Analyzing Industry 4.0 Adoption Barriers of Small and Medium-sized Enterprises and Existing Support

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***Abstract*—Industry 4.0 (I4.0) is vital to advancing manufacturing capabilities to a new level with highly transparent data for decentralized decision-making and flexible manufacturing technologies for mass customization. However, full embracement of I4.0 technologies requires high investments, whereas the resulting return on investment is difficult to predict. This makes adopting I4.0 particularly challenging for small and medium-sized enterprises (SMEs) as they cannot afford investment failures due to severely constrained resources. Despite various studies on SME-specific adoption barriers and methodical approaches, there is no systematic overview of how existing approaches address which barriers. This would be essential to better understand and help develop targeted approaches for successfully adopting I4.0 in SMEs. Based on a systematic literature review, this paper identifies, categorizes and maps I4.0 adoption barriers and existing methodical approaches. Aside from a socio-technical barrier taxonomy, the mapping identifies groups of well-supported barriers and barriers with only limited or even no dedicated approaches. Thus, this paper contributes by mapping adoption barriers and methodical approaches, highlighting popular research areas and gaps for future research. In the medium term, this will help SMEs systematically plan and execute the adoption of I4.0.**

***Keywords*—Industry 4.0; SME; Technology Adoption; Methodical Approach; Barriers; Systematic Literature Review**

I. Introduction

In the current competitive market, manufacturing industry faces challenges such as frequently changing customer demands [1] and needs for customized products with better quality and lower costs, leading to higher product complexity [2]. To cope with these challenges, manufacturing sectors are moving into intelligent manufacturing with digital transformation and process automation, symbolizing the fourth industrial revolution, Industry 4.0 (I4.0). The revolution features mass customization [3], can improve production efficiency, quality, and flexibility, and can enable production customization [2]. Studies have demonstrated the benefits of I4.0, such as increased resource utilization by 13%, reduced project delivery time by 20% and human error by 5% [4], as well as reduction of inventory level by more than 70% and time to deliver by 65% [5]. These benefits would be precious to small and medium-sized enterprises (SMEs) to improve their manufacturing flexibility, productivity, and quality and to reduce the cost and delivery time by adopting I4.0 [6].

However, despite these benefits, I4.0 requires high investment while the return on investment is unclear [7], which causes its challenges. I4.0 adoption is not trivial due to various organizational characteristics of SMEs, such as limited resources, prioritization of production over development, and reliance on a single person for decision-making [8]. SMEs might hesitate when heavy investment or disruption in production is required to update their facilities for new technologies [9]. SMEs also have less internal research and development and fewer I4.0 training programs than large and multinational enterprises [8].

Academia and industry have provided numerous methodical approaches to SMEs. These “approaches” support adoption of I4.0 and are presented in the forms of guidelines, framework, methodology, and roadmap [10, p. 4]. “Guideline Industrie 4.0” by VDMA [11] was one of the earliest guidelines provided by industry. In the guideline, a technological toolbox was provided to the SMEs for understanding their current capabilities and setting goals for a higher maturity level with reference to I4.0 strategy and capabilities. From the academic field, previous studies have proposed approaches such as an adoption roadmap considering SMEs’ budget limitations [12], an adoption framework consisting of a readiness assessment and technology toolboxes [13], and a customer-oriented adoption approach [14]. Despite the variety of existing approaches, several issues have caused confusion and complexity for SMEs. Firstly, there is no common understanding of I4.0 and its technologies between approaches. Secondly, the existing discussion of I4.0 is technology-centric. In contrast, a socio-technical or solution-centric view might be more accessible for SMEs to understand in translating into operation benefits and usefulness of adoption [15], [16]. Finally, although many studies have identified, analyzed, and prioritized the barriers of SMEs, there is a lack of systematic understanding of how existing approaches address the key I4.0 adoption barriers faced by SMEs. Such an effort would allow SMEs to be better supported by providing targeted solutions to tackle the under-discussed adoption barriers.

Based on the overarching question of how SMEs can be supported in adopting I4.0 technologies, the following research

questions of this paper were proposed:
RQ1: What are the existing I4.0 methodical approaches that have addressed barriers faced by SMEs?
RQ2: How well are SMEs supported in addressing the key adoption barriers?
RQ3: What are the gaps and resulting research directions in supporting I4.0 adoption for SMEs?

To answer these questions, this paper uses a systematic literature review to identify and assess existing approaches in addressing barriers faced by SMEs. The results have academic contributions in prioritizing barriers from the perspective of existing adoption approaches. The results also contributed practically to understanding how existing approaches can be applied to address key adoption barriers. In the medium term, this will help develop targeted methodical approaches and thus increase the success of I4.0 adoption and tailor I4.0 to the needs of a specific company and better exploit its full potential.

II. Theoretical background

A. Industry 4.0

I4.0 was introduced in 2011 by a German initiative [17]. Compared to the third industrial revolution (Industry 3.0), which featured mass production [18], I4.0 features mass customization and is characterized by integrating digitalization and automation [3], [17], [19]. I4.0 has several underlying design principles differentiating it from Industry 3.0, such as the interconnection between objects and people, information transparency offered by the interconnection, and decentralized decision-making based on the information [20]. I4.0 can be realized through numerous technologies such as the Internet of Things, cyber-physical systems, cloud computing, big data and artificial intelligence [21], [22]. Selection of technologies varies across companies depending on their manufacturing settings and requirements [23]. The diversity of I4.0 technology and the need to select technologies case-by-case differentiate the adoption of I4.0 from that of single technologies, which causes additional complexity and challenges to SMEs.

B. I4.0 adoption in SMEs

SMEs are the backbone of countries [23]. They are a vital group of firms to economic development [24] and the foundation for manufacturing industry [25]. For example, SMEs formed 99.8% of Australian business in 2022, providing more than half of Australian GDP [26], [27]. However, due to the complexity of I4.0 imposed by the diversity and dynamic evolution of technologies, SMEs struggle to perceive an adequate range of technologies [28].

Organizational size is a critical factor in adopting I4.0, and SMEs adopt I4.0 differently than large enterprises [29]. Due to limited resources and knowledge, SMEs tend to be cautious about adopting I4.0 and are reluctant to invest in uncertain projects. Some SMEs indicate that high transparency might cause unnecessary exposure of sensitive information, which is detrimental to them [30]. Studies also found that SMEs are often late adopters to avoid additional costly investments in immature technologies [25] and instead mimic successful adoption cases [13].

Although literature and industry have provided a variety of approaches for SMEs to adopt I4.0, how SMEs have perceived available approaches remains unclear [31], especially how SME-specific adoption barriers have been addressed. Therefore, this paper evaluated existing approaches and attempted to identify the under-discussed barriers as research gaps.

C. I4.0 adoption barriers

Different studies have explored SME-specific adoption barriers of I4.0, including surveys, interviews, or workshops [31]–[33]. In addition, overview studies have compared and structured barriers to derive a consolidated list. For instance, Ghobakhloo et al. [34] conducted a systematic literature review and developed hierarchies of adoption drivers and barriers using the Technology-Organization-Environmental (TOE) framework [35]. There were also further studies in verifying, categorizing, and prioritizing barriers through empirical studies [36]–[39] or using techniques such as Decision Making Trial and Evaluation Laboratory (DEMATEL) [40], [41], Interpretive Structural Modelling (ISM), Cross-Impact Matrix Multiplication Applied to Classification (MICMAC) [42], [43], Analytic Hierarchy Process (AHP) [37], and Interpretive Ranking Process (IRP) [44]. However, there has not been a study on prioritizing barriers from the perspective of existing adoption approaches.

TABLE I shows a holistic taxonomy of I4.0 adoption barriers that consolidates the mentioned frameworks and adoption barriers. It is based on TOE framework and its combined socio-technical and internal-external company perspective. It was enhanced by an additional structural level to address varying degrees of detail of reported barriers. The barriers are discussed as follows:

Technological barriers. Adopting I4.0 has technological barriers in several aspects, including technology selection complexity, investment risks, implementation complexity, compatibility issues, and cybersecurity risks.

Technology selection for I4.0 is complicated due to the high number of technologies [50]. Furthermore, technologies are rapidly evolving [28], and technological interdependencies become unclear [53]. This also made it hard for SMEs to take their first step in adoption [58].

Financial considerations are another crucial aspect for SMEs in adopting I4.0. On the one hand, investment in I4.0 is costly for SMEs with limited resources [43], [51]. On the other hand, return on investment is usually unclear [7], [51], which makes it hard for SMEs to invest with confidence.

Implementation of I4.0 also has much complexity. Lack of communication standards has made it hard for SMEs to integrate their systems, especially with collaborating partners [49]. There is also a lack of off-the-shelf technologies for SMEs to try themselves [34]. The lack of user-friendly solutions also made it challenging to roll out the technologies for daily operation and training of operators [31], [34].

TABLE I
THE ENHANCED TOE TAXONOMY OF I4.0 ADOPTION BARRIERS.

Category	**Barrier**	**Source**
Technological barriers		
(T1) Cybersecurity risks	(T1.1) Security risks of data sharing	[37], [45], [46]
	(T1.2) Lack of data protection	[29], [31], [33], [34], [36], [38], [41], [44], [47]
(T2) Implementation complexity	(T2.1) Lack of communication standards	[34], [36], [38], [43], [47]–[49]
	(T2.2) Lack of off-the-shelf technologies	[34]
	(T2.3) Lack of user-friendly solutions	[31], [34]
	(T2.4) Unclear Industry 4.0 competency requirements	[36]
(T3) Financial investment risk	(T3.1) High implementation cost	[25], [31], [34], [40], [43]–[45], [47], [48], [50], [51]
	(T3.2) Unclear return on investment	[7], [34], [37], [38], [41], [45], [47], [51], [52]
(T4) Complexity in technology selection	(T4.1) Dynamic evolution and change of technologies	[28]
	(T4.2) Overwhelming choice of technologies	[50]
	(T4.3) Lack of understanding of technological interdependencies	[53]
	(T4.4) Lack of starter solution	[52]
(T5) Lack of compatibility	(T5.1) Lack of compatibility of factory buildings and infrastructure	[31]
	(T5.2) Lack of compatibility with legacy system	[9], [25], [34], [43], [44], [47], [48]
Organizational barriers		
(O1) Organizational and resource constraints	(O1.1) Fear of trade secret exposure	[54]
	(O1.2) Lack of accessibility to recruit competent workforce	[31], [34], [38]
	(O1.3) Lack of financial resources	[31]–[34], [37], [38], [40], [42], [43], [45], [48], [49]
	(O1.4) Focus on daily business operations instead of R&D	[36]
	(O1.5) Required regulatory compliance	[47], [48]
(O2) Lack of management capability	(O2.1) Lack of awareness and knowledge of top management	[34], [36], [42], [43], [45], [50]
	(O2.2) Lack of business model innovation	[30]
	(O2.3) Lack of risk management capabilities	[31], [34]
	(O2.4) Lack of strategic planning and long-term vision	[32], [34], [38], [40], [42], [43], [47], [49], [55]
	(O2.5) Lack of understanding of capability gap	[8]
	(O2.6) Lack of understanding of technology maturity	[56]
(O3) Social barriers	(O3.1) Fear of losing jobs due to new technologies	[7], [38], [40], [42], [43], [45], [47], [48], [57]
	(O3.2) Lack of trust in new technologies	[31], [32], [34]
Environmental barriers		
(E1) Lack of acceptance along supply chain	(E1.1) Lack of customer acceptance	[9], [34], [40]
	(E1.2) Lack of supply chain partner's acceptance	[34], [38], [47]
(E2) Lack of enabling conditions	(E2.1) Lack of accessibility to vendors	[34]
	(E2.2) Low quality of connectivity infrastructure	[33], [34], [37], [45], [48]
(E3) Lack of external support	(E3.1) Lack of accessibility to external training	[37]
	(E3.2) Lack of accessible external financial incentives and support	[34], [37], [41]
	(E3.3) Lack of geographic business clustering and partnerships	[34]
	(E3.4) Lack of collaboration with academia	[34]
	(E3.5) Lack of governmental support and policies	[34], [37], [41], [42], [45]
	(E3.6) Lack of lead adopters	[13], [46]

With unclear competency requirements of I4.0, SMEs also encounter barriers in upskilling their employees [36].

As some SMEs use outdated manufacturing systems, applying new technologies to their existing system might be risky due to compatibility issues [9]. Some SMEs also have old factory buildings and infrastructure, which are not designed for automating internal transports and processes [31].

While I4.0 involves much digital technology [19], the data produced and shared needs to be secured. Inability to secure generated data, security risks in sharing for collaboration with business partners, and leakage of sensitive information have caused barriers to SMEs [29], [33], [45], [46].

Organizational barriers. There are barriers to SMEs related to their organization, such as their characteristics as opposed to large enterprises, capabilities in managing I4.0 projects, and barriers from employees.

Previous studies have outlined the organizational characteristics of SMEs compared to large enterprises [8], [38]. Due to limited resources, SMEs focus on daily business operations instead of research investments [36]. SMEs also have limited access to recruiting competent workforce compared to large enterprises, which are open to global talent market [38]. SMEs also hesitate to adopt I4.0 when there is a need to comply with regulations [48] or to share data, fearing trade secret exposure [54].

Decision-making in SMEs usually depends on the owner [8]. Successful adoption depends on owners' capability to oversee I4.0 in their company. Owners who lack awareness and knowledge can pose barriers in perceiving and adopting I4.0 [50]. Sometimes, SMEs lack an understanding of technology maturity, which causes difficulty in selecting the appropriate technology and avoiding early and risky investment [56]. Unsuccessful adoption can also be associated with SMEs' inability to create an I4.0 vision and create strategic plans, innovate in business model, understand and analyze their capability gap, and manage risk in I4.0 projects [8], [30], [31],

[43], [55].

Social barriers and improper communication with employees also cause barriers. On the one hand, employees might fear losing jobs due to the new technologies [7], [38]. On the other hand, there might be a lack of trust and acceptance for the end operators in using the technologies [31].

Environmental barriers. There are barriers related to the manufacturing environment of SMEs. These are related to enabling conditions, acceptance along supply chain, and other external support.

There are two enabling conditions external to SMEs. Firstly, SMEs rely on technological vendors to implement I4.0. Therefore, accessibility to vendors is critical to SMEs [34]. Secondly, many I4.0 technologies rely on high-speed internet connection. This poses challenges for rural areas with poor connectivity infrastructure [33].

Supply chain consists of upstream suppliers and downstream business partners and customers. Acceptance among supply chain stakeholders directly affects SMEs' decision to implement collaborative I4.0 projects with supply chain partners [47], design new I4.0 products, or provide new I4.0 services to their customers [9].

Lack of other external support crucial to SMEs, such as external training programs, financial incentives, and other governmental support and policies, also poses barriers [34], [37], [41]. Lack of collaboration with academia causes inefficient transfer of newest research to SMEs [34]. Lack of geographic business clustering and partnerships also causes inefficiency in delivering resources to SMEs and engaging collaboration [25], [34]. Finally, since SMEs mimic successful adopters, the absence of lead adopters also poses barriers to adopting I4.0 [13], [46].

The barriers listed in TABLE I were used to assess existing adoption approaches for SMEs. The review steps are described in the next section.

III. Research design and methods

A systematic literature review was conducted to identify published papers on Industry-4.0-SME adoption approaches in a structured manner. This paper adapted the systematic literature review process of [59], which includes the following steps:

Step 1: Database and search terms. An advanced search was conducted on 23rd June 2023 in Elsevier's Scopus database, a systematic and established interdisciplinary literature database [60]. Three sets of search terms were used for searching the literature, which used different synonyms of "Industry 4.0", "SME", and "adoption approach", as shown in Fig. 1. The review included only papers published after 2011, i.e., the year I4.0 was first introduced [17]. To ensure paper quality, the review focused on peer-reviewed journal articles. The results for each search term and filter are shown in Fig. 1, resulting in 478 journal articles for the subsequent screening step.

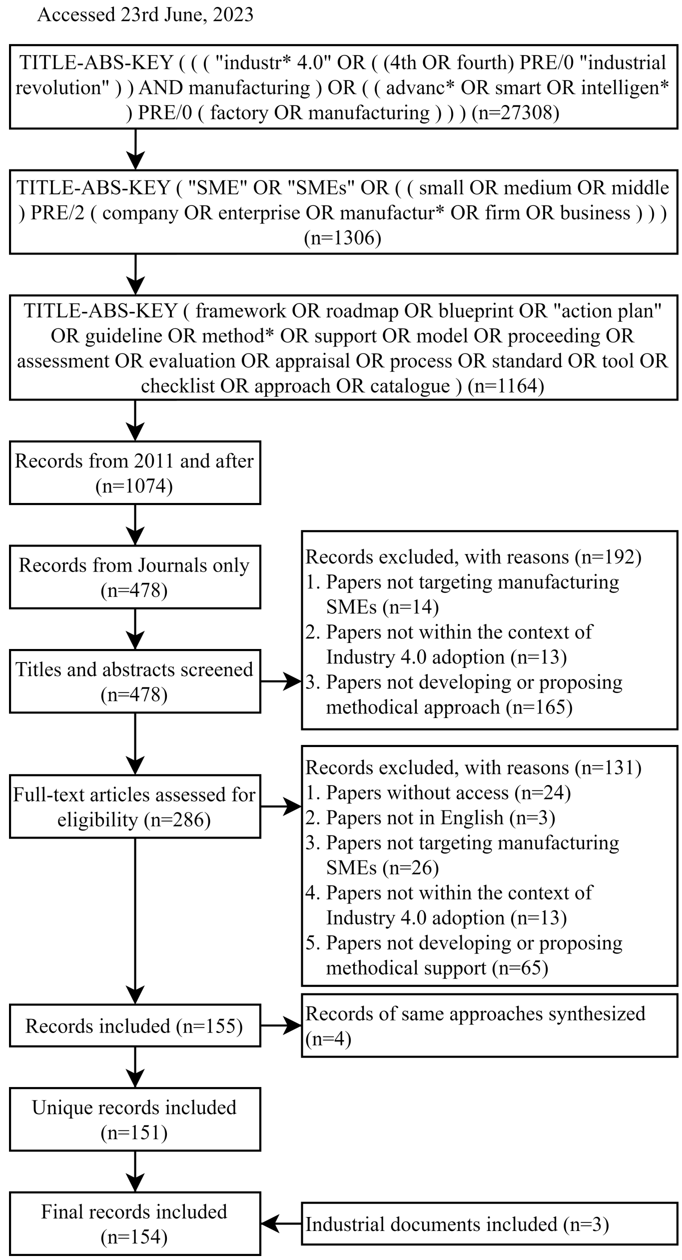

Fig. 1. Review results for different search terms, filters, and stages.

Step 2: Screen and assess papers. The exclusion criteria (see Fig. 1) were developed based on the research questions. In the initial screening step, only titles and abstracts were reviewed, and 192 papers were excluded. In the subsequent detailed assessment, electronic copies of 286 papers were retrieved for full-text reviewing with all exclusion criteria considered, 131 papers were excluded, and four duplicates were removed, as shown in Fig. 1. Finally, 151 papers were included in this step.

Step 3: Extract data. Before reviewing the included papers and extracting data, grey literature like industry reports and guidelines [11], [61], [62] were included to also consider the state of the art in industry in addition to academic publications. Each included paper was assessed and coded 1) on the scope of approach in addressing each barrier in TABLE I and according to the criteria described in TABLE II and 2) on the specificity of the approach according to the criteria described in TABLE III. The extracted data were recorded and organized in Microsoft Excel spreadsheets and were validated with other researchers.

Step 4: Analyze and synthesize data. Data extracted from the review were analyzed and synthesized to answer the research questions proposed in two sub-steps.

Step 4a. For RQ1, relevant approaches were counted and analyzed for each barrier. The number of approaches per barrier was presented in two bar charts, one by the scope (Fig. 3) and another by the specificity (Fig. 4).

Step 4b. To address RQ2 and 3, each approach's scope and specificity were quantified according to values in TABLE II and TABLE III and aggregated to a score through multiplication. The *highest specificity* (i.e., maximum score) and the *accumulated support* (i.e., the weighted sum of approaches) were analyzed for each barrier. The values of *accumulated support* were normalized to be plotted against the *highest specificity*. Using the third quartile of *highest specificity* and that of *accumulated support*, four sections can be differentiated in the portfolio for prioritization, as shown in Fig. 2.

IV. Results and Discussion

This section presents the results and discusses the findings of the review. Firstly, the *highest specificity* and *accumulated support* to the barriers were evaluated to categorize and prioritize the adoption barriers. Secondly, existing approaches for each barrier were analyzed. Finally, alignments of findings with previous studies were discussed, and the resulting research directions were derived.

TABLE II
The assessment criteria of the scope of approaches.

Scope	Value	Description
Holistic approach	1	The approach is in sufficient detail and covers most manufacturing use cases in addressing the barrier.
Semi-holistic approach	0.75	The approach is in sufficient detail but covers limited manufacturing use cases in addressing the barrier.
Context-specific approach	0.5	The approach is in sufficient detail but only covers one manufacturing use case in addressing the barrier.
Abstract approach	0.25	The approach contains high-level concepts to address the barrier.
Not relevant	0	The approach does not address the barrier.

TABLE III
The assessment criteria of the specificity of approaches.

Specificity	Value	Description
Detailed approach	1	Prescriptive approach with detailed steps.
Generic approach	0.75	Prescriptive approach with generic steps.
Conceptual framework	0.5	Prescriptive approach based on heuristics, checklists, or conceptual diagrams.
Use case only	0.25	The approach only describes the use case of an implementation.

A. Evaluation and prioritization of adoption barriers

Using the assessment criteria for the specificity of approaches, the 154 papers consisted of 17 use cases, 28 conceptual frameworks, 41 generic approaches, and 68 detailed approaches. However, only 56 papers were mapped with at least one barrier, and other papers did not address any of the listed barriers in TABLE I.

Approaches for each barrier were summed and grouped by their scope, as shown in Fig. 3. There are 12 barriers without any approach. The barrier of *O2.5 lack of understanding towards capability gaps* has the highest number of approaches, followed by *O2.4 lack of strategic planning and long-term vision*. However, holistic approaches were only identified for *O2.5* and *O2.3 lack of risk management capabilities*. Other approaches for barriers only cover limited manufacturing use cases, with eight barriers only supported by generic approaches.

Approaches for each barrier were also summed and grouped by their specificity, as shown in Fig. 4. The total number of approaches per barrier is the same as in Fig. 3. However, the composition of approaches for each barrier is different. Thirteen barriers have detailed approaches, and others are supported with less specificity.

For further analysis to answer RQ2, the value of each approach was taken into account, where their scores were calculated by the product of their scope and specificity according to TABLE II and TABLE III. *Highest specificity* (i.e., the maximum score) and *accumulated support* (i.e., the weighted sum of approaches) were then analyzed. The results were organized into a portfolio by plotting *highest specificity* against *accumulated support*, as shown in Fig. 5, which shows a more straightforward view of categorized barriers. With the third quartile of *highest specificity* (0.5) and *accumulated support* (0.114), the portfolio was separated into four zones according to Fig. 2. The portfolio shows six well-supported

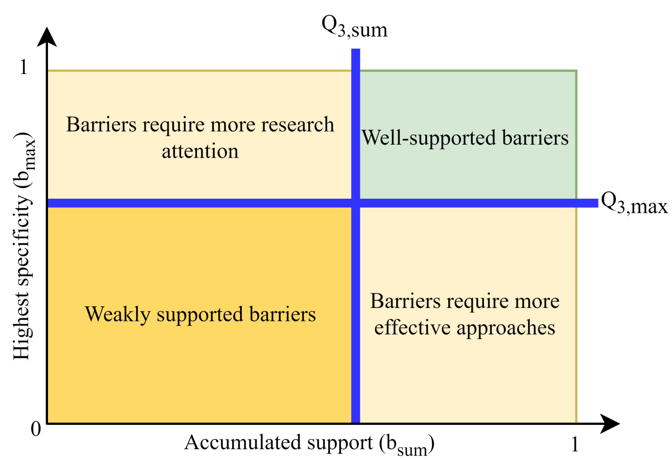

Fig. 2. Portfolio framework of barriers by how well-supported.

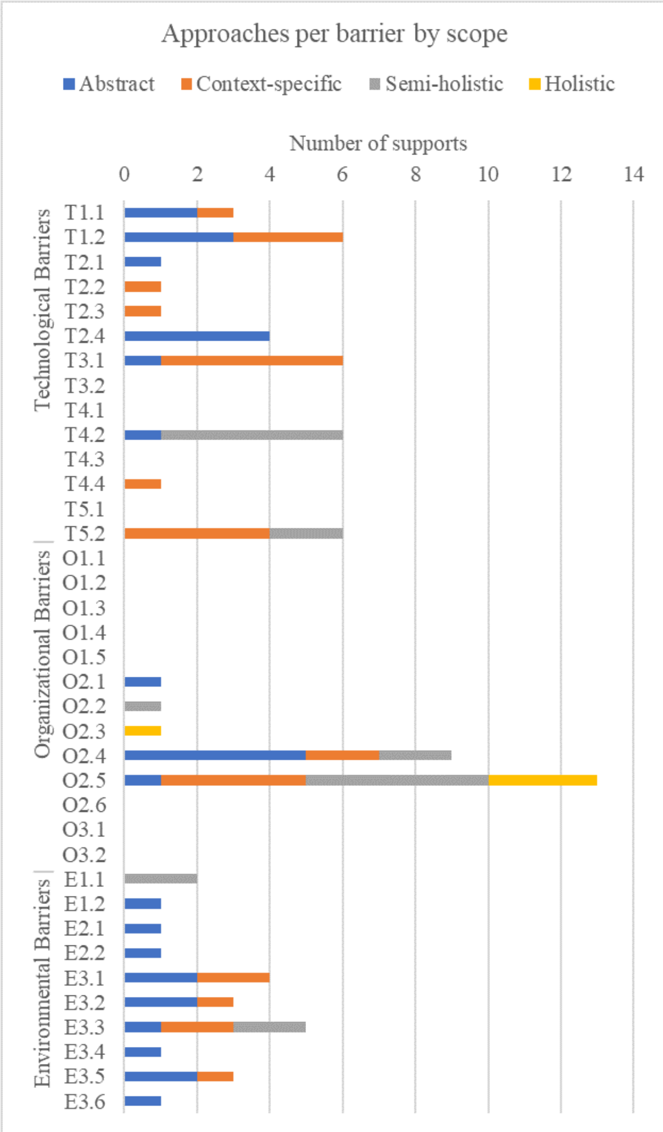

Fig. 3. Number of approaches per barrier detailed with the composition of their scope.

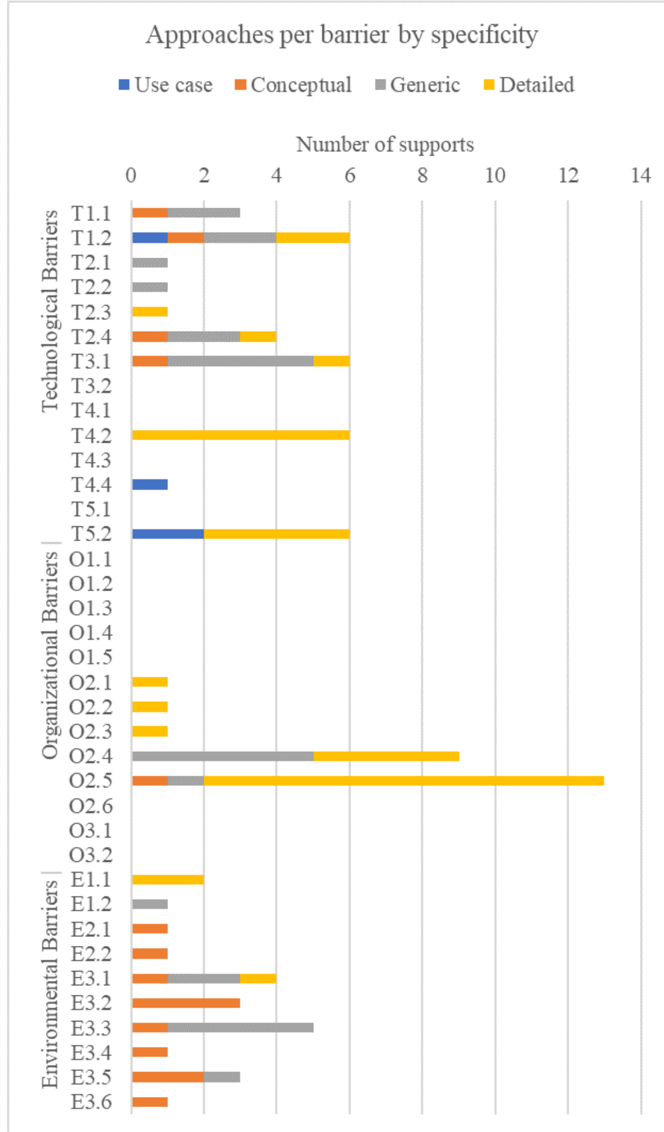

Fig. 4. Number of approaches per barrier detailed with the composition of their specificity.

barriers, three that required more research attention, three that required better-quality approaches, and 25 weakly supported, including 12 without any approach. Compared to the findings from Fig. 3 and Fig. 4, some well-supported or weakly supported barriers are categorized into intermediate categories, which either require more research attention or better-quality approaches. Further details of the approaches are discussed in the next section in deriving the resulting research directions.

B. Existing approaches for adoption barriers

To answer RQ1, approaches included in this paper that address the barriers are discussed from perspectives of technology, organization, and environment:

Approaches that address technological barriers. There are some approaches that address *T1 cybersecurity concerns*, such as [63]–[65], but with limited scope. Although SMEs are expected to rely on vendors and service providers for cybersecurity issues [6], guidelines can be provided to SMEs for building expectations.

Han and Trimi [63] provided a collection of existing communication standards for I4.0 but did not address the connection of systems that use different standards. *T2 high implementation complexity* caused by the lack of communication standards, off-the-shelf technologies, user-friendly solutions, and competency requirements of I4.0 still require specific and practical approaches.

For *T3 high investment risk*, previous studies have supported from two perspectives. On the one hand, several researchers [66]–[69] have proposed low-cost approaches for implementation, however, with limited scope. On the other hand, although the review did not identify any approach for evaluating the return on investment, methodologies such as

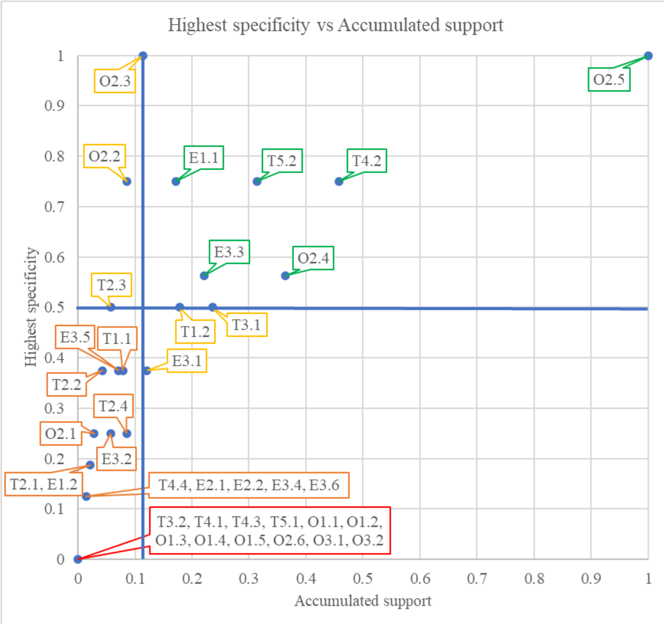

Fig. 5. Scattered plot of quality of approach against research attention.

[70], [71] might provide valuable insights for SMEs.

For *T4 complexity in technology selection*, the review did not identify any approach for monitoring technologies' evolution or interdependencies. However, [28] proposed a methodology for dynamically extracting technologies from Wikipedia, which might be a promising solution. Furthermore, [53] has provided a guide to technological interdependencies, but the applicability to SMEs remains to be assessed. Previous studies such as [13], [72]–[75] have supported SMEs in selecting technologies from the overwhelming choices. However, there is still a gap in providing starter solutions. Amaral and Peças [58] have demonstrated two cases of starter solutions but with limited scope.

For *T5 lack of compatibility*, there were many approaches provided for retrofitting and dealing with compatibility issues [58], [76]–[80]. However, the compatibility of factory buildings and infrastructure for automation is under-discussed.

Approaches that address organizational barriers. The review could not identify any approach that addresses *O1 organizational and resource constraints* and *O3 social barriers*. This complied with literature's understanding that organizational characteristics are natural disadvantages of SMEs that are hardly supported [8]. Nevertheless, the barriers could be addressed indirectly by acquiring external support. For example, lack of financial resources can relate to lack of accessible external financial incentives for easing SMEs' financial difficulties. Similarly, government can also provide support services to recruit competent workforce. Furthermore, employee's fear of job loss and lack of trust in new technologies might be reduced through proper communication and providing training.

More approaches were provided to *O2 lack of manament capability*, which consists of business model innovation methodologies [81], risk management framework [9], road mapping methodologies [5], [12]–[14], [33], [51], [62], [75], [82], [83], readiness and maturity assessment [11], [52], [55], [61], [74], [84]–[89]. Although the review did not identify any approach for understanding technology maturity, methodologies such as [56], [90], [91] might provide useful insights. However, limited approaches were provided to raise awareness and knowledge of top management.

Approaches that address environmental barriers. Previous studies have provided customer-oriented approaches [14]. However, the review identified limited approaches for supply chain-oriented adoption. Previous studies have only provided generic guidance to *E2 lack of enabling conditions* [46]. Also, there were limited studies with a holistic approach that discussed external support. Developing lead adopters would be especially critical because SMEs are late adopters and follow lead adopters to avoid investment failures [13].

C. Resulting research directions

This paper has taken a different perspective in analyzing the barriers by mapping existing approaches to the key adoption barriers and identified 25 barriers (refer to the bottom-left zone of Fig. 5 and TABLE I) with limited or no supporting approaches. This section compares the prioritized barriers with those highlighted by previous studies, discusses future research direction, and answers RQ3.

The results of this paper aligned with existing studies on two major barrier categories—upskilling and financial barriers. On the one hand, findings about upskilling barriers of competency requirements, accessibility to competent workforce and external training aligned with [31]–[33], [36]–[39], [43]–[45]. Although some approaches for external training were identified in the review, their scope is limited. There is a more significant gap in supporting SMEs in perceiving I4.0 competency requirements and recruiting competent workforce. Moreover, clarifying I4.0 competency requirements should provide guidance not only to human resource market but also to academia. On the other hand, findings about prioritization of evaluating return on investment and providing financial support also aligned with [31]–[33], [37], [38], [47]. By justifying the return on investment, SMEs might be able to acquire more investment, and government might provide more financial support.

This paper also found two barriers with different understanding from the literature. Strategic planning and long-term vision were highlighted by [38], [39], [43], and the lack of customer acceptance was highlighted by [40]. However, the review found that these barriers have been relatively well supported, e.g., through road mapping methodologies and customer-oriented adoption approaches. This might show a sign of insufficient knowledge transfer between academia and industry. Nevertheless, with other well-supported barriers, approaches such as technology selection methodologies, compatible solutions, and maturity assessment can provide good references for practitioners in dealing with the barriers and support researchers and industrial parties in developing new adoption guidelines.

To answer RQ3, this paper would like to make suggestions for researchers, technological vendors, and government:

- Future research should focus on supporting the evaluation of return on investment and clarifying I4.0 competency requirements.
- Further research on I4.0 technology should also consider their interdependencies and evaluate their maturity.
- Researchers should also actively engage companies for collaboration and knowledge transfer.
- Technological vendors should support the development and advertisement of lead adopters.
- Vendors should also offer SMEs more off-the-shelf technologies and starter solutions.
- Government should continue to support SMEs by providing financial incentives, legal advice, and training programs.

V. Conclusion

I4.0 can boost capabilities and competitiveness of manufacturing companies. However, SMEs struggle to adopt I4.0 and exploit its full potential successfully. This paper analyzes how well individual adoption barriers have been addressed based on a systematic literature review of existing I4.0 approaches for SMEs. While SMEs are well-supported in strategic planning and capability assessment, there are significant gaps in evaluating the return on investment and supporting upskilling of employees. There are also gaps in dealing with the dynamism of technology and understanding their maturity and interdependencies. Approaches for easing barriers due to organizational characteristics and social barriers are also under-discussed.

This paper contributes to academia by analyzing SMEs' barriers to adopting I4.0 from an alternative perspective of existing adoption approaches and identifies a list of weakly supported barriers that future works should focus on. In the medium term, this will benefit companies by guiding them in identifying suitable approaches when facing various barriers.

This paper has limitations in five aspects:

1) Due to the limited scope of I4.0 adoption for SMEs, approaches for all types of enterprises, including large enterprises, for general technologies, and for other sectors, were not included in the review. These approaches might also provide support to SMEs in adopting I4.0.
2) This paper only included the barriers from SMEs without comparison to general barriers faced by all types of enterprises and those faced by large enterprises. Further comparison can allow a more critical analysis of unique barriers faced by SMEs.
3) This paper also did not consider the interdependencies of adoption barriers. Some of the identified approaches have addressed several barriers, which shows signs of relationships between barriers. Further study can also consider the interdependencies of key adoption barriers from the perspective of adoption approaches [34], which can further refine and prioritize the barriers.
4) This paper did not consider the geographic location of the barriers. Barriers such as low quality of connectivity infrastructure might be a barrier to less developed countries and rural areas rather than to developed countries and metropolitan areas. Approaches can be provided to specific countries and regions by including the geographic attributes of the barrier.
5) This paper considers the approaches provided as accessed by researchers. However, the accessibility and knowledge transfer of existing approaches were not considered.

The next step of this study is to validate the results found in the review through empirical studies and better understand the key adoption barriers by locating them in the adoption process. The goal is to develop guidelines for SMEs in navigating their journey in adopting I4.0.

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References

[1] S. Rakic, M. Pavlovic, and U. Marjanovic, "A precondition of sustainability: Industry 4.0 readiness," *Sustainability*, vol. 13, no. 12, p. 6641, 2021.

[2] S. M. Saad, R. Bahadori, and H. Jafarnejad, "The smart sme technology readiness assessment methodology in the context of industry 4.0," *Journal of Manufacturing Technology Management*, vol. 32, no. 5, pp. 1037–1065, 2021.

[3] P. Zawadzki and K. Żywicki, "Smart product design and production control for effective mass customization in the industry 4.0 concept," *Management and production engineering review*, 2016.

[4] K. Alexopoulos, N. Nikolakis, and E. Xanthakis, "Digital transformation of production planning and control in manufacturing smes-the mold shop case," *Applied Sciences*, vol. 12, no. 21, p. 10788, 2022.

[5] S. Bouchard, G. Abdulnour, and S. Gamache, "Agility and industry 4.0 implementation strategy in a quebec manufacturing sme," *Sustainability*, vol. 14, no. 13, p. 7884, 2022.

[6] 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.

[7] G. Orzes, E. Rauch, S. Bednar, and R. Poklemba, "Industry 4.0 implementation barriers in small and medium sized enterprises: A focus group study," in *2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*. IEEE, 2018, pp. 1348–1352.

[8] 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.

[9] H. S. Birkel, J. W. Veile, J. M. Müller, E. Hartmann, and K.-I. Voigt, "Development of a risk framework for industry 4.0 in the context of sustainability for established manufacturers," *Sustainability*, vol. 11, no. 2, p. 384, 2019.

[10] Blessing and Chakrabarti, *DRM, a design research methodology*. Springer Dordrecht, 2009.

[11] R. Anderl, A. Picard, Y. Wang, J. Fleischer, S. Dosch, B. Klee, and J. Bauer, "Guideline industrie 4.0-guiding principles for the implementation of industrie 4.0 in small and medium sized businesses," in *Vdma forum industrie*, vol. 4, 2015, pp. 1–31.

[12] A. Cotrino, M. A. Sebastián, and C. González-Gaya, "Industry 4.0 roadmap: Implementation for small and medium-sized enterprises," *Applied sciences*, vol. 10, no. 23, p. 8566, 2020.
[13] 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.
[14] V. J. Ramírez-Durán, I. Berges, and A. Illarramendi, "Towards the implementation of industry 4.0: A methodology-based approach oriented to the customer life cycle," *Computers in Industry*, vol. 126, p. 103403, 2021.
[15] J. Macias-Aguayo, G. Yilmaz, A. Mukherjee, and D. McFarlane, "The role of low-cost digitalisation in improving operations management," in *International Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing*. Springer, 2022, pp. 343–355.
[16] B. Schönfuß, D. McFarlane, G. Hawkridge, L. Salter, N. Athanassopoulou, and L. de Silva, "A catalogue of digital solution areas for prioritising the needs of manufacturing smes," *Computers in Industry*, vol. 133, p. 103532, 2021.
[17] 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.
[18] C.-F. Chien, T.-y. Hong, and H.-Z. Guo, "A conceptual framework for "industry 3.5" to empower intelligent manufacturing and case studies," *Procedia Manufacturing*, vol. 11, pp. 2009–2017, 2017.
[19] M. Pedota, L. Grilli, and L. Piscitello, "Technology adoption and upskilling in the wake of industry 4.0," *Technological Forecasting and Social Change*, vol. 187, p. 122085, 2023.
[20] M. Hermann, T. Pentek, and B. Otto, "Design principles for industrie 4.0 scenarios," in *2016 49th Hawaii international conference on system sciences (HICSS)*. IEEE, 2016, pp. 3928–3937.
[21] Z. Suleiman, S. Shaikholla, D. Dikhanbayeva, E. Shehab, and A. Turkyilmaz, "Industry 4.0: Clustering of concepts and characteristics," *Cogent Engineering*, vol. 9, no. 1, p. 2034264, 2022.
[22] M. M. Mabkhot, P. Ferreira, A. Maffei, P. Podržaj, M. Mądziel, D. Antonelli, M. Lanzetta, J. Barata, E. Boffa, M. Finžgar *et al.*, "Mapping industry 4.0 enabling technologies into united nations sustainability development goals," *Sustainability*, vol. 13, no. 5, p. 2560, 2021.
[23] G. Soni, S. Kumar, R. V. Mahto, S. K. Mangla, M. Mittal, and W. M. Lim, "A decision-making framework for industry 4.0 technology implementation: The case of fintech and sustainable supply chain finance for smes," *Technological Forecasting and Social Change*, vol. 180, p. 121686, 2022.
[24] H. K. Mustafa and S. Yaakub, "Innovation and technology adoption challenges: impact on smes' company performance," *International Journal of Accounting*, vol. 3, no. 15, pp. 57–65, 2018.
[25] M. Prause, "Challenges of industry 4.0 technology adoption for smes: the case of japan," *Sustainability*, vol. 11, no. 20, p. 5807, 2019.
[26] A. S. B. a. F. E. Ombudsman. Contribution to Australian Business Numbers — asbfeo.gov.au. [Online]. Available: https://www.asbfeo.gov.au/contribution-australian-business-numbers
[27] ——. Contribution to Australian Gross Domestic Product — asbfeo.gov.au. [Online]. Available: https://www.asbfeo.gov.au/contribution-australian-gross-domestic-product
[28] F. Chiarello, L. Trivelli, A. Bonaccorsi, and G. Fantoni, "Extracting and mapping industry 4.0 technologies using wikipedia," *Computers in Industry*, vol. 100, pp. 244–257, 2018.
[29] J. L. Hopkins, "An investigation into emerging industry 4.0 technologies as drivers of supply chain innovation in australia," *Computers in Industry*, vol. 125, p. 103323, 2021.
[30] 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.
[31] E. Rauch, P. Dallasega, and M. Unterhofer, "Requirements and barriers for introducing smart manufacturing in small and medium-sized enterprises," *IEEE Engineering Management Review*, vol. 47, no. 3, pp. 87–94, 2019.
[32] L. Červenỳ, R. Sloup, T. Červená, M. Riedl, and P. Palátová, "Industry 4.0 as an opportunity and challenge for the furniture industry—a case study," *Sustainability*, vol. 14, no. 20, p. 13325, 2022.
[33] Q. A. Abdulaziz, H. Mad Kaidi, M. Masrom, H. S. Hamzah, S. Sarip, R. A. Dziyauddin, and F. Muhammad-Sukki, "Developing an iot framework for industry 4.0 in malaysian smes: An analysis of current status, practices, and challenges," *Applied Sciences*, vol. 13, no. 6, p. 3658, 2023.
[34] 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.
[35] L. G. Tornatzky, M. Fleischer, and A. K. Chakrabarti, "The processes of technological innovation," *(No Title)*, 1990.
[36] 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, 2021.
[37] Y. Fernando, I. S. Wahyuni-TD, A. Gui, R. B. Ikhsan, F. Mergeresa, and Y. Ganesan, "A mixed-method study on the barriers of industry 4.0 adoption in the indonesian smes manufacturing supply chains," *Journal of Science and Technology Policy Management*, no. ahead-of-print, 2022.
[38] 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.
[39] M. C. Türkeș, I. Oncioiu, H. D. Aslam, A. Marin-Pantelescu, D. I. Topor, and S. Căpușneanu, "Drivers and barriers in using industry 4.0: a perspective of smes in romania," *Processes*, vol. 7, no. 3, p. 153, 2019.
[40] 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, p. 124063, 2020.
[41] V. S. Narwane, R. D. Raut, B. B. Gardas, B. E. Narkhede, and A. Awasthi, "Examining smart manufacturing challenges in the context of micro, small and medium enterprises," *International Journal of Computer Integrated Manufacturing*, vol. 35, no. 12, pp. 1395–1412, 2022.
[42] P. Goel, R. Kumar, H. K. Banga, S. Kaur, R. Kumar, D. Y. Pimenov, and K. Giasin, "Deployment of interpretive structural modeling in barriers to industry 4.0: A case of small and medium enterprises," *Journal of Risk and Financial Management*, vol. 15, no. 4, p. 171, 2022.
[43] S. Joshi, M. Sharma, S. Bartwal, T. Joshi, and M. Prasad, "Critical challenges of integrating opex strategies with i4. 0 technologies in manufacturing smes: A few pieces of evidence from developing economies," *The TQM Journal*, 2022.
[44] V. A. Wankhede and S. Vinodh, "Analysis of barriers of cyber-physical system adoption in small and medium enterprises using interpretive ranking process," *International Journal of Quality & Reliability Management*, vol. 39, no. 10, pp. 2323–2353, 2022.
[45] G. Kumar, A. Bakshi, A. Khandelwal, A. Panchal, and U. Soni, "Analyzing industry 4.0 implementation barriers in indian smes," *Journal of Industrial Integration and Management*, vol. 7, no. 01, pp. 153–169, 2022.
[46] S. Kumar, M. Suhaib, and M. Asjad, "A framework for transforming indian sports goods manufacturing industry," *South Asian Journal of Business and Management Cases*, vol. 10, no. 3, pp. 313–326, 2021.
[47] M. Sharma, R. D. Raut, R. Sehrawat, and A. Ishizaka, "Digitalisation of manufacturing operations: The influential role of organisational, social, environmental, and technological impediments," *Expert Systems with Applications*, vol. 211, p. 118501, 2023.
[48] G. A. Harris, D. Abernathy, L. Lu, A. Hyre, and A. Vinel, "Bringing clarity to issues with adoption of digital manufacturing capabilities: An analysis of multiple independent studies," *Journal of the Knowledge Economy*, pp. 1–22, 2021.
[49] 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.
[50] T. Masood and P. Sonntag, "Industry 4.0: Adoption challenges and benefits for smes," *Computers in Industry*, vol. 121, p. 103261, 2020.
[51] D. Mesa, G. Renda, R. Gorkin III, B. Kuys, and S. M. Cook, "Implementing a design thinking approach to de-risk the digitalisation of manufacturing smes," *Sustainability*, vol. 14, no. 21, p. 14358, 2022.
[52] A. Amaral and P. Peças, "A framework for assessing manufacturing smes industry 4.0 maturity," *Applied Sciences*, vol. 11, no. 13, p. 6127, 2021.

[53] F. Dillinger, O. Bernhard, M. Kagerer, and G. Reinhart, "Industry 4.0 implementation sequence for manufacturing companies," *Production Engineering*, vol. 16, no. 5, pp. 705–718, 2022.
[54] J. Brodeur, R. Pellerin, and I. Deschamps, "Collaborative approach to digital transformation (cadt) model for manufacturing smes," *Journal of Manufacturing Technology Management*, vol. 33, no. 1, pp. 61–83, 2022.
[55] F. Pirola, C. Cimini, and R. Pinto, "Digital readiness assessment of italian smes: a case-study research," *Journal of Manufacturing Technology Management*, vol. 31, no. 5, pp. 1045–1083, 2020.
[56] G. C. Zutin, G. F. Barbosa, P. C. de Barros, E. B. Tiburtino, F. L. F. Kawano, and S. B. Shiki, "Readiness levels of industry 4.0 technologies applied to aircraft manufacturing—a review, challenges and trends," *The International Journal of Advanced Manufacturing Technology*, vol. 120, no. 1-2, pp. 927–943, 2022.
[57] R. Kumar, R. Sindhwani, and P. L. Singh, "Iiot implementation challenges: Analysis and mitigation by blockchain," *Journal of Global Operations and Strategic Sourcing*, vol. 15, no. 3, pp. 363–379, 2022.
[58] A. Amaral and P. Peças, "Smes and industry 4.0: Two case studies of digitalization for a smoother integration," *Computers in Industry*, vol. 125, p. 103333, 2021.
[59] Y. Xiao and M. Watson, "Guidance on conducting a systematic literature review," *Journal of planning education and research*, vol. 39, no. 1, pp. 93–112, 2019.
[60] A. Martín-Martín, E. Orduna-Malea, M. Thelwall, and E. D. López-Cózar, "Google scholar, web of science, and scopus: A systematic comparison of citations in 252 subject categories," *Journal of informetrics*, vol. 12, no. 4, pp. 1160–1177, 2018.
[61] G. Schuh, R. Anderl, R. Dumitrescu, A. Krüger, and M. t. Hompel, "Industry 4.0 maturity index: Managing the digital transformation of companies– update 2020. acatech, munich," 2020.
[62] R. Automation, "The connected enterprise maturity model," 2014.
[63] H. Han and S. Trimi, "Towards a data science platform for improving sme collaboration through industry 4.0 technologies," *Technological Forecasting and Social Change*, vol. 174, p. 121242, 2022.
[64] S. Lazarova-Molnar, N. Mohamed, and J. Al-Jaroodi, "Data analytics framework for industry 4.0: enabling collaboration for added benefits," *IET Collaborative Intelligent Manufacturing*, vol. 1, no. 4, pp. 117–125, 2019.
[65] Y. Zhang, X. Xu, A. Liu, Q. Lu, L. Xu, and F. Tao, "Blockchain-based trust mechanism for iot-based smart manufacturing system," *IEEE Transactions on Computational Social Systems*, vol. 6, no. 6, pp. 1386–1394, 2019.
[66] H. Kim, W.-K. Jung, I.-G. Choi, and S.-H. Ahn, "A low-cost vision-based monitoring of computer numerical control (cnc) machine tools for small and medium-sized enterprises (smes)," *Sensors*, vol. 19, no. 20, p. 4506, 2019.
[67] R. Kumar, K. S. Sangwan, C. Herrmann, and S. Thakur, "A cyber physical production system framework for online monitoring, visualization and control by using cloud, fog, and edge computing technologies," *International Journal of Computer Integrated Manufacturing*, pp. 1–19, 2023.
[68] F. Malapelle, D. Dall'Alba, D. Dalla Fontana, I. Dall'Alba, P. Fiorini, and R. Muradore, "Cost effective quality assessment in industrial parts manufacturing via optical acquisition," *Procedia Manufacturing*, vol. 11, pp. 1207–1214, 2017.
[69] M. Vuković, O. Jorg, M. Hosseinifard, and G. Fantoni, "Low-cost digitalization solution through scalable iiot prototypes," *Applied Sciences*, vol. 12, no. 17, p. 8571, 2022.
[70] J. Butt, "A conceptual framework to support digital transformation in manufacturing using an integrated business process management approach," *Designs*, vol. 4, no. 3, p. 17, 2020.
[71] G. F. Barbosa, S. B. Shiki, and I. B. da Silva, "R&d roadmap for process robotization driven to the digital transformation of the industry 4.0," *Concurrent Engineering*, vol. 28, no. 4, pp. 290–304, 2020.
[72] P. Bhatia and N. Diaz-Elsayed, "Facilitating decision-making for the adoption of smart manufacturing technologies by smes via fuzzy topsis," *International Journal of Production Economics*, vol. 257, p. 108762, 2023.
[73] W. de Paula Ferreira, F. Armellini, L. A. de Santa-Eulalia, and V. Thomasset-Laperrière, "A framework for identifying and analysing industry 4.0 scenarios," *Journal of Manufacturing Systems*, vol. 65, pp. 192–207, 2022.
[74] E. Rauch, M. Unterhofer, R. A. Rojas, L. Gualtieri, M. Woschank, and D. T. Matt, "A maturity level-based assessment tool to enhance the implementation of industry 4.0 in small and medium-sized enterprises," *Sustainability*, vol. 12, no. 9, p. 3559, 2020.
[75] A. T. Sufian, B. M. Abdullah, M. Ateeq, R. Wah, and D. Clements, "Six-gear roadmap towards the smart factory," *Applied Sciences*, vol. 11, no. 8, p. 3568, 2021.
[76] B.-Y. Ooi, W.-K. Lee, M. Shubert, Y.-W. Ooi, C.-Y. Chin, and W.-H. Woo, "A flexible and reliable internet-of-things solution for real-time production tracking with high performance and secure communication," *IEEE Transactions on Industry Applications*, 2023.
[77] T.-A. Chen, S.-C. Chen, W. Tang, and B.-T. Chen, "Internet of things: Development intelligent programmable iot controller for emerging industry applications," *Sensors*, vol. 22, no. 14, p. 5138, 2022.
[78] A. Averyanov, S. Aheleroff, J. Polzer, and X. Xu, "Digitising a machine tool for smart factories," *Machines*, vol. 10, no. 11, p. 1093, 2022.
[79] Á. García, A. Bregon, and M. A. Martínez-Prieto, "A non-intrusive industry 4.0 retrofitting approach for collaborative maintenance in traditional manufacturing," *Computers & Industrial Engineering*, vol. 164, p. 107896, 2022.
[80] J. I. García, R. E. Cano, and J. D. Contreras, "Digital retrofit: A first step toward the adoption of industry 4.0 to the manufacturing systems of small and medium-sized enterprises," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 234, no. 8, pp. 1156–1169, 2020.
[81] J. M. Müller, "Business model innovation in small-and medium-sized enterprises: Strategies for industry 4.0 providers and users," *Journal of Manufacturing Technology Management*, vol. 30, no. 8, pp. 1127–1142, 2019.
[82] M. Spaltini, C. Sassanelli, M. Rossi, S. Terzi, M. Taisch *et al.*, "Using wastes as driver to integrate digital and engineering practices maturity in the product development process: an application case," ... *SUMMER SCHOOL FRANCESCO TURCO. PROCEEDINGS*, pp. 1–6, 2021.
[83] K. Bär, Z. N. L. Herbert-Hansen, and W. Khalid, "Considering industry 4.0 aspects in the supply chain for an sme," *Production Engineering*, vol. 12, pp. 747–758, 2018.
[84] S. R. B. Rahamaddulla, Z. Leman, B. H. T. B. Baharudin, and S. A. Ahmad, "Conceptualizing smart manufacturing readiness-maturity model for small and medium enterprise (sme) in malaysia," *Sustainability*, vol. 13, no. 17, p. 9793, 2021.
[85] E. Oztemel and S. Ozel, "A conceptual model for measuring the competency level of small and medium-sized enterprises (smes)." *Advances in Production Engineering & Management*, vol. 16, no. 1, 2021.
[86] H. M. Naeem and P. Garengo, "The interplay between industry 4.0 maturity of manufacturing processes and performance measurement and management in smes," *International Journal of Productivity and Performance Management*, vol. 71, no. 4, pp. 1034–1058, 2022.
[87] J. Lee, S. Jun, T.-W. Chang, and J. Park, "A smartness assessment framework for smart factories using analytic network process," *Sustainability*, vol. 9, no. 5, p. 794, 2017.
[88] A. P. T. Ellefsen, J. Oleśków-Szłapka, G. Pawłowski, and A. Toboła, "Striving for excellence in ai implementation: Ai maturity model framework and preliminary research results," *LogForum*, vol. 15, no. 3, 2019.
[89] M. Spaltini, F. Acerbi, M. Pinzone, S. Gusmeroli, and M. Taisch, "Defining the roadmap towards industry 4.0: The 6ps maturity model for manufacturing smes," *Procedia CIRP*, vol. 105, pp. 631–636, 2022.
[90] G. Schuh, P. Scholz, and M. Patzwald, "Technological trends in context of industry 4.0 and their industrial applications," in *2019 60th International Scientific Conference on Information Technology and Management Science of Riga Technical University (ITMS)*. IEEE, 2019, pp. 1–6.
[91] M. M. Queiroz, S. Fosso Wamba, C. J. Chiappetta Jabbour, A. B. Lopes de Sousa Jabbour, and M. C. Machado, "Adoption of industry 4.0 technologies by organizations: a maturity levels perspective," *Annals of Operations Research*, pp. 1–27, 2022.