TEM-23-0821

Barriers and Enablers for Industry 4.0 in SMEs: A Combined Integration Framework

Julian M. Müller, Nazrul Islam, Nikolai Kazantsev, Rubina Romanello, Gilson Olivera, Debabrata Das, and Reza Hamzeh

Abstract— **Although Industry 4.0 was introduced a decade ago, many small and medium-sized enterprises (SMEs) still have not adopted several technologies. Therefore, integrating SMEs along horizontal, vertical, and end-to-end engineering dimensions remains challenging. Due to the importance of SMEs for industrial value chains, understanding SMEs' barriers and respective enablers for Industry 4.0 integration is vital. Applying a multiple case study approach, this paper investigates their experience in Industry 4.0 through technological, organizational, and environmental factors. We aggregate the barriers and respective enablers to Industry 4.0 into an integration framework, which helps to understand Industry 4.0 in SMEs from a broader viewpoint inside these firms, upstream and downstream supply chains, and beyond manufacturing. The findings show that the success of Industry 4.0 integration is more oriented toward operational benefits than strategic advantages and depends upon how these technologies are integrated with various stakeholders across the supply chain, such as original equipment manufacturers, R&D agencies, or sub-suppliers.**

Index Terms— **Industry 4.0, Barriers, Enablers, Small and Medium-Sized Enterprises, Digitalization**

I. INTRODUCTION

INDUSTRY 4.0, a new paradigm to digitally enable horizontal and vertical interconnection of industrial value creation, has gained broad interest in academic research and managerial practice (Xu et al., 2018). Based on the concept's initial introduction by the German government in 2011, Industry 4.0 has three central characteristics: horizontal interconnection, vertical interconnection, and end-to-end engineering (Kagermann et al., 2013). Vertical interconnection describes the digital interconnection within enterprises, i.e., different company functions. Horizontal interconnection refers to digital interconnection across company boundaries, i.e., the supply chain. Further, end-to-end engineering describes interconnection from product development, production, usage, and recycling, i.e., following the entire product lifecycle (Kagermann et al., 2013).

The core technologies of Industry 4.0 are centered around Cyber-Physical Systems (CPS) and the Internet of Things (IoT). While the former allows merging the virtual and real worlds and data collection through sensors, the IoT enables data transmission between humans, products, and production facilities. Data evaluation and simulation will be enabled based on artificial intelligence or big data analytics in cloud computing environments. Several named technologies or their predecessors were known before the concept of Industry 4.0. However, their broad integration, increased amount of sensors and thus data to be analyzed, and comprehensive digital interconnection allow horizontal and vertical integration and end-to-end engineering that was impossible before (Kagermann et al., 2013). In addition to those "base technologies" of Industry 4.0, "front-end technologies" (Frank et al., 2019) include prominent examples such as additive manufacturing, smart robots, or augmented and virtual reality (Mittal et al., 2020; Xu et al., 2018).

Despite their importance for industrial value creation, Small and Medium-Sized Enterprises (SMEs) struggle to be integrated within Industry 4.0 (Moeuf et al., 2018, 2020; Müller et al., 2018, 2022). This is due to several characteristics of SMEs: First, SMEs typically have no access to information flows within the supply chain (Moeuf et al., 2018, 2020; Müller et al., 2018). Hence, they have a limited intention to share their operational data, representing a central requirement for Industry 4.0. Second, due to low levels of standardization, SMEs cannot take advantage of economies of scale required for many Industry 4.0 technologies, such as data analytics (Estensoro et al., 2022). However, the entire supply chain cannot be digitally integrated without those technologies, which are further prerequisites for Industry 4.0 (Schmidt et al., 2023). Third, SMEs typically have difficulties accessing financial resources or lack skills and access to trained personnel. This limits their capabilities, especially in areas like data curation or cybersecurity, where they cannot present adequate solutions for their customers (Arroyabe et al., 2024; Estensoro et al., 2022).

Regardless of the rapid increase in the literature on Industry 4.0, there is limited empirical evidence of Industry 4.0 adoption among manufacturing SMEs beyond one or two countries

Julian M. Müller is with Erfurt University of Applied Sciences, Germany, Seeburg Castle University, Austria and Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany.

Nazrul Islam is with the Royal Docks School of Business and Law, University of East London (University Square Stratford), London, E15 1NF, U.K. (e-mail: Nazrul.Islam@uel.ac.uk). (Corresponding author)

Nikolai Kazantsev is with the Institute of Manufacturing, University of Cambridge, U.K.

Rubina Romanello is with Università degli Studi di Trieste, Italy. (e-mail: rubina.romanello@units.it). (Corresponding author)

Gilson Olivera is with Universidade Tecnológica Federal do Paraná, Brazil.

Debabrata Das is with Indian Institute of Management Mumbai, India.

Reza Hamzeh is with Mechanical Engineering and Manufacturing Systems, The University of Auckland, New Zealand

(Müller & Voigt, 2018). Particularly, extant research has explored this phenomenon in specific areas of the world, such as the European Union (e.g., Müller et al., 2018, 2022; Moeuf et al., 2018, 2020), United States (e.g., Mittal et al., 2018, 2020), and Brazil (e.g., Frank et al., 2019). Therefore, Industry 4.0 experiences in SMEs are fragmented and are rarely put together and analyzed for international contexts (Müller & Voigt, 2018). In this context, our research investigates the barriers and respective enablers emerging during the adoption process by analyzing Industry 4.0 adopters in different settings.

For this purpose, we conducted a multiple case study to grasp different perspectives worldwide in an exploratory approach that investigates both barriers and respective enablers to overcome those barriers. As many supply chains consist of SMEs as suppliers worldwide, this approach is relevant for understanding global value chains and managerial practice. We investigate 15 SMEs regarding their Industry 4.0 adoption that operate in 10 different countries and industries. Drawing from the Technology-Organization-Environment framework, we propose an integrated Industry 4.0 integration framework consisting of the interplay of barriers to Industry 4.0 adoption in SMEs and the enablers needed to approach them, which we captured from the literature review and multiple case study on Industry 4.0.

The results are organized according to the framework of four central characteristics of Industry 4.0: vertical integration inside SMEs, horizontal integration upstream existing supply chains, horizontal integration downstream existing supply chains, and end-to-end engineering leading to customers. We propose an integration model for the Industry 4.0 integration process in SMEs, focused on benefits, barriers, and solutions based on national SMEs' experiences. Based on this, we discuss several recurring patterns relevant to developing the SMEs' integration model. The study contributes that while some country-specific factors exist, general integration barriers can be observed regardless of national contexts. Notably, the integration of suppliers relating to the specific nature of products and services of the respective SME can be decisive in supporting SMEs on their path towards Industry 4.0 (Schmidt et al., 2023).

SME managers, their counterparts in large enterprises, or policy representatives can use the combined implementation framework based on data from ten countries to better understand their progress in terms of Industry 4.0 adoption. While barriers to Industry 4.0 adoption for SMEs are well-known, especially their direct interrelation with technological, organizational, and environmental enablers to overcome those barriers offers valuable insights for managers.

The remainder of this paper is organized as follows. Section 2 presents an overview of extant literature regarding barriers to Industry 4.0 adoption, addresses research gaps, and outlines the TOE framework. Section 3 explains the method, followed by the results in section 4. The results are then transferred into an integration framework in section 5, followed by contributions to theory, literature, and managerial implications. Section 6 concludes the paper with limitations and avenues for future research.

II. Literature Review

II.1 The barriers to Industry 4.0 adoption in SMEs

Integrating Industry 4.0 technologies among SMEs is crucial for successful integration across global value chains (Horváth & Szabó, 2019; Müller et al., 2018). In this context, the driving factors are strongly related to the expected outcomes regarding innovation, productivity, flexibility, efficiency, environmental sustainability, and quality improvements (Cugno et al., 2022). In contrast to large enterprises, SMEs struggle with limited resources, niche-oriented business models, low levels of automation, and unstandardized operative processes (Horváth & Szabó, 2019; Mittal et al., 2018; 2020; Müller & Buliga, 2019). Industry 4.0 adoption entails a certain degree of complexity for SMEs because each technology can be implemented in different value chain activities following specific purposes while possessing limited resources (Estensoro et al., 2022).

Past studies have highlighted perceived barriers in this process on the one hand but also underlined potential drivers for Industry 4.0 integration (Estensoro et al., 2022). For example, technological awareness might represent a pivotal barrier to selecting and adopting Industry 4.0, mainly since there is a potential time lag between technological investments and expected returns. Another barrier can depend on the lack of finance that typically characterizes SMEs, while Industry 4.0 investments tend to be capital and resource-intensive (Moeuf et al., 2018; 2020; Müller et al., 2018). Other challenges derive from the organizational transformation, especially regarding data standards and interfaces across company boundaries. In this sense, SMEs often encounter difficulties collaborating with partners, particularly when it requires integrating production data (Estensoro et al., 2022).

Furthermore, due to SMEs' limited financial resources required to develop complex enablers independently (Stentoft et al., 2020), the interconnection between SMEs and their suppliers and customers can only be achieved through close connection integration. However, this is a barrier for SMEs since they cannot afford full system integration. They struggle to establish reciprocal collaboration rules in the supply chain alongside high contracting and coordination costs (Kazantsev et al., 2022). Hence, SMEs risk getting lost in this transition toward Industry 4.0 (OECD, 2021).

II.2 Research Gap and Research Question

Table I below highlights the research gap addressed by this paper. It explains the main focus of extant publications on Industry 4.0 in SMEs and their primary focus.

TABLE I
SELECTION OF EXTANT PUBLICATIONS ON BARRIERS AND ENABLERS OF INDUSTRY 4.0 IN SMES

Reference	Main Focus	Differentiation
Agostini and Nosella (2019)	Adoption of Industry 4.0 technologies in SMEs	Focused on six European regions rather than concentrate on management support and

		absorptive capacity as enablers
Brodeur et al. (2023)	Organizational changes to facilitate Industry 4.0 integration in SMEs	Focused on only one country (US) and a single SME, focus on organizational aspects
Dutta et al. (2021).	Factors for quality control processes of Industry 4.0 in SMEs	Focused on only one country (India), the main focus is on quality aspects and not enablers and barriers
Dutta et al. (2020).	Maturity framework of Industry 4.0 adoption in SMEs	Focused on only one country (India), the main focus is on maturity factors and levels, but not their enablers and barriers
Estensoro et al. (2022)	Drivers for SMEs towards more advanced stages of Industry 4.0	Focused on only one region (Basque Country, Spain), lacking specific barriers
Ghobakloo et al. (2022)	Technological determinants of Industry 4.0 adoption in SMEs	Not based on empirical data (literature analysis)
Ghobakloo and Ching (2019)	Determinants of Industry 4.0 technology adoption in SMEs	Focused on two countries (Iran and Malaysia), rather factors for adoption than barriers
Kumar et al. (2020)	Challenges of Industry 4.0 integration towards ethical and sustainable targets in SMEs	Focused on only one country (India), no analysis of enablers
Masood and Sonntag (2020)	Industry 4.0 adoption Challenges and Benefits for SMEs	Focused on only one country (UK), mainly focused on performance or financial indicators
Moeuf et al. (2020)	Critical success factors, risks, and opportunities of Industry 4.0 in SMEs	Based on a Delphi study rather than primary data from SMEs, no international focus
Müller and Voigt (2018)	Potentials and challenges of Industry 4.0 for SMEs in the context of sustainability	Focused on two countries (Germany and China), rather potentials than concrete enablers
Stentoft et al. (2020)	Drivers and barriers for Industry 4.0 readiness and integration in SMEs	Focused on only one country (Denmark), foremost relating to strategy, management, and workforce

Conclusively, while several publications exist on drivers or barriers of Industry 4.0 integration in SMEs, an empirical approach combining data from several countries worldwide cannot be found in extant literature (Müller et al., 2022). Thus, our study aims at answering the following research question (RQ): Which barriers impede SMEs from Industry 4.0 integration, and which enablers can help overcome them?

II.3 The TOE framework

Past research has identified the lack of experience in SMEs, especially a limited number of explicit adoption and integration models reflecting the specific requirements and challenges of SMEs (Estensoro et al., 2022; Mittal et al., 2018), targeted aspects for Industry 4.0 integration (Veile et al., 2019) and adoption patterns (Frank et al., 2019). For this reason, it is urgent to investigate barriers and respective enablers of Industry 4.0 among SMEs in different settings to expand limited extant knowledge from single countries (Khanzode et al., 2020; Raj et al., 2020).

To conceptualize the barriers and solutions of SMEs towards Industry 4.0, this paper utilizes the Technological, Organizational, and Environmental (TOE) framework (DePietro et al., 1990). Several authors have used the TOE framework in the context of Industry 4.0 and SMEs, such as Ghobakloo and Ching (2019), Ghobakloo et al. (2022), Marrucci et al. (2023), and Raj and Jeyaraj (2023). Extending their mostly literature-based results, we give empirical insights and extend their literature reviews on TOE-related enablers and barriers of Industry 4.0. Further, we extend Marucci et al. (2023) regarding further dimensions and in an international context. Thus, we argue it is a reasonable choice and offers the opportunity to compare results, as done in our discussion section. As a novel contribution of this paper, we combine empirical data from ten countries, as described in the next section.

III. Research Method

We chose a multiple case study approach (Eisenhardt, 1989; Yin, 2009) to identify barriers and enablers related to Industry 4.0 by investigating a sample of 15 SMEs in 10 different countries across five continents. Since the majority of extant research is limited in either geographical scope or only investigates a part of our research scope (see Table 2 above), we decided to use a case study approach (Eisenhardt, 1989; Miles & Huberman, 1994) which is appropriate when collecting initial empirical evidence about new phenomena in an exploratory manner. Further, a case study approach enabled us to combine the TOE framework with barriers for SMEs in horizontal integration, vertical integration, and end-to-end engineering, allowing us to draw how and why connections (Eisenhardt, 1989).

III.1 Cross-country analysis procedure

Cross-country qualitative comparisons can be criticized for lacking trustworthiness due to bias and equivalence (Sinkovics et al., 2008). Therefore, we adopted rigorous case selection and data collection and analysis procedures to ensure data comparability. Specifically, we developed a unified research design (Eisenhardt, 1989; Yin, 1993), including four empirical research steps: problem definition, data collection, data preparation, and data analysis.

To reduce equivalence bias, we developed a unified research objective and assessed the phenomenon of Industry 4.0 in different foreign countries (Sinkovics et al., 2008). Then, we agreed on the Industry 4.0 definition based on Kagermann et al. (2013) and identified an initial framework upon which we organized the semi-structured questionnaires. All international co-authors who conducted the interviews were briefed on the different applications and functionalities of Industry 4.0 technologies to avoid linguistic or interpretation biases.

III.2 Case Selection

We involved country investigators from different countries to collect data from SMEs in different socio-economic, cultural, and institutional environments by including advanced and emerging economies and ensuring the representativeness of different continents. We have selected 15 leading SMEs in 10 countries to derive cross-country evidence on implementing Industry 4.0 (George et al., 2005), which are country-level similarities and differences.

As a result, we developed an international comparative analysis of Industry 4.0 adoption among the leading SMEs in

Brazil, Germany, India, Iran, Italy, New Zealand, Poland, Russia, South Africa, and the UK. Thus, we can report from established industrial economies in Europe (Germany, Italy, UK) and Poland, a European country that has undergone significant transitions in its manufacturing industry. Brazil and India represent developing economies with huge potentials from Southern America and Asia. Iran, New Zealand, Russia, and South Africa represent comparably established industrial nations but with different cultural backgrounds and thus enrich our international understanding of Industry 4.0 adoption in SMEs. We note that countries like China, Japan, Korea, or the US are not included in our analysis. Still, we expected comparable results (on a global scale) as for India or established European countries, respectively.

As definitions of SMEs vary due to the variety of settings, we mainly applied the EU Recommendation (2003/361): SMEs with up to 250 employees and a turnover of fewer than 50 million Euros. Since local currencies vary, we referred to the local definition for the financial aspect. For instance, in South Africa, SMEs are defined with less than R64 million annual turnover or less than R10 million in capital assets. Further, India defines SMEs by financial criteria, such as capital expenditure of less than INR 500 million (OECD, 2021).

As case selection must be carefully developed to generate meaningful results (Yin, 2009), we leveraged the researchers' local knowledge of Industry 4.0 projects to identify and select leading SMEs that had adopted Industry 4.0 core technologies over the last five years. We used a purposive sampling approach (Miles & Huberman, 1994), following a theoretical sampling strategy for companies according to the following key criteria: (1) have less than 250 employees as per the EU definition and a maximum turnover of 50 million Euros or an alternative, local financial boundary (see above); (2) have already successfully implemented core Industry 4.0 technologies; 3) have the ultimate goal of implementing the Industry 4.0 concept in the long run; 4) be established companies and not start-ups. These four selection criteria were used to ensure comparability in the first place.

Secondly, our selection reflected the purpose of including SMEs with comparable features and similar implemented Industry 4.0 technologies. For instance, we focused on metals, electronics, automotive, and machinery industries as the primary target sectors of Industry 4.0 (Kagermann et al., 2013). Whereas the exact products vary, the Industry 4.0 solutions adopted include specific IoT applications, often alongside sensor technologies, robotics, or cloud-based technologies (Frank et al., 2019).

Table II below shows the contents described above with our international sample of 15 manufacturing SMEs.

TABLE II
MAIN CHARACTERISTICS OF CASE STUDY COMPANIES

Firm Index	Country	Firm Age	Sector	Empl.	Turnover, mln.	Main products	Examples of Industry 4.0 solutions employed
BR	Brazil	19	Metals	250	86 (BR)	Laminates	Cloud Computing, Big Data, Additive Manufacturing, robots, IoT
GE1	Germany	42	Electronics	100	10 (EUR)	Circuit board components	Production load and forecast sharing with customers and suppliers, IoT
GE2	Germany	19	Automotive	240	30 (EUR)	Car interior	Process data mining with supply chain partners, IoT
IN1	India	27	Machinery	105	4.2 (USD)	Special-purpose machinery	Additive manufacturing, robots, IoT, Cloud ERP
IN2	India	23	Electro-mechanical	200	39 (USD)	Commutator switches, Switchgear	Industrial robots, IoT
IR1	Iran	22	Metals/ Auto	42	3.6 (USD)	Various types of fasteners	Smart sensors, computer vision, robots, additive manufacturing, AI-based production scheduling and control, IoT
IR2	Iran	17	Machinery	63	65 (USD)	Passenger conveyors, escalator lifts	Cloud resource planning, AI-based automated precision testing, additive manufacturing, robots, simulation, IoT
IT	Italy	19	Metals & Machinery	38	7 (EUR)	Precision mechanics	Interconnected machines, robots and cobots in IoT
NZ	New Zealand	48	Steel	150	50 (USD)	Steel components for construction	Cloud-based control system, IoT, AI-based production scheduling and control, Digital Twin
PL	Poland	40	Mining machinery	230	43 (EUR)	Drilling and anchoring machines	Embedded systems, IoT, robots
RU1	Russia	25	Electronics	100	1.5 (USD)	GPS terminals	Sensors for data

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3365771

						and fuel level sensors	integration, IoT
RU2	Russia	20	Electronics	75	1.5 (USD)	Multilayer printed circuit boards	QR-based feed automation system, IoT
SA	South Africa	2	Agriculture Machinery	100	4.8 (SAR)	Poultry	Cloud platform, IoT IoT sensors
UK1	UK	35	Automotive	130	10 (GBR)	Composite parts	IoT sensors and robotics
UK2	UK	10	Automotive	78	5 (GBR)	Tooling products	IoT sensors and robotics

III.3 Data Collection

To ensure the comparability of data, a researcher with background experience in international research coordination was instructed to coordinate data collection and analysis. Qualitative data was collected through in-depth interviews based on a semi-structured questionnaire in English, which was translated into each national language. The questionnaire translation was validated through double and reverse translation: from the original language to English and back. It reduced construct and item bias related to poor or inadequate item formulations (Sinkovics et al., 2008). In addition, the content was pre-tested with several SME representatives to identify deceptive or unclear questions, which were then improved accordingly. Data was collected between September and December 2020. Interviews were recorded and transcribed. The content of the interviews referred to the selection and integration process of Industry 4.0 technologies, barriers and enablers, their relation to horizontal and vertical integration, as well as end-to-end engineering, and additional questions on the firm background and characteristics. Besides, to increase the reliability of results and reduce observer bias, we performed data triangulation with external sources like websites and national databases (Welch & Piekkari, 2017).

An initial interview protocol was developed to ensure the homogeneity of findings (Yin, 2009) and rigorously followed for data collection and analysis. The research coordinator kept a supervising role by stimulating discussion and critical analysis. Researchers in each country focused on their country's contexts and independently interviewed companies' respondents.

III.4 Data Analysis

The answers were inductively coded through an interpretive process of detailed reading and reviewing the content, and the descriptive codes were allocated into interpretive codes. We used preliminary defined themes (interpretive codes) using 12 categories of barriers (Raj et al., 2019) to arrange the data. The codes were allocated for horizontal integration (upstream), vertical integration, horizontal integration (downstream), and end-to-end integration (Kagermann et al., 2013). For the group of barriers, we organized data according to the Technology–Organization–Environment (TOE) framework (DePietro et al., 1990). Table A in the Appendix illustrates the results of cross-case analysis based on data coding according to the TOE framework.

We stopped data collection when we reached saturation, as the improvements brought by additional cases were considered marginal (Eisenhardt, 1989). When the analysis no longer identified new codes, we confirmed theoretical saturation and the structure of the final coding schemes. Inter-coder reliability was ensured by following an iterative process for analyzing content using documented peer-review and reflection of our coding, contributing to the reliability of the study (Miles & Huberman, 1994). External validity was ensured by reviewing previous literature on Industry 4.0 and SMEs to remove the observer bias (Eisenhardt & Graebner, 2007).

To allow the comparability of data, we uploaded all the data to the specialized software (NVIVO 9.2). We used it as a database to derive a final table (Table A in the Appendix). Then, we carefully compared emergent frames against the evidence from each case to assess how well they fit the case data. This process led to the identification of cross-case patterns (Yin, 2009). Next, the lead author checked translation consistency with the national representatives to reduce interpretation and linguistic barriers. Finally, national representatives cross-validated the findings, and the team discussed to achieve a consensus when deviations emerged.

As this paper aims to develop an integration model that is valid and generalizable for many SMEs worldwide, we did not focus on the individual level of each SME despite having done this individual analysis. However, Section 4 and Table A in the Appendix do not refer to SME-specific aspects aside from some country-specific findings.

IV. Findings

VI.1 Barriers and enablers for Industry 4.0 integration

SMEs from several countries agree on central barriers, such as the high cost of implementing technologies, unclear return on investments, and the lack of digital skills to benefit from Industry 4.0. The continuous exchange of data along the entire supply chain leads to increased transparency, initially a potential of Industry 4.0, which is, however, feared by many SMEs. Further, increased security measures are necessary for secure data storage and transmission.

Table III summarizes the twelve barriers to Industry 4.0 integration and respective enablers. The enablers in Table 3 represent summarized overarching categories from extant literature. Table A in the appendix shows several examples that are based on the cross-case analysis from the themes extracted. If similar examples occurred, those were paraphrased and combined in Table A. It is derived from the coding process of the interviews based on the 15 SMEs investigated. Further, Table A divides the examples for horizontal integration, vertical integration, and end-to-end engineering. In contrast, Table 3 below relates to the integration framework introduced in Figure 1 with categories (i) demand from customers and their role in the supply chain, (ii) employee skills and culture of manufacturers, (iii) local digital policy, and (iv) technology

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3365771

aspects.

TABLE III
BARRIERS AND RESPECTIVE ENABLERS FOR INDUSTRY 4.0 INTEGRATION IN SMES

TOE dimension	Barrier	Enablers address the barrier and implement Industry 4.0 in SMEs
Organizational	1) High Investment Industry 4.0 Integration	(i) Collaborative work of SMEs to align standards with customers (e.g., Kazantsev et al., 2022; 2023) (i) Customer demand for Industry 4.0 solutions (e.g., Estensoro et al., 2022; Khanzode et al., 2020) (iii) Public financing opportunities and industry-wide standards and approaches (e.g., Ghobakhloo and Fathi, 2019) (iv) Provision of technologically capable solutions but "downsized" to the needs of SMEs (e.g., Moeuf et al., 2018, 2020; Müller et al., 2018; Ghobakhloo & Fathi, 2019)
Organizational	2) Lack of Clarity Regarding Economic Benefit	(i) Data exchange is supported if customers' benefits are passed on to SMEs (e.g., Wagire et al., 2020) (i) Customer demand Industry 4.0 for solutions (e.g., Estensoro et al., 2022; Khanzode et al., 2020) (ii) Need to understand technologies from the long-term perspective (e.g., Hamzeh et al., 2018; Mittal et al., 2018, 2020) (iii) Public data storage and analysis solutions (e.g., Wagire et al., 2020)
Technological	3) Risk of Security Breaches	(iii) Public data storage and analysis solutions (e.g., Wagire et al., 2020) (iv) Secure data transmission systems referring to SMEs' requirements (e.g., Raj et al., 2019; Hamzeh et al., 2018; Ghobakhloo & Fathi, 2019)
Technological	4) Low Maturity Level of Preferred Technology	(ii) Change in culture toward new technologies (e.g., Horváth and Szabó, 2019; Stentoft et al., 2020) (ii) Long-term perspective/understanding of technologies (e.g., Estensoro et al., 2021; Hamzeh et al., 2018) (iv) The need for scalable solutions that can be adapted during the integration (e.g., Mittal et al., 2018, 2020)
Environmental	5) Inequality and Disruption to Existing Jobs	(iii) Policymakers must offer training and retraining possibilities (outside SMEs' power) (e.g., Khanzode et al., 2020)
Environmental	6) Lack of Standards, Regulations, and Forms of Certification	(i) New forms of supplier contracts (Kazantsev et al., 2022; Schmidt et al., 2023) (ii) Development of a department-arching understanding and plan for Industry 4.0 (e.g., Mittal et al., 2018, 2020; Hamzeh et al., 2018; Ghobakhloo & Fathi, 2019) (iii) Support of industrial associations to define standards suitable for SMEs (e.g., Estensoro et al., 2022; Kazantsev et al., 2022) (iii) Public data storage and analysis solutions (e.g., Wagire et al., 2020)
Environmental	7) Lack of Infrastructure	(ii) Change of mindset toward industry-common standards (e.g., Mittal et al., 2018, 2020; Hamzeh et al., 2018) (iii) Public investments in terms of internet connection and infrastructure (e.g., Estensoro et al., 2022) (iii) Public data storage and analysis solutions (e.g., Wagire et al., 2020)
Organizational	8) Lack of Digital Skills	(i) A better understanding of customer requirements and standards (Hamzeh et al., 2018; Müller et al., 2018; Santos et al., 2023) (ii) Development of digital skills in non-production functions (Marrucci et al., 2023; Müller et al., 2018; Santos et al., 2023) (iv) Provision of technologically capable solutions but "downsized" to the needs of SMEs (e.g., Moeuf et al., 2018, 2020; Müller et al., 2018; Ghobakhloo & Fathi, 2019)
Technological	9) Challenges in Ensuring Data Quality	(iii) Public data storage and analysis solutions (e.g., Wagire et al., 2020) (iv) technologically capable Solutions but "downsized" to the needs of SMEs (e.g., Müller et al., 2018; Ghobakhloo & Fathi, 2019) (iv) Ensuring data consistency (e.g., Moeuf et al., 2018, 2020; Kazantsev et al., 2022)
Organizational/ Technological	10) Lack of Internal Digital Culture and Training	(ii) Change of mindset and skills towards trust in systems and solutions provided (e.g., Kazantsev et al., 2022; Kumar et al., 2023) (ii) Development of a department-arching understanding and plan for Industry 4.0 (e.g., Mittal et al., 2018, 2020; Ghobakhloo & Fathi, 2019) (ii) Customer acceptance of offered solutions (e.g., Khanzode et al., 2020) (ii) Change toward collaborative culture (e.g., Schmidt et al., 2023)
Organizational	11) Resistance to Change and Ineffective Change Management	(ii) Change of mindset towards new technologies (e.g., Estensoro et al., 2022; Horváth & Szabó, 2019; Kazantsev et al., 2022) (ii) Development of a department-arching understanding and plan for Industry 4.0 (e.g., Mittal et al., 2018, 2020; Ghobakhloo & Fathi, 2019) (ii) Customer acceptance of offered solutions (e.g., Müller et al., 2018)
Organizational	12) Lack of a Digital Strategy alongside Resource Scarcity	(i) Definition of own standards for suppliers based on customers' systems and standards (e.g., Kazantsev et al., 2022) (ii) Development of a department-arching understanding and plan for Industry 4.0 (e.g., Mittal et al., 2018, 2020; Ghobakhloo & Fathi, 2019) (ii) Alignment of digital strategy with (main) customers (e.g., Estensoro et al., 2022) (iii) Political institutions and industry associations must develop a shared understanding and standards across entire industries and supply chains (e.g., Schmidt et al., 2023)

IV.2 Country-specific aspects

Regarding country-specific aspects, there are differences in technologies employed for the Industry 4.0 integration. For instance, for the European countries that have been intensively supported by ERP and MRP systems in the 1990s, such as Germany and Italy, the major technology for data interchange with partners remains the Electronic Data Interface (EDI). In contrast, some countries were less supported by IT systems in the past and thus less dependent on existing technologies for interconnection, such as Brazil and South Africa, where the data indicates more application of sensors and IoT technologies.

Some countries, like New Zealand, have more specific challenges with access to advanced manufacturing technologies and equipment and required expertise due to "the geographical situation that makes it difficult to transfer technology overseas and collaborate with pioneers in this field." However, the results do not indicate too country-specific results but comparable barriers for Industry 4.0 integration in SMEs. Comparably, South Africa claims the difficulties in enabling best practices from the European Union and avoiding non-efficiency in "regulation which becomes a burden for SMEs to compete with Big corporates."

While SMEs from the investigated countries agree on the critical barriers – lack of Industry 4.0 infrastructure and related skills and workforce – the exact contents of the barriers and their enablers are often specific. One SME from India reports, "Old, long-serving workforce fears to be replaced," requiring education programs for raising digital skills. At the same time, this brings additional concerns as Poland, India, and the UK indicate "Disruption [of Industry 4.0]to existing jobs" and the related fears that jobs will be lost. A further example that confirms existing studies in Germany (e.g., Müller et al., 2018) shows that barriers for SMEs are valid throughout the world is, as an Indian SME suggests, "Old machinery cannot supply adequate data" that indicates a technological gap between the existing technology and the required tools for realizing the Industry 4.0 concept. The same can be said for New Zealand, where "integrating old and advanced machines, equipment and software packages" is challenging. Finally, in Iran, significant barriers comprise "data ownership concerns" hampering

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3365771

information sharing in the supply chain.

V. Discussion

V.1 Enablers related to overcoming barriers to Industry 4.0 adoption

i) Environment: Market demand for Industry 4.0 production

The data suggest that customers' demand and their role in the supply chain are essential enablers because they influence the integration of Industry 4.0 at the time of investment. Especially regarding horizontal integration through Industry 4.0, it remains unclear which supply chain players should attract investments. Another aspect is the unknown impact of changes due to Industry 4.0 integration and how these changes will affect pricing, margins, and revenue models. Therefore, customers' needs require new skills to understand the entire industrial life cycle, ecosystem, and processes. In particular, SMEs need to be supported by policy and regulation to remain competitive in this transition. It is still difficult to see the benefits of Industry 4.0 for several SMEs and their customers due to the limited use of available data within SMEs themselves. So far, for many customers of SMEs, data-driven business models are not demanded or are even not accepted yet. Also, data security plays an important role: On the one hand, there is increased transparency along the supply chain, allowing several potentials, but SMEs fear it. On the other hand, consumers request an increased data security level.

Regarding change management and resistance to change, it can be said that both customers and suppliers prefer to work with established systems and processes. Further, it is essential to point out that customers and suppliers have different digital strategies and systems alongside resource scarcity. At the same time, a lack of collaboration is mentioned mainly on the supplier side. Hence, as an expert from Poland puts it, a clearly defined "agreement between supplier and buyer on the data management and sharing policy" would advance Industry 4.0 across company borders. By employing an adequate mindset, SMEs can fruitfully collaborate towards their standard requirements of Industry 4.0. Comparably, the type of product or services offered and the position in the value chain play a crucial role in how Industry 4.0 is perceived and unfolds.

(ii) Organization: Digital skills and culture

The skills of employees and the company's culture are key enablers as, in many cases, Industry 4.0 enablers are associated with reducing jobs. Especially old and low-skilled employees are expected to fall into this risk group. Further, there are changes in job profiles. Limited retraining and training opportunities are available but are required. Due to the increased complexity of technologies and integration into the SMEs' infrastructures, skilled workers are essential. In addition to the lack of skilled workers, Industry 4.0 experts have increased payment demands that are hard to satisfy by SMEs. The lack of internal digital culture further prevents the successful integration of Industry 4.0. A general mistrust of digital technologies is central, even at the management level. Existing conservative structures and differences between departments are further barriers experienced. For some SMEs, hand or semi-automated labor is still cheaper and more flexible up to a specific production volume. Therefore, changes in company culture and incentives by public institutions are required. As described for South Africa, "There needs to be top-down [as well as] bottom-up communication and forged relationship amongst all stakeholders."

(iii) Environment: Digital policy

Local digital policies are necessary for Industry 4.0 integration in two regards. First, standards and regulations should be established, as this is the only way to ensure a smooth data exchange. Second, the lack of data standards makes data transparency challenging, especially in horizontal integration. Moreover, this leads to data integration and security issues. Matching enablers are access to funding and public data storage and analysis, such as those practiced by several European approaches. Insufficient local policies increase contracting costs. Further, the lack of IT infrastructure, such as internet speed and access, is highlighted in several countries. Hence, the expert from Italy describes the requirement of "Gradual investments in Industry 4.0 4.0 over the years to be able to sustain investments both on the financial side and on the human resource side […] by funds obtained through national and regional support".

(iv) Technology

Technological aspects include identifying the right technology and generating the necessary data, which still poses challenges for SMEs. Further, the existing technologies are not yet fully developed, and finding the right partners is difficult. In general, already established systems are preferred, as new technologies also mean new investments, uncertainty, and unclear benefits. Another point cited is customers' and suppliers' lack of acceptance or demand for new technologies. Besides, the lack of infrastructure, such as databases, servers, and IT infrastructure, generally influences the acceptance of new digital enablers. Especially in data exchange, the infrastructure plays a decisive role. Without it, the advantages of the new technologies cannot be fully exploited, notably regarding data exchange across company borders. Finally, many enablers must be downsized to meet the requirements of SMEs while still maintaining interoperability with industry-wide standards and systems. As a German SME representative puts it, "Sometimes for an SME, we are not looking for a best practice example, but a good enough practice example that can be integrated and expanded easily."

In Figure 1 below, the results are organized according to the framework of three central characteristics of Industry 4.0. At the same time, we subdivided horizontal integration into upstream and downstream (Kagermann et al., 2013): vertical integration inside SMEs, horizontal integration upstream existing supply chains, horizontal integration downstream existing supply chains, and end-to-end engineering leading to customers. The results comprise the following categories: (i) demand from customers and their role in the supply chain, (ii) employee skills and culture of manufacturers, (iii) local digital

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3365771

policy, and (iv) technology aspects. Section 4.2 discusses several recurring patterns relevant to developing the framework based on the multiple case study and their combination with extant literature findings.

V.2 Contribution to Literature and Theoretical Implications

Based on a sample of 15 SMEs from 10 countries and five continents combined with a literature analysis, this study extends existing literature and theory regarding several aspects explained below.

First, this paper conducts a cross-country analysis of SMEs concerning Industry 4.0, revealing that while some country-specific factors exist, general integration barriers can be observed. While there are extant publications on barriers and enablers or drivers (of Industry 4.0 in SMEs, their analysis is only based on empirical data from one country or region (e.g., Estensoro et al., 2022). Other publications do not present specific enablers (Kumar et al., 2020), barriers (Müller & Voigt, 2018), or no barriers and enablers at the same time (Dutta et al., 2021; 2020). Further, their analysis is often focused on specific factors such as strategy, management, organizational aspects, and workforce (Agostini & Nosella, 2019; Brodeur et al., 2023; Stentoft et al., 2020) or financial indicators (Masood & Sonntag, 2020). While Moeuf et al. (2020) present a broader set of barriers and drivers, their analysis is not based on empirical data and does not have an international focus. Moreover, the extant works do not combine the TOE framework regarding barriers and respective enablers.

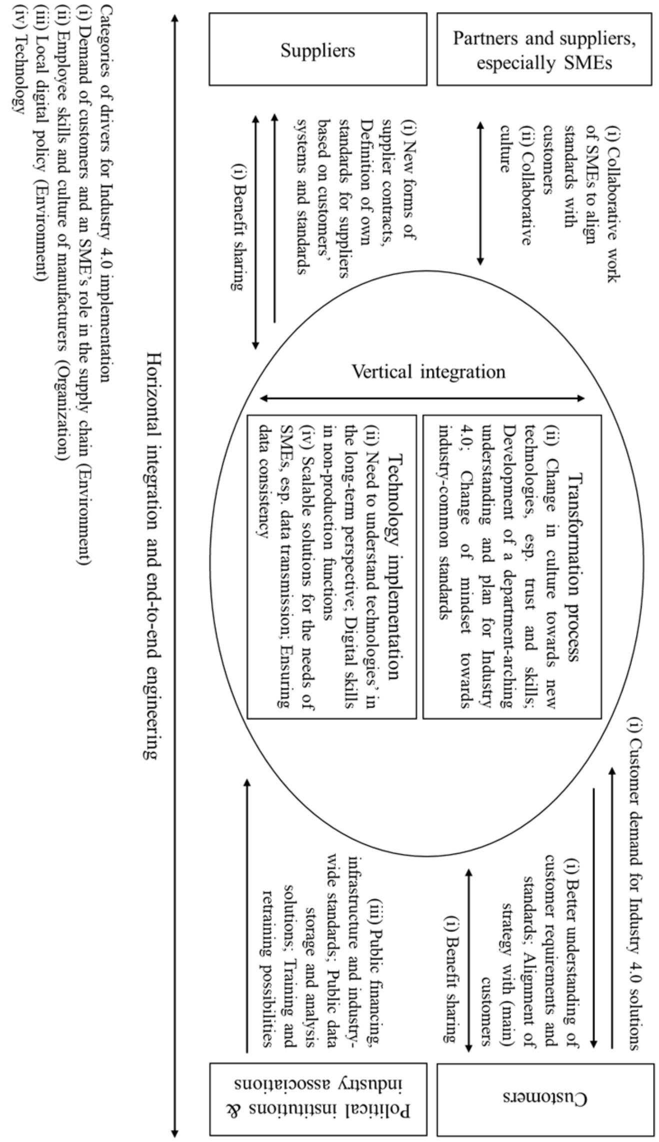

Fig. 1. The combined integration framework for Industry 4.0 in SMEs

Further, extant publications that employ the TOE framework do not relate the results to horizontal and vertical integration and end-to-end engineering as central characteristics of Industry 4.0 (Kagermann et al., 2013). Hence, we can present a comprehensive analysis that combines the perspective of several of the works above while validating it in an international sample. Still, the works mentioned earlier can present an interesting comparison regarding specific aspects while our analysis remains comparably holistic.

Second, we extend extant research applying the TOE framework in the context of Industry 4.0 and SMEs. For instance, we extend Ghobakloo and Ching (2019), who based their analysis on only two countries that did not cover barriers in-depth. Ghobakloo et al. (2022) did not include empirical data. We further extend Raj and Jeyaraj (2023), who did not focus on SMEs specifically. As for the previous paragraph, none of the three extant works relate the results to horizontal and vertical integration or end-to-end engineering as central

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3365771

characteristics of Industry 4.0 (Kagermann et al., 2013).

Third, we contribute to understanding the supply chain spanning the nature of Industry 4.0. Herein, the study confirms and extends the importance of SME integration into supply chains (e.g., Mishra et al., 2023; Schmidt et al., 2023). In particular, the integration of suppliers and customers referring to many organizational and technological aspects relating to the specific nature of products and services of the respective SME can be decisive in supporting SMEs on their path towards Industry 4.0 (Schmidt et al., 2023).

Fourth, the study emphasizes that the integration of Industry 4.0 in SMEs is more oriented toward operational benefits than strategic advantages, which leads to a lack of digital strategy in many SMEs (e.g., Sahi et al., 2020). Therefore, skills and mindset need to be developed towards Industry 4.0 to solve several barriers successfully (Horváth & Szabó, 2019; Matt et al., 2020; Mittal et al., 2018, 2020).

Fifth, the need for support of SMEs towards Industry 4.0 is underlined in this paper by both political institutions and industrial associations. A strong organization and support can help SMEs make up for deficiencies in strategy, skillset, or technological standards towards Industry 4.0, among other aspects (e.g., Moeuf et al., 2018; 2020; Veile et al., 2019). Fourth, this paper emphasizes and details the requirement of Industry 4.0 integration to provide adequate, affordable, and scalable technological enablers. It also concerns publicly available data storage and analysis enablers, which could be provided by public institutions or industrial associations (e.g., Mittal et al., 2018; 2020; Moeuf et al., 2018; 2020).

Conclusively, Industry 4.0 can help SMEs strengthen their competitive position in the local and regional markets (Müller et al., 2018) and global value chains. For instance, if suppliers integrate with customers, a lock-in effect leads SMEs to convert the current global value chains into a network economy driven by smaller companies (Schmidt et al., 2023). In this vein, SMEs can start collecting data about the products' uses and performances after sales to enable improvements due to data-driven analytics to improve and innovate products. SMEs with neither big-data processing facilities nor capacities to store transactional data could supply their data to OEMs or platforms and receive, in exchange, data-driven analytics to optimize their local decision-making (Ietto et al., 2022). However, SMEs who interconnect shop-floor machinery can benefit only when Industry 4.0 crosses the firm borders, leading to different interconnecting actors in the value chain, including suppliers and customers (Schmidt et al., 2023; Veile et al., 2019).

V.3 Managerial and Policy Implications

SME managers can use the findings from this study to benchmark their progress in terms of Industry 4.0 adoption in their industry against their counterparts globally. We summarized the challenges faced by SMEs during the adoption of Industry 4.0 technologies as far as horizontal, vertical, and end-to-end integration are concerned. Finally, the strategies to overcome these challenges are also discussed in depth, which could benefit SME managers since they are resource-constrained in terms of cost, technology, human resources, and capacity. While managers and decision-makers need to find customized enablers related to digitizing their processes and operations, common barriers suggest that a common backbone strategy can be used as a starting point for such enablers. From a practical point of view, SMEs and their managers and decision-makers have, at first, a perspective of different contexts. The detailed contents of Table A can compose the strategic planning of SMEs with medium and long-term actions.

Since the present study surveys SMEs from ten countries across five continents worldwide, the findings capture a broad global perspective on integrating Industry 4.0 technologies. The integration framework presented in this study could be a guideline for SME managers to implement Industry 4.0 technologies better. Further, the present study highlights that Industry 4.0 integration cannot stop at company borders but must be thought of and executed with suppliers, customers, and specifics of the value generation within an SME. As Industry 4.0 is based on horizontal and vertical interconnection and aims toward End-to-End processes, SMEs are necessarily part of this interconnection and must, therefore, also consider how to approach it. Due to insufficient resources, technological capabilities, market embeddedness, and framework conditions, SMEs are especially challenged with integration. The present study gives an overview of such barriers and the enablers for successful integration, differentiated into several categories typically for SMEs and distinguished for different core characteristics of the concept of Industry 4.0.

In addition, this study captures these differences effectively by collecting data related to SMEs from ten countries and five continents. The success of Industry 4.0 integration in SMEs depends upon how these technologies are integrated with various stakeholders across the supply chain, such as original equipment manufacturers, R&D agencies, or sub-suppliers.

SMEs could shorten their path to the customer by joining digital collaboration platforms and collectively fulfilling manufacturing orders (Kazantsev et al., 2022; Ricci et al., 2021). These dynamics, however, require an openness to collaboration, data collection and sharing, and coordinated production and operations planning. However, most SMEs could be reluctant to share data and fear losing control of their core activities (Kazantsev et al., 2022; Müller et al., 2018). Such supply chain partners could limit the operational efficiency and productivity of the whole production network. Although the adoption process in conventional supply chains can be incremental, collaborative R&D activities with universities co-funded by supranational bodies can increase it by improving mutual trust (Müller et al., 2022; Veile et al., 2019).

As such, more support is needed from the policy-making perspective. Several initiatives, like GAIA-X, facilitate the creation of European data and Artificial Intelligence-driven industrial or manufacturing ecosystems (Kazantsev et al., 2023). To guarantee data sovereignty, those need to be expanded over international borders. In addition, industry collaboration governance rules are subject to formalization and enforcement (Kazantsev et al., 2022).

Finally, our results show that the required corporate culture is absent in several regarded SMEs because it supports Industry

4.0 integration. To ensure the necessary training of employees and thus secure jobs, cooperation with educational institutions can be entered into, which has scarcely been done by SMEs so far. In addition, this opportunity can be used to recruit young, well-trained employees from universities, supporting the requirement for new job profiles and complementing the existing skillset of the workforce.

VI. CONCLUSION

This research contributes to understanding Industry 4.0 regarding barriers and enablers for SMEs worldwide. Based on a sample of 15 SMEs from 10 countries worldwide and a literature analysis, we are able to transfer central patterns of enablers into an integration framework that can be transferred to various national settings. Nevertheless, our approach has several limitations that could be addressed in future research, as explained in the following subsections.

VI.1 Limitations

The apparent limitations relate to countries' selection and the limited number of sampled SMEs involved in the research. However, to our knowledge, this represents the first cross-country qualitative research investigating SMEs in several countries and continents around the world concerning Industry 4.0. We followed a rigorous procedure to select, collect, and analyze our data (Eisenhardt, 1989). Nevertheless, the fact that the salient conditions overlap or match in different country contexts demonstrates the transferability of the research findings, which represents an alternative way to measure generalizability in qualitative studies (Welch & Piekkari, 2017). Still, despite choosing a broad sample of ten countries on five continents, local legislations and cultural differences do not allow a direct transfer of our results to any other country, limiting our generalizability. Likewise, our view on cultural barriers and differences was not the focus of this study and is thus lacking in our analysis.

Another limitation arises because the interviews were conducted in several languages and by different researchers. However, to ensure comparability, the network manager was appointed to read all the translated interviews and Excel tables and provide cross-validation of the sample's data and interpretations. Also, the rigorous procedures adopted to ensure equivalence and reduce the bias increase the credibility and the dependability of the results, which can be considered alternative terms to reliability and validity proposed in quantitative studies (Sinkovics et al., 2008). Further, although a single response bias is acceptable when investigating leading SME personnel with oversight across the entire enterprise, this potential bias must be noted for this research.

VI.2 Future research

For future research, the developed integration framework for Industry 4.0 in SMEs must be validated within the different countries, preferably by quantitatively analyzing a broader sample of SMEs. In addition, other studies could deepen underrepresented countries like the US, Japan, or China. Hereby, differences in cultural legislation could be investigated more in-depth.

Further, we suggest prioritizing actions of the general integration framework relating to different characteristics and requirements of SMEs towards Industry 4.0. It is crucial to consider different characteristics that prove decisive in how Industry 4.0 is perceived and implemented. These include the role of the Industry 4.0 provider or user, the position within the value chain, the level of internationalization, or whether it is a family enterprise (Estensoro et al., 2022). Additionally, since the national priorities and socio-political circumstances that impact the integration of Industry 4.0 technologies differ across SMEs around the globe, a systematic analysis is required to capture these differences. Finally, a longitudinal study investigating the influences of crises in the last years could pose an interesting future research avenue.

APPENDIX

TABLE A

RESULTS OF CROSS-CASE ANALYSIS BASED ON DATA CODING

Barriers	Horizontal Integration (Upstream)	Vertical Integration	Horizontal Integration (Downstream)	End-to-End Engineering
1) High Investment in Industry 4.0 Implement ation	Lack of understanding of who should attract investments Uncertainties with regard to its ROI	High investments required are not feasible or not available Investment rates are declining due to market heterogeneity Lack of evidence of investment efficiency Industry 4.0, on a larger scale, will potentially disrupt the business process. High cost of implementing technologies at the factory	Lack of understanding of who should attract investments Customers are sceptical about 4.0 rapid industry changes and how it is going to impact the pricing High cost of advanced manufacturing machines and equipment	Difficult to find sources of financing Lack of best practice examples No synergy in terms of the adoption, rollout, and implementation of Industry 4.0 High cost of data acquisition as well as storage Own product is integrated into a larger, closed system
2) Lack of Clarity Regarding Economic Benefit	Data exchange with suppliers in real-time seems like overengineering Unclear economic benefits on investment in Industry 4.0 / early adopters, e.g., due to missing data from different suppliers	Some Departments within SMEs are not certain about the ROI of Industry 4.0 within the projects they are working on	Customers do not demand Data-driven business models Data validation efforts and economic effect on the customer are inadequate Not clear financial benefits of new technology	High costs of data storage and standardization vs benefits for SME Unclear industry turnover and economic benefits
3) Risk of Security Breaches	Knowledge protection costs Lack of data security standards Feared transparency to third parties	Disclosure of critical inter-organisation information Risk of production stoppage due to a security breach	Too high feared transparency towards customers and larger enterprises with higher bargaining power Cybersecurity as a key challenge for robots	Some consumers demand an increased level of security Cybersecurity as a key challenge for robots Currently, there are no industry security policies Data safety is costly

This article has been accepted for publication in IEEE Transactions on Engineering Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TEM.2024.3365771

4) Low Maturity Level of Preferred Technology	Existing technologies have insufficient functionality Difficulty identifying technologies and interpreting the data Most SMEs are comfortable with the technology they are using, new technology means extra funds, resources and human capital. Suppliers are not ready yet Difficulty identifying technologies and partners	Forecasting level for applicability of technology is difficult to observe for short term Departments exploit technological opportunities only partially Difficulty identifying technologies and partners	Customers prefer a system that they are familiar and comfortable with. Customers are not ready yet	No data consistency across the lifecycle of products No accurately scheduled preventative maintenance is available yet The industry seems to be comfortable status quo Lack of proper ERP systems that can be integrated into existing systems
5) Inequality and Disruption to Existing Jobs		Old, long-serving workforce fears being replaced Internal documentation changes existing jobs position Low-skilled workers as a risk group Rather old and in diverse management positions		Little possibility of retraining of workers and inadequate training and integration of younger workforce across disciplines
6) Lack of Standards, Regulations and Forms of Certification	SME suppliers cannot provide appropriate data formats No common standards Partner contracting costs Provision of consistent and accurate data in different formats to customers Data integration and security issues	Internal standards, regulations are in place, but most often, internal departments do not implement or adhere to them	Restrictive contracting practices Data integration and security issues	Lack of common standard of data exchange/legacy silos Implementation of industry standards and regulations is challenging Data integration and security issues
7) Lack of Infrastructure	Problems outside the major cities Back-end solutions need to be connected properly with databases Existing tools are not able to keep pace with the rate of technology change Every SME operates in silos within its infrastructure and platforms	No server solutions for real-time access to large amounts of data Multiple systems for exchanging data make workflow slower Legacy systems Lack of reliable communication networks	Lack of infrastructure for testing with customers Customers depend on SMEs' databases achieves for information Inappropriate IT Infrastructure Insufficient telecommunications infrastructure in the country	Data storage facilities are not accessible for SMEs Non-optimised maintenance and logistics operations There are no data banks and unified infrastructure for all players to the plugin Inappropriate IT Infrastructure
8) Lack of Digital Skills	Purchasing departments do not have digitisation solutions yet Lack of collaborative skills The high complexity of ERP systems due to the complexity of processes Suppliers have different levels of digital skills	Technology is difficult to integrate into the company's IT-architecture Requirements for routinised use of algorithms and predictable data Lack of skilled workers Skilled specialists have been increasing pay demands	Customers have different levels of digital skills and sometimes lack of knowledge, qualifications and competencies to realise the full potential of advancing technology	Conservative methods of production organisation Lack of understanding of customer requirements Inadequate number of mechatronic engineers and IT experts
9) Challenges in Ensuring Data Quality	Lack of ability to utilise partners' data The lack of accurate big data analytics makes it impossible for SMEs to make informed decisions Unclear which data shall be shared	Old machinery cannot supply adequate data Lack of expert time expenditure on evaluation Data entry challenges Ethical data application challenge Missing data makes it hard to determine what is available to offer customers Lack of standardisation for data integration Mismatch data	Inaccurate and inconsistent data makes it hard for customers to pace relevant codes and purchases Lack of standardisation for data integration, the complexity of data retrofitting	The problem of cleaning the input data Accuracy in terms of data exchange remains a challenge Lack of standard and reliable communication networks
10) Lack of Internal Digital Culture and Training	Network distrust Coordination costs Suppliers are comfortable with systems that are currently in place	Hand labour is cheaper and more flexible for low production volumes Departmental differences Lack of trust in digitalisation even among high-level managers	Customers are also not willing to accept change Some customers have a lack of internal digital culture	Conservative structures corporate culture Partner opportunism There is no clear culture of promoting full digital skills and digital migration
11) Resistance to Change and Ineffective Change Management	Problems when interacting with contractors or small suppliers Partner search costs Enterprises within the industries are still comfortable using the currently in place systems and processes of providing services to their customers	Long-serving department heads with little digital experience Conservative management Incomparability of departments in understanding some emerging problematics due to different background Fears about mass job losses caused by automation	Customer search costs Lack of direct access to downstream orders Customers themselves are still sceptical of online orders and purchasing, and they state that they feel vulnerable when using online purchasing Managers and employees have no digital workplace experience; workers are afraid that their job will be eliminated	Aged workforce
12) Lack of a Digital Strategy alongside Resource Scarcity	Suppliers have different systems for large customers Partner search costs No collaborative systems by suppliers to respond to the demands of the industry Suppliers have different digital strategies and systems	There is no clear systems communication between sales, production, control and other departments	A new mindset is required. Customers have different demands and different digital strategies	No synergy to accelerate and transform the entire industry
Exemplary solutions for solving the challenges	Robot-process automation to digitise manual input from suppliers Cooperation with the developers of fleet management systems Data exchange agreements for further and closer	Retrofitting of existing machines Applying new managerial principles to the department structure Redefine current systems to meet the needs of industry demand	Supplier-buyer contracts for data sharing and privacy Equipment that uses machine learning to predict outcomes and further projection between	Improvement of human resources management, development of digital skills, digital business development strategy Through the adoption of data science

	communication through the Supply Chain network Protecting anti-virus software	Developing a reliable communication network through the whole system Weekly data backup (local and Cloud backup) Annual training plan for each employee	suppliers and customer Agreement between supplier and buyer on the data management and sharing policy	technology and data analytics, enterprises must provide accurate data Data from the Basic Monitory Standard Report are used for new machinery development and production
Exemplary Industry 4.0 technology implemented	Electronic Data Interface (EDI) in real-time Fleet management Machine learning IoT Blockchain Artificial intelligence Interconnected ERP systems	Radiofrequency (RF) and Quick Response Code (QR) identification CAD / CAM Computer Manufacturing Digital sensor automation with product identification and operating conditions, flexible lines Production monitoring and remote control with MES and SCADA systems Additive manufacturing, rapid prototyping or 3D printing Cloud systems	Machine-to-Machine (M2M) communication Virtual and Augmented Reality, 3D testing beds Machine to customer communication Big data collection, processing and analysis Incorporation of digital services into products	Electronic design automation (EDA) Big Data Analytics Integrated Engineering Systems for Product Development and Product Manufacturing Using Product-Associated Cloud Services Simulations/analysis of virtual models (e.g., Finite Elements and Computational Fluid Dynamics) for design and commissioning MIS and MES systems, Retrofitting, M2M communication

References

L. Agostini and A. Nosella, "The adoption of Industry 4.0 technologies in SMEs: results of an international study," *Management Decision*, vol. 58, no. 4, pp. 625-643, 2019.

M. F. Arroyabe, C. F. Arranz, I. F. de Arroyabe, and J. C. F. de Arroyabe, "The effect of IT security issues on the implementation of Industry 4.0 in SMEs: Barriers and challenges," *Technological Forecasting and Social Change*, vol. 199, p. 123051, 2024.

F. Arcidiacono, A. Ancarani, C. Di Mauro, and F. Schupp, "Where the rubber meets the road. Industry 4.0 among SMEs in the automotive sector," *IEEE Engineering Management Review*, vol. 47, no. 4, pp. 86-93, 2019.

J. Brodeur, I. Deschamps, and R. Pellerin, "Organisational changes approaches to facilitate the management of Industry 4.0 transformation in manufacturing SMEs," *Journal of Manufacturing Technology Management*, 2023.

M. Cugno, R. Castagnoli, G. Büchi, and M. Pini, "Industry 4.0 and production recovery in the covid era," *Technovation*, vol. 114, p. 102443, 2022.

L. S. Dalenogare, G. B. Benitez, N. F. Ayala, and A. G. Frank, "The expected contribution of Industry 4.0 technologies for industrial performance," *International Journal of Production Economics*, vol. 204, pp. 383-394, 2018.

R. DePietro, E. Wiarda, and M. Fleischer, "The context for change: Organisation, technology and environment," in *The processes of technological innovation*, L. G. Tornatzky and M. Fleischer, Eds. Lexington, MA: Lexington Books, 1990, pp. 151-175.

G. Dutta, R. Kumar, R. Sindhwani, and R. K. Singh, "Digitalisation priorities of quality control processes for SMEs: A conceptual study in perspective of Industry 4.0 adoption," *Journal of Intelligent Manufacturing*, vol. 32, no. 6, pp. 1679-1698, 2021.

G. Dutta, R. Kumar, R. Sindhwani, and R. K. Singh, "Digital transformation priorities of India's discrete manufacturing SMEs–a conceptual study in perspective of Industry 4.0," *Competitiveness Review: An International Business Journal*, vol. 30, no. 3, pp. 289-314, 2020.

K. M. Eisenhardt, "Building theories from case study research," *Academy of management review*, vol. 14, no. 4, pp. 532-550, 1989.

M. Estensoro, M. Larrea, J. M. Müller, and E. Sisti, "A resource-based view on SMEs regarding the transition to more sophisticated stages of Industry 4.0," *European Management Journal*, vol. 40, no. 5, pp. 778-792, 2022.

A. G. Frank, L. S. Dalenogare, and N. F. Ayala, "Industry 4.0 technologies: Implementation patterns in manufacturing companies," *International Journal of Production Economics*, vol. 210, pp. 15-26, 2019.

A. L. George, A. Bennett, S. M. Lynn-Jones, and S. E. Miller, "Case studies and theory development in the social sciences," MIT Press, 2005.

M. Ghobakhloo, M. Iranmanesh, M. Vilkas, A. Grybauskas, and A. Amran, "Drivers and barriers of Industry 4.0 technology adoption among manufacturing SMEs: a systematic review and transformation roadmap," *Journal of Manufacturing Technology Management*, vol. 33, no. 6, pp. 1029-1058, 2022.

M. Ghobakhloo and N. T. Ching, "Adoption of digital technologies of smart manufacturing in SMEs," *Journal of Industrial Information Integration*, vol. 16, p. 100107, 2019.

M. Ghobakhloo and M. Fathi, "Corporate survival in Industry 4.0 era: the enabling role of lean-digitised manufacturing," *Journal of Manufacturing Technology Management*, vol. 31, no. 1, pp. 1-30, 2019.

D. A. Gioia, K. G. Corley, and A. L. Hamilton, "Seeking qualitative rigor in inductive research: Notes on the Gioia methodology," *Organisational research methods*, vol. 16, no. 1, pp. 15-31, 2013.

R. Hamzeh, R. Zhong, and X. W. Xu, "A survey study on industry 4.0 for New Zealand manufacturing," *Procedia Manufacturing*, vol. 26, pp. 49-57, 2018.

D. Horváth and R. Z. Szabó, "Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?" *Technological Forecasting and Social Change*, vol. 146, pp. 119-132, 2019.

B. Ietto, C. Ancillai, A. Sabatini, E. G. Carayannis, and G. L. Gregori, "The Role of External Actors in SMEs' Human-Centered Industry 4.0 Adoption: An Empirical Perspective on Italian Competence Centers," *IEEE Transactions on Engineering Management*, 2022.

H. Kagermann, J. Helbig, A. Hellinger, and W. Wahlster, "Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 Working Group," 2013.

N. Kazantsev, O. Petrovskyi, and J. M. Müller, "From supply chains towards manufacturing ecosystems: A system dynamics model," *Technological Forecasting and Social Change*, vol. 197, p. 122917, 2023.

N. Kazantsev, G. Pishchulov, N. Mehandjiev, P. Sampaio, and J. Zolkiewski, "Investigating barriers to demand-driven SME collaboration in low-volume high-variability manufacturing," *Supply Chain Management: An International Journal*, vol. 27, no. 2, pp. 265-282, 2022.

A. G. Khanzode, P. R. Sarma, S. K. Mangla, and H. Yuan, "Modeling the Industry 4.0 Adoption for Sustainable Production in Micro, Small & Medium Enterprises," *Journal of Cleaner Production*, vol. 279, p. 123489, 2020.

S. Kumar, R. D. Raut, E. Aktas, B. E. Narkhede, and V. V. Gedam, "Barriers to adoption of industry 4.0 and sustainability: a case study with SMEs," *International Journal of Computer Integrated Manufacturing*, vol. 36, no. 5, pp. 657-677, 2023.

R. Kumar, R. K. Singh, and Y. K. Dwivedi, "Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: Analysis of challenges," *Journal of Cleaner Production*, vol. 275, 2020.

A. Marrucci, R. Rialti, and M. Balzano, "Exploring paths underlying Industry 4.0 implementation in manufacturing SMEs: a fuzzy-set qualitative comparative analysis," *Management Decision*, 2023.

T. Masood and P. Sonntag, "Industry 4.0: Adoption challenges and benefits for SMEs," *Computers in Industry*, vol. 121, p. 103261, 2020.

D. T. Matt, G. Orzes, E. Rauch, and P. Dallasega, "Urban production–A socially sustainable factory concept to overcome shortcomings of qualified workers in smart SMEs," *Computers & Industrial Engineering*, vol. 139, p. 105384, 2020.

M. B. Miles and M. Huberman, "Qualitative data analysis: An expanded sourcebook," Sage, 1994.

R. Mishra, R. K. Singh, and A. Gunasekaran, "Digitalisation of supply chains in Industry 4.0 environment of manufacturing organisations: conceptualisation, scale development & validation," *Production Planning & Control*, pp. 1-20, 2023.

S. Mittal, M. A. Khan, J. K. Purohit, K. Menon, D. Romero, and T. Wuest, "A smart manufacturing adoption framework for SMEs," *International Journal of Production Research*, vol. 58, no. 5, pp. 1555-1573, 2020.

S. Mittal, M. A. Khan, D. Romero, and T. Wuest, "A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs)," *Journal of manufacturing systems*, vol. 49, pp. 194-214, 2018.

A. Moeuf, S. Lamouri, R. Pellerin, S. Tamayo-Giraldo, E. Tobon-Valencia, and R. Eburdy, "Identification of critical success factors, risks and opportunities of Industry 4.0 in SMEs," *International Journal of Production Research*, vol. 58, no. 5, pp. 1384-1400, 2020.

A. Moeuf, R. Pellerin, S. Lamouri, S. Tamayo-Giraldo, and R. Barbaray, "The industrial management of SMEs in the era of Industry 4.0," *International Journal of Production Research*, vol. 56, no. 3, pp. 1118-1136, 2018.

J. M. Müller, O. Buliga, and K. I. Voigt, "The role of absorptive capacity and innovation strategy in the design of industry 4.0 business Models - A comparison between SMEs and large enterprises," *European Management Journal*, vol. 39, no. 3, pp. 333-343, 2022.

J. Müller and O. Buliga, "Archetypes for data-driven business models for manufacturing companies in Industry 4.0," in *Proceedings of the International Conference on Information Systems (ICIS)*, Munich, 2019.

J. M. Müller, O. Buliga, and K. I. Voigt, "Fortune favors the prepared: How SMEs approach business model innovations in Industry 4.0," *Technological Forecasting and Social Change*, vol. 132, pp. 2-17, 2018.

J. M. Müller and K. I. Voigt, "Sustainable industrial value creation in SMEs: A comparison between industry 4.0 and made in China 2025," *International Journal of Precision Engineering and Manufacturing-Green Technology*, vol. 5, pp. 659-670, 2018.

OECD, "The Digital Transformation of SMEs," [Online]. Available: https://www.oecd.org/industry/smes/PH-SME-Digitalisation-final.pdf. [Accessed: 21-Mar-2023].

A. Raj and A. Jeyaraj, "Antecedents and consequents of industry 4.0 adoption using technology, organisation and environment (TOE) framework: A meta-analysis," *Annals of Operations Research*, vol. 322, no. 1, pp. 101-124, 2023.

A. Raj, G. Dwivedi, A. Sharma, A. B. L. de Sousa Jabbour, and S. Rajak, "Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective," *International Journal of Production Economics*, p. 107546, 2019.

R. Ricci, D. Battaglia, and P. Neirotti, "External knowledge search, opportunity recognition and industry 4.0 adoption in SMEs," *International Journal of Production Economics*, vol. 240, p. 108234, 2021.

G. K. Sahi, M. C. Gupta, and T. C. E. Cheng, "The effects of strategic orientation on operational ambidexterity: a study of Indian SMEs in the industry 4.0 era," *International Journal of Production Economics*, vol. 220, p. 107395, 2020.

B. Santos, M. Dieste, G. Orzes, and F. Charrua-Santos, "Resources and capabilities for Industry 4.0 implementation: evidence from proactive Portuguese SMEs," *Journal of Manufacturing Technology Management*, vol. 34, no. 1, pp. 25-43, 2023.

M. C. Schmidt, J. W. Veile, J. M. Müller, and K. I. Voigt, "Industry 4.0 implementation in the supply chain: a review on the evolution of buyer-supplier relationships," *International Journal of Production Research*, vol. 61, no. 17, pp. 6063-6080, 2023.

R. R. Sinkovics, E. Penz, and P. N. Ghauri, "Enhancing the trustworthiness of qualitative research in international business," *Management International Review*, vol. 48, no. 6, pp. 689-714, 2008.

F. M. Somohano-Rodríguez, A. Madrid-Guijarro, and J. M. López-Fernández, "Does Industry 4.0 really matter for SME innovation?" *Journal of Small Business Management*, vol. 60, no. 4, pp. 1001-1028, 2020.

J. Stentoft, K. Adsbøll Wickstrøm, K. Philipsen, and A. Haug, "Drivers and barriers for Industry 4.0 readiness and practice: empirical evidence from small and medium-sized manufacturers," *Production Planning & Control*, vol. 32, no. 10, pp. 811-828, 2020.

J. W. Veile, D. Kiel, J. M. Müller, and K. I. Voigt, "Lessons learned from Industry 4.0 implementation in the German manufacturing industry," *Journal of Manufacturing Technology Management*, vol. 31, no. 5, pp. 977-997, 2019.

A. A. Wagire, R. Joshi, A. P. S. Rathore, and R. Jain, "Development of maturity model for assessing the implementation of Industry 4.0: learning from theory and practice," *Production Planning & Control*, pp. 1-20, 2020.

R. K. Yin, *Case study research: Design and methods (4th Ed.)*, Thousand Oaks, CA: Sage, 2009.

C. Welch and R. Piekkari, "How should we (not) judge the 'quality of qualitative research? A re-assessment of current evaluative criteria in International Business," *Journal of World Business*, vol. 52, no. 5, pp. 714-725, 2017.

L. D. Xu, E. L. Xu, and L. Li, "Industry 4.0: state of the art and future trends," *International Journal of Production Research*, vol. 56, no. 8, pp. 2941-2962, 2018.

R. K. Yin, *Case study research: Design and methods (Vol. 5)*. Sage, 2009.

Julian M. Müller is Full Professor of Digital Business at Seeburg Castle University, Austria and Professor for Supply Chain Management at Erfurt University of Applied Sciences, Germany. Further, he is Private Lecturer (Privatdozent) at Friedrich-Alexander-Universität Erlangen-Nürnberg, where he also received his venia legendia (Habilitation) and Ph.D. degree. His research interests include Industry 4.0 and Digital Transformation in the context of Supply Chain Management, Technology and Innovation Management, and Sustainability.

Nazrul Islam received the Ph.D. degree in innovation management from Tokyo Institute of Technology, Tokyo, Japan, in 2008. Prof Islam is Chair Professor of Business & Director of Research Degrees, and Associate Director for UEL Centre of FinTech at Royal Docks School of Business and Law, University of East London, UK. His research interest focuses on interdisciplinary fields: the management of technology, innovation and entrepreneurship, the emergence and growth of disruptive and digital technology-based innovation and SMEs business sustainability. Prof Islam is an Associate Editor for *Technological Forecasting & Social Change*, Department Editor (Technology Management) for *IEEE Transactions on Engineering Management*, and Editor-in-Chief of *International Journal of Technology Intelligence and Planning*.

Nikolai Kazantsev received his PhD from the Alliance Manchester Business School, The University of Manchester. He is a postdoctoral research associate at the Institute for Manufacturing, recently appointed as a fellow of Clare Hall, University of Cambridge. Nikolai investigates socio-technical issues in manufacturing ecosystems, such as demand-driven collaborations, data sharing, and augmented reality (industrial metaverse).

Rubina Romanello is Assistant Professor at with Università degli Studi di Trieste, Italy. She holds a PhD in Business Studies from University of Udine. She carried on two post-doctoral research programs in Management on the topic of Industry 4.0 technologies adoption among manufacturing companies. Her research and teaching interests are in the area of International Business, Innovation and Technology Management, Operations Management and Management of Cultural Enterprises, Creative Industries and Performing Arts.

Gilson Olivera is a full professor at the Federal University of Technology (UTFPR), in Paraná (Brazil). His research and teaching interests are quantitative methods applications, investment analysis lean and green product development, and Industry 4.0 implementation in SMEs.

Debabrata Das is Associate Professor of Analytics and Data Science at Indian Institute of Management Mumbai, India. His research and teaching interests are in the area of Supply Chain Modelling and Optimization, Multi-Objective Optimization, Indus-trial System Dynamics and Simulation, Closed-loop Supply Chain Management and Circular Economy.

Reza Hamzeh is a researcher in mechanical engineering and manufacturing systems and part of Laboratory for Industry 4.0 Smart Manufacturing Systems (LISMS) at University of Auckland, New Zealand. His research interests are in the area of technology management, Industry 4.0 and IoT-based technologies.