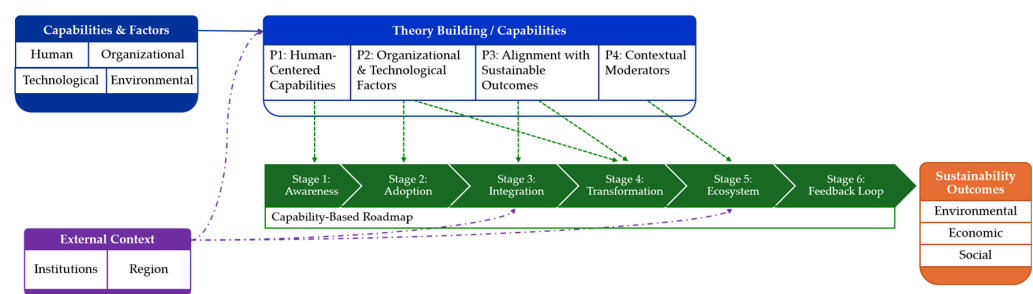


Figure 18. Capability-based roadmap.

6.1. Stage 1: Awareness and Capability Initiation

The initial stage centers on fostering core human-centered skills and increasing awareness of digital transformation. As outlined in P1, leadership commitment, organizational culture, and digital skills are crucial at this stage. Hence, the first step for SMEs is to recognize the strategic importance of digital transformation, identify its critical processes to boost competitiveness and achieve sustainability. This involves nurturing a shared vision among managers and employees, promoting openness to change and innovation, and providing basic digital skills training.

At this stage, SMEs need to integrate sustainability considerations into their strategic planning and goals. Due to limited resources, SMEs often focus on efficiency-driven goals (economic sustainability); however, by embedding environmental and social objectives early on, these firms ensure that future technological adoption aligns with broader sustainability aims.

However, inhibiting factors (e.g., lack of skills and resistance to change) often limit progress. Overcoming these barriers involves targeted actions, including employee training, leadership engagement, and external advisory support.

6.2. Stage 2: Incremental Adoption and Capability Accumulation

The second stage involves gradually adopting digital technologies and building organizational and technological capabilities. In line with P2, this phase is marked by path-dependent development, in which accumulated experience and prior investments shape future transformation paths.

SMEs start by adopting basic digital tools (e.g., digital communication platforms, enterprise systems, and cloud solutions) to boost operational efficiency. These initial efforts improve the company's ability to absorb new technologies, allowing it to adopt more advanced systems and technological solutions over time.

As previously discussed, organizational factors (e.g., process integration and resource availability) are crucial at this stage. At the same time, constraints like technological complexity and limited financial resources can slow down progress.

From a sustainability perspective, this stage offers opportunities to achieve early gains in resource efficiency, such as optimizing energy use, reducing paper consumption, improving logistics coordination, and identifying unnecessary waste. These incremental improvements lay the foundation for more substantial sustainability outcomes in later stages.

The firm needs to promote an entrepreneurial orientation to foster an organizational culture of proactiveness, innovation, and willingness to take strategic risks. It should also encourage collaborative efforts with external partners, such as supply chain partners or academic institutions. When well understood and implemented, technological capabilities provide the means to manage information and knowledge, enhancing strategic, tactical, and operational decision-making processes. Information and knowledge management enable SME decision-makers to identify opportunities to access new resources, government support, customers, or partners, and to recognize critical risks that could lead to further weaknesses.

6.3. Stage 3: Integration, Optimization, and Sustainability Alignment

P3 emphasizes that aligning technological capabilities with sustainability goals is crucial. Therefore, at the third stage, SMEs move from isolated digital efforts to fully integrating and optimizing technologies throughout their business processes.

Firms leverage advanced tools (e.g., AI platforms, data analytics, and automation) to enhance decision-making, streamline operations, and generate value. The adoption

of these technologies allows SMEs to achieve significant improvements in productivity and innovation.

At a fundamental level, this stage marks a turning point at which digital transformation can be intentionally and explicitly aligned with sustainability goals. SMEs can implement solutions that support waste reduction, circular-economy practices, and energy efficiency, particularly in production processes and supply chain management. The fruition of these benefits relies on strategic alignment. Firms that neglect to integrate sustainability considerations into their digital strategies risk failing to exploit the transformative potential and competitive advantages of their technological capabilities.

6.4. Stage 4: Transformation and Business Model Innovation

The fourth stage involves reconfiguring business models and fully integrating digital technologies into the SME's value-creation process. This stage highlights the cumulative, dynamic, and path-dependent nature of capability development (P2) and aligns strategically with sustainability outcomes (P3).

SMEs at this stage shift from process optimization to innovation-driven transformation. They may develop digital services, adopt platform-based models, or redesign their value propositions to include sustainability as a key element, for example, real-time data integration for sustainable supply chain management, the implementation of digital platforms for circular business models, and the development of customer-focused digital services that encourage responsible consumption. Therefore, this fourth stage requires advanced dynamic capabilities, including the ability to continuously respond to market changes, reconfigure resources, and adopt new technologies. It also calls for a long-term strategic perspective that balances economic performance with environmental and social pursuits.

6.5. Stage 5: Contextual Adaptation and Ecosystem Integration

This fifth stage stresses the importance of institutional and environmental factors, as highlighted in P4. Therefore, SMEs need to tailor their digital transformation strategies to the institutional and regional contexts in which they operate.

At this stage, firms actively engage and collaborate with external ecosystems, including technology providers, industry networks, innovation hubs, and government programs. Access to financing mechanisms, digital infrastructure, and regulatory support becomes essential for maintaining transformation efforts.

The feasibility and pace for advancing through the roadmap are heavily influenced by these contextual factors. SMEs in developed areas may benefit from advanced infrastructure and supportive policies, while those in developing regions may need to take more incremental or adaptable steps.

Finally, this stage highlights that digital transformation is not just an internal process but a systemic one, embedded within wider socio-technical and institutional environments. Successful SMEs align internal capabilities with external opportunities and constraints.

6.6. Stage 6: Feedback Loop and Continuous Improvement

This final stage establishes a feedback loop where digital maturity outcomes guide future strategic decisions and capability development. Digital transformation is increasingly seen as a crucial enabler of long-term resilience and sustainability in SMEs, helping to align with broader sustainability objectives. This phase underscores the iterative, evolving nature of digital transformation and promotes the use of long-term research approaches.

Overall, the proposed roadmap provides a theoretically grounded and comprehensive guide for industrial SMEs to navigate their digital transformation. By explicitly linking each stage to the underlying propositions, this roadmap ensures coherence be-

tween theory and practice while addressing current gaps in the literature on sustainable digital transformation.

7. Conclusions

This study offers both theoretical and practical contributions. Based on a sequential-stage, semi-systematic literature review method, 20 clusters were generated, from which we selected 9 (digital technologies, information technology, digital transformation, open innovation, smart manufacturing, agility, projects, big data, and data collection). From a theoretical perspective, the study provides conceptualizations of digital transformation and technological capabilities for industrial SMEs within the context of I4.0, offering an alternative to existing definitions. The study provides a systematic framework for determining the technological capabilities of industrial SMEs and found that technological capabilities and resources positively foster digital transformation, enabling SMEs to identify, manage, evaluate, and innovate in emerging technologies to enhance the competitiveness of their business sectors.

Given that digital transformation is a key factor in integrating SMEs into Industry 4.0, the factors that promote or inhibit it were identified. Factors that facilitate the integration of SMEs into Industry 4.0 include organizational culture, the environment in which they operate, leadership strategies, market orientation, processes and operations, and human resources. The most relevant factors identified as promoting digital transformation are technological availability, access to financial resources for operations, investment (innovation, employee training, technologies, etc.), competitiveness and productivity, and the skills to adopt technologies. Additionally, several factors that inhibit incorporation into Industry 4.0 are systematized: an organizational culture without focus, a lack of government policies, a lack of technology, a loss of leadership, and a lack of trained human resources.

Furthermore, this research proposed four theoretical propositions outlining a pathway towards sustainable digital transformation in SMEs that results from the interaction between internal capabilities and external contextual factors. Human-centered capabilities provide the basis for recognizing and seizing opportunities, while path-dependent processes influence technological capabilities over time. When aligned with sustainability goals, these capabilities lead to multidimensional performance outcomes. Finally, regional and institutional contexts determine how effectively these processes can be implemented.

The proposed framework thus creates a theoretically grounded (Section 5) connection between empirical observations (Section 4) and practical guidance (Section 6), providing a comprehensive view for understanding and implementing SME digital transformation.

Due to its qualitative design, this SLR has limitations. This review encompassed 117 articles, primarily published in English, from prominent academic journals in the research areas of digital transformation, technological capabilities, industrial SMEs, and I4.0. However, this only represents a sample of the scientific publications related to the study. Furthermore, the selected databases and the analysis period may have missed some articles relevant to this research. Finally, although this work provides an explicit theoretical framework to define and structure the relationships among technological capabilities, digital transformation, the driving factors and sustainability outcomes for achieving an I4.0 environment, further work is required to develop empirical predictions or to define a specific domain.

Future studies should include maturity models for industrial SMEs and complement this study's findings to assess the current state of the firms and provide a starting point, thereby enabling the creation of empirical roadmaps that will allow organizations to base their decisions on their intrinsic variables, thereby enhancing their incorporation into I4.0. Furthermore, it would develop an evaluation model for SMEs that integrates variables

related to digital transformation and their interrelationships, providing an appropriate, focused guideline that allows firms to concentrate their efforts on the aspects they need to enhance I4.0 adoption.

Finally, it is necessary to evaluate the proposed framework in SMEs across countries at different levels of development and to perform a differentiated analysis by specific industries, such as manufacturing and processing, to determine its applicability to the environments in which the firms operate and to provide more targeted guidance for various enterprises.

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Abbreviations

The following abbreviations are used in this manuscript:

SMEs	Small and medium-sized enterprises
I4.0	Industry 4.0
IoT	Internet of Things
GDP	Gross domestic product
WTO	World Trade Organization
AI	Artificial intelligence
R&D	Research and development
CNC	Computer Numerical Control
ERP	Enterprise resource planning
MTM	Machine-to-machine
HMI	Human–Machine Interconnection
RBV	Resource-based view
DCT	Dynamic capability theory
IIoT	Industrial Internet of Things
BD	Big data
ML	Machine learning
ICTs	Information and communication technologies
ISTs	Intelligent Sensors Technologies
Cobots	Collaborative Robots
AGVs	Automated guided vehicles
HM	Human resources

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