Modeling of barriers to digital transformations in Indian manufacturing small and medium-sized enterprises

Article *in* Journal of Science and Technology Policy Management · June 2024

DOI: 10.1108/JSTPM-10-2023-0175

3 authors, including:

Tejendra Singh Gaur
Manipal University Jaipur

Vinod Yadav
Manipal University Jaipur

Modeling of barriers to digital transformations in Indian manufacturing small and medium-sized enterprises

Nikita Borana
Indian Institute of Management Sirmaur, Paonta Sahib, India, and
Tejendra Singh Gaur and Vinod Yadav
Department of Mechanical Engineering, Manipal University Jaipur, Jaipur, India

Received 19 October 2023
Revised 13 February 2024
Accepted 15 May 2024

Abstract

Purpose – In recent times, digital transformation (DT) has witnessed a surge in popularity, not only within large enterprises (LEs) but also among small and medium-sized enterprises (SMEs). Various sectors, including manufacturing, have shown a keen interest in embracing DT for their operational and supply chain needs. Beyond delivering benefits such as improved product quality, revenue growth, enhanced customer service and heightened safety measures, DT offers a range of advantages, including heightened productivity, risk mitigation and environmental protection. However, in developing countries like India, manufacturing SMEs encounter significant challenges when attempting to embrace DT. Therefore, this study aims to identify and model the obstacles that impede DT adoption within the context of Indian manufacturing SMEs.

Design/methodology/approach – The literature review was used to pinpoint the barriers to adopting DT. Subsequently, these identified barriers underwent validation within the specific context of Indian manufacturing SMEs through the assessment of an expert team. The expert team proceeded to model these barriers using the interpretive structural modeling approach.

Findings – This study shows that high investment, return on investment and multiskilled workforces are the most crucial barriers to DT adoption. The proposed study aids policy and decision-makers in identifying the connections and dependencies between the barriers.

Originality/value – It provides a guideline for practitioners to deal with DT adoption barriers in the Indian manufacturing SMEs.

Keywords Digital transformation, Manufacturing, SMEs, Barriers, Interpretive structural modelling, Industry 4.0

Paper type Research paper

1. Introduction

Small and medium-sized enterprises (SMEs) are known as significant participants in extensive supply chain networks of various sectors (Busto Parra *et al.*, 2022). In the manufacturing sector, SMEs are required to produce products with better quality, flexibility and variation, as well as quicker deliveries and lesser costs due to increased competition and narrow profit margins (Rad *et al.*, 2022; Shukla and Shankar, 2022). Unfortunately, manufacturing SMEs experience poor organizational performance because of low productivity, poor quality, larger lead times for product development and high inventories (Ali and Aboelmaged, 2022; Tripathi and Gupta, 2021a). The adoption of digital

Journal of Science and Technology Policy Management
© Emerald Publishing Limited
2053-4620
DOI 10.1108/JSTPM-10-2023-0175

transformation (DT) could play a noteworthy role in solving the issues and gaining a competitive advantage (Rocha *et al.*, 2023; Tieng *et al.*, 2022).

Manufacturing SMEs are keen on DT for their operations and supply chains (Austin, 1994; Kevin Tseng and Johnsen, 2011). Along with better products, revenue growth, improved customer service and increased safety, DT has various benefits such as enhancing output, lowering risks and safeguarding the environment (Khan *et al.*, 2023a; Pfaff *et al.*, 2023; Wang and Shang, 2023). However, developed countries have adopted DT but developing countries like India are still facing numerous hurdles to adopting DT. DT has been applied sparingly too SMEs thus far (Kumar *et al.*, 2023a). The suitability of DT for Indian manufacturing SMEs is called into question given its limited application. This article aims to respond to that query.

Indian manufacturing SMEs are making efforts to implement DT in their businesses, but they are facing numerous hurdles while adopting DT (Kumar *et al.*, 2022). With the advancement of internet-based technologies, the risk of security breaches has become a major issue (Culot *et al.*, 2019; Hajda *et al.*, 2021). In SMEs, the workforce does not have sufficient knowledge about the DT which may lead to failure in the implementation of DT (Demirkesen and Tezel, 2021; Jankowska *et al.*, 2023). To overcome this barrier, training and skill development programs for their untrained personnel are crucial and required additional funding (Aranda Jiménez *et al.*, 2022; Chen and Su, 2023; Dobrosotskiy *et al.*, 2019; Kumar *et al.*, 2022). Even after providing training to workers, there could be possibility that workers could not adopt DT because of various reasons. This situation can be called as resistance to change. (Demirkesen and Tezel, 2021; Tripathi and Gupta, 2021a). Additional investment is also required if a company wants to hire talented personnel. Another hindrance may be because of uncertainty about return on investment (ROI) for DT (Bakhtari *et al.*, 2021; Ronaghi, 2022; Sundarakani *et al.*, 2021). In addition, the heterogeneity of information makes DT implementation difficult (Raj *et al.*, 2020).

Several studies have provided various barriers to DT (Ajmera and Jain, 2019; Joseph Jerome *et al.*, 2022; Raj *et al.*, 2020), but studies that have provided barriers to DT in Indian manufacturing SMEs context are scant. Therefore, the current study aims to explore the various barriers to adopting DT. Section 2 throws light on the existing literature on SMEs, DT and the challenges to adopting DT. Section 3 shows research methodology, in Section 4, results are provided, Section 5 comprises discussion with implications and Section 6 shows conclusion, limitations and future research direction.

2. Theoretical background

SMEs play a paramount role, exclusively in the developing economy like India. It can also be seen as a remarkably appealing and creative system that provides support to larger companies in some areas of operations where they are better able to supply. The contribution of SMEs to social stability, economic growth and job creation is also significant (ALshubiri *et al.*, 2023; Kumar *et al.*, 2017; Kumar *et al.*, 2023b; Raj *et al.*, 2020). SMEs are often more efficient at emerging tasks such as the supply of unprocessed materials and delivering finished goods (Kumar *et al.*, 2020).

The implementation of DT within SMEs holds significant importance in terms of generating competitive advantages and bolstering national economies. Historically, a nation's economic progress has been closely linked to the development and expansion of its manufacturing sectors (Ahmad and Schreyer, 2016). Specifically, within manufacturing, DT has the potential to benefit SMEs by enhancing production efficiency, reducing operational expenses, elevating product quality and fostering innovation in the creation of new products

(Doh and Kim, 2014; Kusiak, 2018; Parida *et al.*, 2021; Zhang *et al.*, 2023). By reducing time-consuming tasks through automation, IoTs offers a competitive advantage, enabling businesses to use innovative technology and continuously improve their processes (Aamer *et al.*, 2023; De La Vega Hernández and Diáz Amorin, 2023; Müller *et al.*, 2018). Industrial businesses primarily use DT to self-monitor operations and production processes (Bag *et al.*, 2020). Although large corporations have implemented DT, SMEs are still facing difficulties to adopt DT, particularly from the production, logistics, managerial and administrative perspectives (Modrak *et al.*, 2019; Sachdeva *et al.*, 2021). DT adoption is problematic for SMEs because their priorities may differ from those of large enterprises (Les), they are more concerned with immediate benefits and costs and some of them lack prior knowledge or experience (Masood and Sonntag, 2020).

Jung and Jin (2018) studied the adoption of DT, taking three SMEs in South Korea as a case study. These three SMEs were not reluctant to adopt DT because of shortage of funds. Even though they are very interested in creating low-level implementations, they face significant challenges in scaling these implementations due to limited resources and expertise. More research is being conducted on the technological implementation of DT, and the majority of case studies show obstacles to SME acknowledgment due to a number of technical issues (Contreras Pérez *et al.*, 2018; Nimawat and Gidwani, 2021). Orzes *et al.* (2018) attempted to empirically identify the most current hurdles in DT adoption with the help of a group study of 37 SMEs in several countries. Six challenges were identified by the proposed study. These barriers were technical, economic, cultural, financial, legal, implementation processes and competence and resources. Masood and Sonntag (2020) mentioned that limitation of financial resources, knowledge resources and technology awareness are key barriers to DT adoption in SMEs context. Establishing clear and authoritative segments is essential to achieve the seamless coordination needed for DT. This type of hurdle becomes more pronounced when multiple organizations within the value chain seek to integrate. Greater connectivity, including complex connections among various companies in the value chain, raises concerns regarding the privacy implications of sharing data with partner channels (Geissbauer *et al.*, 2014). When several businesses along the value chain need integration partners in addition, the difficulty in the adoption of DT is increased (Raj *et al.*, 2020).

The team needed to carry out DT mainly consists of data analysts, data scientists, skilled coders familiar with data and experts in specific subjects. However, there's a scarcity of these talents in today's job market and hiring them can be expensive. This puts businesses in competition with major online companies for top-notch professionals (Melaka Malaysia and Ahmed, 2020; Geissbauer *et al.*, 2014). Buer *et al.* (2018), noted that high implementation costs have been a significant barrier to adopting DT. Rajput and Singh (2019) emphasized that addressing issues related to semantic interoperability and the digitization process is crucial for effective implementation and should be carefully considered. Consistency, culmination, exactness and excess are four perspectives on information (Chen *et al.*, 2014; Dutta *et al.*, 2020). In the age of widely recognized big data, where businesses are heavily interconnected, a massive amount of diverse and complex information is generated. This makes it difficult to determine the accuracy and completeness of this information, raising the risk of incorrect findings (Dutta *et al.*, 2020). A hindrance to DT is a workforce that is resistant to embracing new technologies and innovations. This workforce opposes the introduction of new practices and procedures (Haddud *et al.*, 2017).

Breunig *et al.* (2016) talked about businesses being concerned about digital security and the risk of their data being compromised by external software and service providers. According to Raj *et al.* (2020), highly interconnected systems offer hackers greater opportunities for attacks, making companies more worried about exchanging information with service providers and external software. In a study by Buntz (2016), it was found that 33% of respondents in Penton's survey identified the absence of a framework as a challenge when dealing with IoT. The survey also revealed that numerous companies are currently collaborating instead of competing when it comes to the essential framework development needed for DT. Maintaining consistent and accurate information can be a significant challenge when data constantly changes among different colleagues, especially in the context of increased business connectivity brought about by DT (Khan *et al.*, 2014). According to Geissbauer *et al.* (2014), one of the foremost hindrances to DT adoption is the presence of underqualified employees because organizations are becoming more reliant on data and need a skilled workforce. Xia *et al.* (2023) revealed that labour cost is acting as a barrier in cotton industries of China. Arroyabe *et al.* (2024) mentioned that European small and medium-sized manufacturing businesses encounter challenges when trying to embrace DT. These challenges can arise from within the organization, like a shortage of funds, knowledge or internal resistance. External factors, such as uncertainties in the environment and regulatory gaps, can also contribute to these difficulties. Lack of familiarity with technology, high costs, absence of regulations, technological challenges and scalability issues are significant barriers that have a strong impact (Vern *et al.*, 2023).

Most of the studies were focused on barriers to adoption of DT in developing and developed countries and fewer studies were focused on SMEs. The proposed study aims to fill this research gap and provide contextual relationship among the DT adoption barriers to Indian manufacturing SMEs.

3. Research methodology

Current study aims to identify DT adoption barriers in the Indian manufacturing SMEs and create a model for these barriers. This modelling process elucidates the connections among these barriers. The methodology used for proposed study is depicted in Figure 1. First, existing literature was reviewed to find the barriers. Several databases for instance ScienceDirect, Emerald, Wiley, Taylor & Francis and Springer were used to identify relevant literature sources. A barrier list was prepared with the help of existing literature. To validate these barriers within the specific context of Indian manufacturing SMEs, an expert team comprising five members was formed (see Table 1). Here it was assumed in this study that the expert team has sufficient experience and could have significant insights on adoption of DT. Expert's opinions are generalized, and insights of the study could be applied to whole Indian manufacturing SMEs.

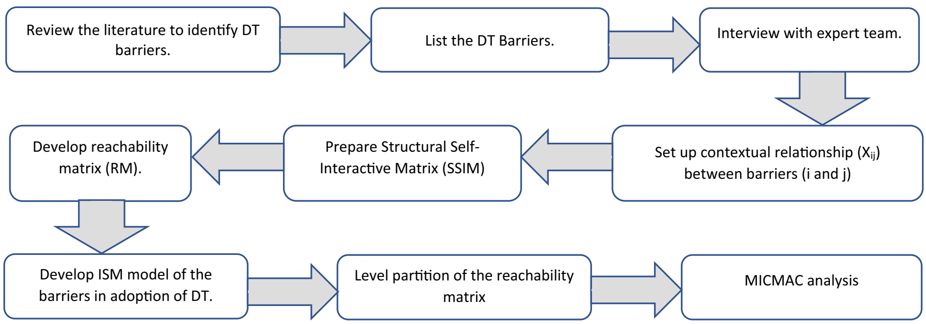


Figure 1. Research methodology

Source: Authors own work

The identified barriers were discussed with experts in the form of an interview for validation purposes. The expert team was interviewed through MS Teams. The length of the interview was around 2 h. In the discussion, it was found that the barriers are interrelated to each other and therefore interpretive structural modeling (ISM) was used to deal with interdependent factors. ISM stands as a proven method for advancing theories, aiding researchers in recognizing and confirming connections among distinct elements that jointly characterize a system. This system could pertain to a specific problem, issue or phenomenon. ISM stands out in crafting visual depictions of intricate systems and transforming ambiguous and loosely expressed mental concepts into organized and significant hierarchical models (Ching *et al.*, 2022). Dealing with complex systems can be difficult because they involve numerous interrelated aspects. We require a system that can recognize and rank these elements to simplify the process. This issue can be resolved using the ISM approach. It is a method of decision-making that builds a model of all the variables that affect a system. This model explains the relationships between the most significant components and their relative complexity.

Ravi and Shankar (2005) used ISM approach to find interaction among 11 identified reverse logistics barriers. Yadav *et al.* (2019) used ISM tool to model the interrelationship among lean barriers in SMEs context. The ISM approach is not thoroughly explained in this work because such information is already available in the literature (Agrawal *et al.*, 2019; Ravi and Shankar, 2005; Yadav *et al.*, 2019).

ISM proves to be a valuable tool for comprehending the interconnections among the identified barriers to DT in SMEs. The ISM model is constructed through a series of steps, as outlined below:

- Step 1 – It involves identifying the variables that exert an influence on the system under study.
- Step 2 – Next, structural self-interactive matrix (SSIM) is formed by selecting contextual relationships that illustrate the interdependence between all potential pairs of elements.
- Step 3- The reachability matrix (RM) is then generated using the SSIM and is put through transitivity testing. The essential tenet of ISM is that contextual interactions are transitive. This indicates that X must be related to Z if variable X is related to Y and Y is related to Z.
- Step 4 – MICMAC analysis is applied to categorize variables according to their dependent and driving power.
- Step 5 – Levels are assigned to RM obtained in Step 4.

S.N.	Designation	Experience (in years)	Field
1	Professor	15	Production and operations management
2	Professor	20	Product development and small business management
3	Supply chain manager	12	FMCG
4	Production manager	13	Automobile
5	Product development managers	15	Manufacturing

Source: Authors' own work

Table 1. Details of the expert team

- Step 6 – The connections found in RM are used to construct a directed graph or ISM model, and transitive links are removed.
- Step 7 – For any conceptual consistency gaps, the ISM model developed in Step 6 is carefully examined and any necessary corrections are performed.

The results stemming from the ISM analysis are presented and discussed in the subsequent section.

4. Results

Through literature review, eight barriers to adopting DT were identified and then validated by the expert team. ISM tool was used to model the barriers by the opinion of the expert team. The results of ISM are presented step by step below:

4.1 Identification of barriers

Eight barriers to DT adoption were identified by the literature review. These barriers were validated by the expert team in Indian manufacturing SMEs (see Table 2).

4.2 Contextual relationship

Based on expert interviews the contextual relationship (X_{ij}) between barriers (i and j) are created (Barve *et al.*, 2007).

4.3 SSIM for barriers

SSIM is prepared by contextual relationships as shown in Table 3. In this, the relation (X_{ij}) between barriers (*i* and *j*) is denoted by four symbols "V," "A," "X" and "O" and these symbols are used when "*i*" leads to "*j*," "*j*" leads to "*i*," "*i*" and "*j*" leads each other and "*i*" and "*j*" are not related to each other, respectively. For example, there is no interrelationship between B1 (High investment) and B8 (Resistance to change), therefore in first cell of first row and column, "O" is filled in the SSIM.

4.4 RM

RM is created by replacing "V," "A," "X" and "O" by "1" and "0" as per following substitution rule as shown in Table 4:

For input "V," (*i*, *j*) and (*j*, *i*) become 1 and 0, respectively.
Similarly, for input "A," (*i*, *j*) and (*j*, *i*) become 0 and 1, respectively.
For input "X," both (*i*, *j*) and (*j*, *i*) become 1.
And for input "O," both (*i*, *j*) and (*j*, *i*) become 0.

The final RM is then created from the initial RM using the transitivity principle, as shown in Table 5. According to this principle if A leads to B and B leads to C then A will lead to C.

4.5 Level partitioning

The structure of RM consists of tiers each containing a reachability set and an antecedent set, for every barrier. The reachability set for each barrier includes not the barrier itself but any additional barriers that contribute to its achievement. Similarly, the antecedent set includes the barriers in question and any others that help in their completion. The intersection set for each barrier is determined by identifying the barriers between the reachability and antecedent sets. At the level the barrier is positioned with the collection of reachability and intersection elements. Consequently, when a barrier reaches an intersection set first it moves to the level of hierarchy called Level 1. Once a barrier reaches this level it is

S. no.	Barriers	Brief explanation	References
1	High investment (B1)	Significant funds are required for DT adoption. Funds may be for infrastructure, providing training and awareness programs, hiring multiskilled employees, etc	(Breunig *et al.*, 2016; Buer *et al.*, 2018; Geissbauer *et al.*, 2014; Kache and Seuring, 2017; Kamble *et al.*, 2018; Oesterreich and Teuteberg, 2016; Raj *et al.*, 2020; Xia *et al.*, 2023)
2	Return on investment (B2)	Usefulness gains and financial advantages of mechanical execution are muddled because of divided execution across the worth chain	(Alraja *et al.*, 2023; Kamble *et al.*, 2018; Oesterreich and Teuteberg, 2016; Raj *et al.*, 2020)
3	Risk of security breaches (B3)	Information exchange among value chain partners may lead to the loss of private data	(Breunig *et al.*, 2016; Buer *et al.*, 2018; Geissbauer *et al.*, 2014; Kamble *et al.*, 2018; Lee and Lee, 2015; Oesterreich and Teuteberg, 2016; Petrillo *et al.*, 2018; Raj *et al.*, 2020; Xu *et al.*, 2018)
4	Standard infrastructure (B4)	A wide-ranging broadband digital infrastructure is required	(Buntz, 2016; Kamble *et al.*, 2018; Raj *et al.*, 2020; Xu *et al.*, 2018)
5	Value-chain integration (B5)	When several value stream components require integration, the difficulty is increased	(Breunig *et al.*, 2016; Buer *et al.*, 2018; Geissbauer *et al.*, 2014; Kamble *et al.*, 2018; Petrillo *et al.*, 2018; Raj *et al.*, 2020; Surucu-Balci *et al.*, 2024; Xu *et al.*, 2018)
6	Data management (B6)	The complex nature of heterogeneous data is responsible for data accuracy	(Buer *et al.*, 2018; Z. K. Chen *et al.*, 2014; Haddud *et al.*, 2017; N. Khan *et al.*, 2014; Raj *et al.*, 2020; Xu *et al.*, 2018)
7	Multiskilled workforce (B7)	Multiskilled employees are required in DT adoption as they can change overall system performance	(Breunig *et al.*, 2016; Falco and Kleinhans, 2018; Geissbauer *et al.*, 2014; Kamble *et al.*, 2018)
8	Resistance to change (B8)	Employees that are using traditional ways/ processes or technology may not accept DT	(Haddud *et al.*, 2017; Raj *et al.*, 2020)

Source: Authors' own work

Table 2.
Identified barriers

Barriers	B8	B7	B6	B5	B4	B3	B2	B1
High investment (B1)	O	V	V	V	V	V	O	
Return on investment (B2)	O	V	V	V	V	V		
Risk of security breaches (B3)	O	A	A	A	A			
Standard infrastructure (B4)	A	A	V	V				
Value-chain integration (B5)	A	A	V					
Data management (B6)	O	A						
Multiskilled workforce (B7)	V							
Resistance to change (B8)								

Source: Authors' own work

Table 3.
Structural self-interactive matrix

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	Driving power
B1	1	0	1	1	1	1	1	0	6
B2	0	1	1	1	1	1	1	0	6
B3	0	0	1	0	0	0	0	0	1
B4	0	0	1	1	1	1	0	0	4
B5	0	0	1	0	1	1	0	0	3
B6	0	0	1	0	0	1	0	0	2
B7	0	0	1	1	1	1	1	1	6
B8	0	0	0	1	1	0	0	1	3
Dependence power	1	1	7	5	6	6	3	2	

Source: Authors' own work

Table 4.
Reachability matrix

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	Driving power
B1	1	0	1	1	1	1	1	1*	7
B2	0	1	1	1	1	1	1	1*	7
B3	0	0	1	0	0	0	0	0	1
B4	0	0	1	1	1	1	0	0	4
B5	0	0	1	0	1	1	0	0	3
B6	0	0	1	0	0	1	0	0	2
B7	0	0	1	1	1	1	1	1	6
B8	0	0	1*	1	1	1*	0	1	5
Dependence power	1	1	8	5	6	7	3	4	

Source: Authors' own work

Table 5.
Final reachability matrix

removed from levels after partitioning. Subsequently, a similar process is followed to determine the level of each barrier as described in Kannan and Haq (2007). The partitioning of levels for a total of eight barriers, with seven levels can be found in Table 6.

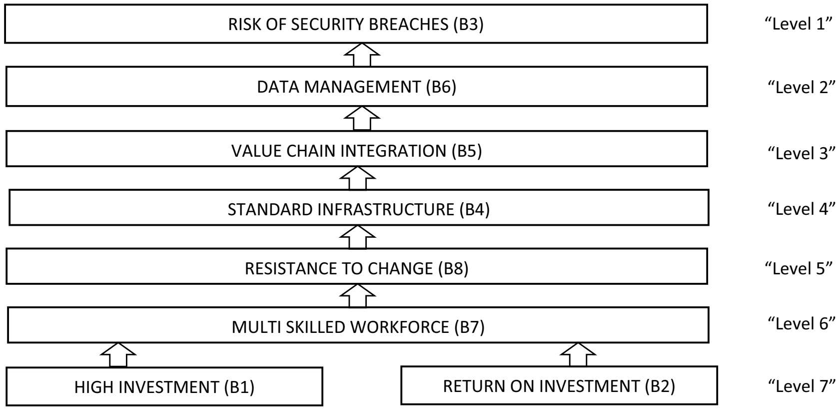
4.6 Digraph (interpretive structural modeling model)

The hierarchical model is generated based on the ultimate partition level (Table 6), and its representation is depicted in Figure 2. This model takes the form of a hierarchical structure,

Barriers	Reachability	Antecedent	Intersection	Level
B1	1, 3, 4, 5, 6, 7, 8	1	1	7
B2	2, 3, 4, 5, 6, 7, 8	2	2	7
B3	3	1, 2, 3, 4, 5, 6, 7, 8	3	1
B4	3, 4, 5, 6	1, 2, 4, 7, 8	4	4
B5	3, 5, 6	1, 2, 4, 5, 7, 8	5	3
B6	3, 6	1, 2, 4, 5, 6, 7, 8	6	2
B7	3, 4, 5, 6, 7, 8	1, 2, 7	7	6
B8	3, 4, 5, 6, 8	1, 2, 7, 8	8	5

Source: Authors own work

Table 6.
Level partition of the final reachability matrix



Source: Authors own work

Figure 2.
ISM model

illustrating the interrelationships among various factors at different levels of interdependence. At the highest tier of the ISM-based model, we find Level I barriers, followed by Level II factors in the next tier and so forth, ultimately culminating with Level VI barriers at the lowest level. Each level of barriers serves to facilitate the completion of the barriers situated above them. The arrangement of these barriers in the ISM-based model offers valuable insights into their impact on the adoption of DT.

The MICMAC principle relies on the matrix multiplication properties. In this context, MICMAC analysis was applied to delve deeper into identifying the primary barriers that must be addressed initially when embracing DT. This study identified four distinct categories of barriers: autonomous, dominated/dependent, relay/linkage and independent barriers (see Figure 3) (Shukla and Shankar, 2022; Yadav *et al.*, 2019). Table 5 contains the estimated dependent and driving powers for each barrier:

(1) Autonomous (Zone I) – Barriers situated within this zone exhibit minimal interdependence and influence. They do not exert a substantial effect on the overall system. According to Figure 3, there are no barriers categorized within the autonomous zone. This signifies that every barrier exerts some level of influence on the adoption of DT.

(2) Dependent (Zone II) – The dependent zone encompasses barriers characterized by low driving force and high dependence on other independent barriers. Within this category, we find barriers such as security risk (B3), data management (B6) and value chain integration (B5). These barriers are influenced by the actions or conditions of other independent barriers. These results are align with results of several studies (Ajmera and Jain, 2019; Joseph Jerome *et al.*, 2022)

(3) Linkage (Zone III) – The linkage zone encompasses barriers with significant driving power and dependence. Within this category, we find resistance to change (B8) and standard infrastructure (B4). These barriers are both influential in driving the system and are influenced by other factors, placing them in the linkage zone. These results are align with the study of (Joseph Jerome *et al.*, 2022) which was focused on challenges to DT in procurement process.

(4) Driver/independent (Zone IV) – This zone has high driving and low dependency power barriers. High investment (B1), return on investment (B2) and multiskilled

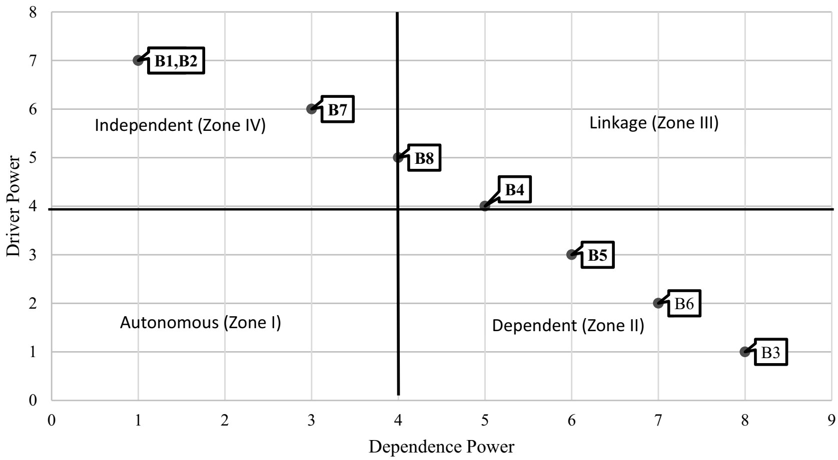


Figure 3.
MICMAC analysis

Source: Authors own work

workforce (B7) are included in this zone. The study of (Majumdar *et al.*, 2021) contradicts our results. His study concluded that both barriers (B2) and (B1) lies in dependent zone. The reason could be that our study has focused on Indian manufacturing SMEs, but his study was focused on textile and clothing industries.

5. Discussion and implications

The several obstacles to adoption of DT in Indian manufacturing SMEs have been explored in this article. In addition, using ISM tool, the interdependence of these barriers is examined and the hierarchical model for barriers is developed. The barriers, "High Investment" (B1) and "Return on Investment" (B2), which have lowest dependence and the highest driving power and are evidently the major barriers to the adoption of DT (see Figure 2). According to Sharma *et al.* (2023), high investment and return on investment are crucial barriers to DT adoption. A study of Joseph Jerome *et al.* (2022) also mentioned that these barriers have high impact on supply chain in manufacturing firms. In addition, this study also categorized these barriers (B1 and B2) into independent zone. Goswami and Daultani (2022) also revealed in his study that ROI is common issue in adoption of DT. According to experts' opinions, Indian SMEs fear of ROI as the initial investment is high. Investing in new technologies, systems, infrastructure and training can be challenging for many Indian SMEs due to high initial costs. This is particularly difficult for them because they have smaller IT teams that handle multiple responsibilities, making it hard to find time for researching, implementing and supporting DT projects. Ultimately, the limited access to capital hinders the advancement of digital initiatives. These barriers primarily affect the "Multiskilled Workforce" (B7). Khan *et al.* (2023b) highlighted that lack of technically skilled workforce is influencing and key barrier to DT. In the study of Ajmera and Jain (2019), barrier "Multiskilled Workforce" (B7) also lied in independent zone. This study was focused on adoption of DT in health-care industries. In our study, "B7" also lies in independent zone. That mean, this barrier is crucial in several sectors. Therefore, it could be taken on priority while solving various challenges. A workforce with a variety of skills (B7) has a strong driving force and a moderate dependence power. Figure 3 further supports the idea that a multiskilled workforce is a significant obstacle to the adoption of DT (Zone IV). Experts told that in Indian manufacturing SMEs, investing in new technologies, systems, infrastructure and Trai Industries frequently face challenges in recruiting and retaining employees with digital skills. In addition, there are limited chances to train existing staff in new technologies. This skills gap can make it difficult for SMEs to adopt DT strategies and fully benefit from emerging technologies. "Standard Infrastructure" (B4) and "Resistance to Change" (B8) are also crucial obstacles to the adoption of DT, and according to Figure 3, both have significant dependence and driving power. It is evident from the blank autonomous zone (blank) and ISM analysis that each acknowledged barrier has a significant impact on the adoption process. Few studies also stated that limited infrastructure facilities are hindering the adoption of DT in SMEs (Goel *et al.*, 2022; Jain and Ajmera, 2022). The expert team mentioned that Indian manufacturing SMEs usually lack access to the advanced digital tools that big companies use to streamline processes. Their restricted budgets make it challenging to acquire, integrate and oversee new software, hardware and technologies. Competing with limited funds can be perplexing. Without the appropriate tools, these businesses face obstacles in digitizing workflows, gathering and analyzing customer data and automating repetitive tasks. This struggle hampers their ability to stay current with the rapid digital changes and innovations in their industries, consuming valuable time, energy and resources. Top management could provide technical sessions to boost their digital skill to reduce the risk of resistance to change. "Data Management" (B6), "Value Chain Integration" (B5) and "Risk of Security Breaches" (B3) are examples of barriers with low driving and high dependence power that may be driven by any decision made on barriers falling under the independent and linkage zone. According to experts, to overcome barrier B3 and B5, Indian manufacturing SMEs could provide training program to employees to enhance their digital data management skills and could use cloud-based solutions for accessible data management and value chain integration. Furthermore, expert team provided their opinion on barrier B3 that in the digital realm, cybersecurity risks are an unavoidable challenge for Indian manufacturing SMEs. As these businesses embrace more technology and shift operations online, their exposure to cyber threats increases. Due to limited resources, SMEs often struggle to invest in strong security systems and protocols. A cyberattack has the potential to severely impact their operations, finances and reputation. It is correct to note that small businesses typically lack the resources available to larger companies. The dependence and driving powers of the key barriers provide a number of insightful conclusions about their relative importance according to the MICMAC analysis, which emphasizes the connections between these barriers. As the current study was focused on Indian manufacturing SMEs, the identified barriers could be common in other developing countries.

SMEs may face economic challenges to high investment in DT. Inadequate funds for DT, e.g. "Multiskilled Workforce," "Standard Infrastructure" and "Data Management," affect the implementation in the SME context (Kamble *et al.*, 2018). Awareness programs and training workshops should be provided to the current workforce so that they can understand the benefits of DT and adopt it in an effective manner. This may eliminate the "Resistance to Change" and "Multiskilled Workforce" barriers to the adoption of DT. But training and awareness program requires significant funds. By providing facilities to the current workforce like "Standard Infrastructure," industries can expect a good ROI.

5.1 Implications

The study's findings have unveiled eight crucial obstacles to the adoption of DT within the context of Indian manufacturing SMEs. The used framework proves to be valuable as it elucidates the intricate relationships among these barriers. This, in turn, empowers practitioners to formulate effective frameworks and strategies for embracing DT based on the novel insights derived from the study. These barriers can be categorized into two distinct groups through empirical analysis: the influential group and the dependent group. It is imperative for policymakers to accord immediate attention to the obstacles categorized as influential because they possess the potential to exert a substantial impact on the successful implementation of DT. Notably, according to the MICMAC analysis, "'High Investment," "Multiskilled Workforce" and "Return on Investment" all fall under the influential factors, thus serving as primary contributors to the dependent barriers. To mitigate the impact of the dependent barriers, practitioners should ensure that they have control over the mechanisms for addressing the influential barriers. This proactive approach will enable practitioners to curtail systemic inconsistencies effectively. Collaboration among stakeholders is pivotal in establishing a robust framework and devising concerted strategies to address the challenges associated with DT adoption. Furthermore, the insights gleaned from this research model's findings can assist practitioners in crafting adaptable decision-making plans for the implementation of DT.

The current study also provides social implications. The adoption of DT depends critically on the focus on creating a highly skilled labor force. This strategy promotes social empowerment by increasing economic competitiveness and opening doors for professional and personal development. The development of SMEs in the digital economy is vital, as they are acknowledged as the foundation of economies. SMEs can serve as channels for the transfer of technology and the development of skills, which can greatly boost the economy and create jobs.

6. Conclusion and limitations

SMEs in manufacturing sectors face competition and the need to enhance their quality, flexibility and cost efficiency. They encounter challenges such as productivity and subpar quality. To tackle these issues and gain, DT offers a solution. While DT brings benefits like productivity, reduced risks and environmental sustainability, it is mainly implemented by developed countries. In India, LEs have adopted DT but the adoption of DT is limited to manufacturing SMEs. The current study delves into the applicability of DT for Indian manufacturing SMEs

With the help of literature review, eight barriers to DT were identified, which are "High investment," "Return on investment," "Risk of security breaches," "Standard infrastructure," "Value-chain integration," "Data management," "Multiskilled Workforce" and "Resistance to change." These barriers were validated by an expert team of Indian manufacturing SMEs. Because the identified barriers were interrelated, this study used the ISM method to assess these barriers and formulate adaptable, long-term decision-making strategies. The ISM methodology plays a pivotal role in uncovering the internal dependencies among these barriers and transforming vague and poorly articulated system models into structured ones. Given these reasons, the study places a strong emphasis on bridging these gaps. The barriers to DT implementation exhibit a hierarchical and intricate structure. According to the research findings, three primary influential barriers emerge: "High Investment," "Return on Investment" and "Multiskilled Workforce." These barriers are of paramount importance, as they often exert a significant impact on the entire system. In contrast, independent barriers tend to have a limited ability to influence dependent ones. To grasp the structure and impact of these barriers, the current ISM-based model, derived from an iterative approach, proves indispensable. Furthermore, it offers a more coherent representation of the problem and suggests logical interactions among the barriers, thereby providing valuable insights for stakeholders and policymakers.

6.1 Limitations and future direction

Moreover, the implications of this research are beneficial for the Indian manufacturing SMEs. However, it is important to acknowledge that there are some limitations in the present work. With only eight barriers related to DT implementation in Indian manufacturing SMEs, the ISM methodology used here serves as an interrelationship model. This methodology does have its own constraints, and the model's effectiveness relies heavily on the decisions made by the expert panel. Put differently, the fundamental constraint of this paper is expert opinion, which could be addressed through the Delphi method, which involves participants reaching a consensus after two or more rounds of idea exchange. The authors have outlined eight obstacles to DT adoption in manufacturing SMEs from an Indian perspective. These insights might be faced by other sectors and nations. As a result, the findings cannot be generalized. The study can be further validated by empirical evidence and numerous case studies in various circumstances. The results may also be assessed using additional multi-criteria decision making methodologies, such as TOPSIS, ANP, DEMATEL, TISM, ELECTRE and VIKOR, among others. DEMATEL methodology could be used to identify priority ranking of barriers and for categorization into cause-and-effect groups. To find the studies and compile a list of the main DT adoption hurdles, the current study searched Emerald, ScienceDirect, Wiley, Taylor & Francis and Springer. To find more relevant studies to support the current study, more databases could be included by the researchers. This is because it is likely that certain studies that have an impact on DT adoption have not been found or considered.

References

Aamer, A., Sahara, C.R. and Al-Awlaqi, M.A. (2023), "Digitalization of the supply chain: transformation factors", *Journal of Science and Technology Policy Management*, Vol. 14 No. 4, pp. 713-733, doi: 10.1108/JSTPM-01-2021-0001.

Agrawal, P., Narain, R. and Ullah, I. (2019), "Analysis of barriers in implementation of digital transformation of supply chain using interpretive structural modelling approach", *Journal of Modelling in Management*, Vol. 15 No. 1, pp. 297-317, doi: 10.1108/JM2-03-2019-0066.

Ahmad, N. and Schreyer, P. (2016), "Are GDP and productivity measures up to the challenges of the digital economy?", *International Productivity Monitor*, Vol. 30 No. 4, available at: www.csls.ca/ipm/30/ahmadandschreyer.pdf

Ajmera, P. and Jain, V. (2019), "Modelling the barriers of Health 4.0–the fourth healthcare industrial revolution in India by TISM", *Operations Management Research*, Vol. 12 Nos 3/4, pp. 129-145, doi: 10.1007/s12063-019-00143-x.

Ali, I. and Aboelmaged, M.G.S. (2022), "Implementation of supply chain 4.0 in the food and beverage industry: perceived drivers and barriers", *International Journal of Productivity and Performance Management*, Vol. 71 No. 4, pp. 1426-1443, doi: 10.1108/IJPPM-07-2020-0393.

Alraja, M.N., Alshubiri, F., Khashab, B.M. and Shah, M. (2023), "The financial access, ICT trade balance and dark and bright sides of digitalization nexus in OECD countries", *Eurasian Economic Review*, Vol. 13 No. 2, pp. 177-209, doi: 10.1007/s40822-023-00228-w.

ALshubiri, F., ALmaashani, A.A. and Thuaar, S.M. (2023), "The impact of the digital economy paradigm on the productivity and monetary system of Oman", *Journal of Science and Technology Policy Management*, Vol. 14 No. 5, pp. 830-858, doi: 10.1108/JSTPM-07-2021-0097.

Aranda Jiménez, J.R., Campos-García, I. and De-Pablos-Heredero, C. (2022), "Vocational continuing training in Spain: contribution to the challenge of Industry 4.0 and structural unemployment", *Intangible Capital*, Vol. 18 No. 1, p. 20, doi: 10.3926/ic.1870.

Arroyabe, M.F., Arranz, C.F.A., Arroyabe, I.F.D. and Arroyabe, J.C.F.D. (2024), "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, doi: 10.1016/j.techfore.2023.123051.

Austin, S. (1994), "Barriers to investment: the appraisal and financing of new manufacturing technologies in SMEs", *Journal of Small Business and Enterprise Development*, Vol. 1 No. 1, pp. 38-46, doi: 10.1108/eb020931.

Bag, S., Gupta, S. and Luo, Z. (2020), "Examining the role of logistics 4.0 enabled dynamic capabilities on firm performance", *The International Journal of Logistics Management*, Vol. 31 No. 3, pp. 607-628, doi: 10.1108/IJLM-11-2019-0311.

Bakhtari, A.R., Waris, M.M., Sanin, C. and Szczerbicki, E. (2021), "Evaluating Industry 4.0 implementation challenges using interpretive structural modeling and fuzzy analytic hierarchy process", *Cybernetics and Systems*, Vol. 52 No. 5, pp. 350-378, doi: 10.1080/01969722.2020.1871226.

Barve, A., Kanda, A. and Shankar, R. (2007), "Analysis of interaction among the barriers of third party logistics", *International Journal of Agile Systems and Management*, Vol. 2 No. 1, pp. 109-129.

Breunig, M., Kelly, R., Mathis, R. and Wee, D. (2016), "Getting the most out of Industry 4.0", available at: www.mckinsey.com/~/media/McKinsey/Business%20Functions/McKinsey%20Digital/Our%20Insights/Getting%20the%20most%20out%20of%20Industry%204%200/Getting%20the%20most%20out%20of%20Industry%2040.pdf

Buer, S.-V., Strandhagen, J.O. and Chan, F.T.S. (2018), "The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda", *International Journal of Production Research*, Vol. 56 No. 8, pp. 2924-2940, doi: 10.1080/00207543.2018.1442945.

Buntz, B. (2016), "Top 10 reasons people aren't embracing the IoT", available at: www.iotworldtoday.com/security/top-10-reasons-people-aren-t-embracing-the-iot

Busto Parra, B., Pando Cerra, P. and Álvarez Peñín, P.I. (2022), "Combining ERP, lean philosophy and ICT: an industry 4.0 approach in an SME in the manufacturing sector in Spain", *Engineering Management Journal*, Vol. 34 No. 4, pp. 655-670, doi: 10.1080/10429247.2021.2000829.

Chen, H. and Su, W. (2023), "Innovation and application of enterprise's supply chain management mode under the background of Industry 4.0", *International Journal of Technology Management*, Vol. 91 Nos 1/2, p. 19, doi: 10.1504/IJTM.2023.127855.

Chen, Z.K., Yang, S.Q., Tan, S., Zhao, H., He, L., Zhang, G. and Yang, H.Y. (2014), "The data allocation strategy based on load in NoSQL database", *Applied Mechanics and Materials*, Vol. 513/517, pp. 1464-1469, doi: 10.4028/www.scientific.net/AMM.513-517.1464.

Ching, N.T., Ghobakhloo, M., Iranmanesh, M., Maroufkhani, P. and Asadi, S. (2022), "Industry 4.0 applications for sustainable manufacturing: a systematic literature review and a roadmap to sustainable development", *Journal of Cleaner Production*, Vol. 334, p. 130133, doi: 10.1016/j.jclepro.2021.130133.

Contreras Pérez, J.D., Cano Buitrón, R.E. and García Melo, J.I. (2018), "Methodology for the retrofitting of manufacturing resources for migration of SME towards Industry 4.0", In Florez, H., Diaz, C. and Chavarriaga, J. (Eds), *Applied Informatics*, Springer International Publishing, Cham. Vol. 942, pp. 337-351, doi: 10.1007/978-3-030-01535-0_25.

Culot, G., Fattori, F., Podrecca, M. and Sartor, M. (2019), "Addressing Industry 4.0 cybersecurity challenges", *IEEE Engineering Management Review*, Vol. 47 No. 3, pp. 79-86, doi: 10.1109/EMR.2019.2927559.

De La VegaHernández, I.M. and Diáz Amorin, J. (2023), "Longitudinal scientific mapping of emerging and converging trends between the Internet of Things and digital transformation", *Journal of Science and Technology Policy Management*, doi: 10.1108/JSTPM-11-2022-0183.

Demirkesen, S. and Tezel, A. (2021), "Investigating major challenges for industry 4.0 adoption among construction companies", *Engineering, Construction and Architectural Management*, doi: 10.1108/ECAM-12-2020-1059.

Dobrosotskiy, V.I., Semenova, G.N., Kazarinova, E.B. and Falina, N.V. (2019), "Venture investments into digital education in the conditions of industry 4.0: problems of attraction and directions of usage", *On the Horizon*, Vol. 27 Nos 3/4, pp. 213-218, doi: 10.1108/OTH-07-2019-0035.

Doh, S. and Kim, B. (2014), "Government support for SME innovations in the regional industries: the case of government financial support program in South Korea", *Research Policy*, Vol. 43 No. 9, pp. 1557-1569, doi: 10.1016/j.respol.2014.05.001.

Dutta, G., Kumar, R., Sindhwani, R. and Singh, R.K. (2020), "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, doi: 10.1108/CR-03-2019-0031.

Falco, E. and Kleinhans, R. (2018), "Beyond technology: identifying local government challenges for using digital platforms for citizen engagement", *International Journal of Information Management*, Vol. 40, pp. 17-20, doi: 10.1016/j.ijinfomgt.2018.01.007.

Geissbauer, R., Schrauf, S., Koch, V. and Kuge, S. (2014), "Industry 4.0-Opportunities and barriers of the industrial internet", available at: www.pwc.nl/en/assets/documents/pwc-industrie-4-0.pdf

Goel, P., Kumar, R., Banga, H.K., Kaur, S., Kumar, R., Pimenov, D.Y. and Giasin, K. (2022), "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, doi: 10.3390/jrfm15040171.

Goswami, M. and Daultani, Y. (2022), "Make-in-India and Industry 4.0: technology readiness of select firms, barriers and socio-technical implications", *The TQM Journal*, Vol. 34 No. 6, pp. 1485-1505, doi: 10.1108/TQM-06-2021-0179.

Haddud, A., DeSouza, A., Khare, A. and Lee, H. (2017), "Examining potential benefits and challenges associated with the Internet of Things integration in supply chains", *Journal of Manufacturing Technology Management*, Vol. 28 No. 8, pp. 1055-1085, doi: 10.1108/JMTM-05-2017-0094.

Hajda, J., Jakuszewski, R. and Ogonowski, S. (2021), "Security challenges in Industry 4.0 PLC systems", *Applied Sciences*, Vol. 11 No. 21, p. 9785, doi: 10.3390/app11219785.

Jain, V. and Ajmera, P. (2022), "Modelling the barriers of industry 4.0 in India using fuzzy TISM", *International Journal of Business Performance Management*, Vol. 23 No. 4, p. 347, doi: 10.1504/IJBPM.2022.10050338.

Jankowska, B., Mińska-Struzik, E., Bartosik-Purgat, M., Götz, M. and Olejnik, I. (2023), "Industry 4.0 technologies adoption: barriers and their impact on Polish companies' innovation performance", *European Planning Studies*, Vol. 31 No. 5, pp. 1029-1049, doi: 10.1080/09654313.2022.2068347.

Joseph Jerome, J.J., Saxena, D., Sonwaney, V. and Foropon, C. (2022), "Procurement 4.0 to the rescue: catalysing its adoption by modelling the challenges", *Benchmarking: An International Journal*, Vol. 29 No. 1, pp. 217-254, doi: 10.1108/BIJ-01-2021-0030.

Jung, J. and Jin, K. (2018), "Case studies for the establishment of the optimized smart factory with small and medium-sized enterprises", *Proceedings of the 2nd International Symposium on Computer Science and Intelligent Control*, pp. 1-5, doi: 10.1145/3284557.3284692

Kache, F. and Seuring, S. (2017), "Challenges and opportunities of digital information at the intersection of big data analytics and supply chain management", *International Journal of Operations and Production Management*, Vol. 37 No. 1, pp. 10-36, doi: 10.1108/IJOPM-02-2015-0078.

Kamble, S.S., Gunasekaran, A. and Sharma, R. (2018), "Analysis of the driving and dependence power of barriers to adopt industry 4.0 in Indian manufacturing industry", *Computers in Industry*, Vol. 101, pp. 107-119, doi: 10.1016/j.compind.2018.06.004.

Kannan, G. and Haq, A.N. (2007), "Analysis of interactions of criteria and Sub-criteria for the selection of supplier in the built-in-order supply chain environment", *International Journal of Production Research*, Vol. 45 No. 17, pp. 3831-3852, doi: 10.1080/00207540600676676.

Kevin Tseng, K. and Johnsen, R.E. (2011), "Internationalisation and the internet in UK manufacturing SMEs", *Journal of Small Business and Enterprise Development*, Vol. 18 No. 3, pp. 571-593, doi: 10.1108/14626001111155718.

Khan, I.S., Ahmad, M.O. and Majava, J. (2023a), "Industry 4.0 innovations and their implications: an evaluation from sustainable development perspective", *Journal of Cleaner Production*, Vol. 405, p. 137006, doi: 10.1016/j.jclepro.2023.137006.

Khan, S., Haleem, A., Husain, Z., Samson, D. and Pathak, R.D. (2023b), "Barriers to blockchain technology adoption in supply chains: the case of India", *Operations Management Research*, Vol. 16 No. 2, pp. 668-683, doi: 10.1007/s12063-023-00358-z.

Khan, N., Yaqoob, I., Hashem, I.A.T., Inayat, Z., Mahmoud Ali, W.K., Alam, M., Shiraz, M. and Gani, A. (2014), "Big data: survey, technologies, opportunities, and challenges", *The Scientific World Journal*, Vol. 2014, pp. 1-18, doi: 10.1155/2014/712826.

Kumar, A., Mangla, S.K. and Kumar, P. (2022), "Barriers for adoption of industry 4.0 in sustainable food supply chain: a circular economy perspective", *International Journal of Productivity and Performance Management*, doi: 10.1108/IJPPM-12-2020-0695.

Kumar, S., Raut, R.D., Aktas, E., Narkhede, B.E. and Gedam, V.V. (2023a), "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, doi: 10.1080/0951192X.2022.2128217.

Kumar, D., Samalia, H.V. and Verma, P. (2017), "Exploring suitability of cloud computing for small and medium-sized enterprises in India", *Journal of Small Business and Enterprise Development*, Vol. 24 No. 4, pp. 814-832, doi: 10.1108/JSBED-01-2017-0002.

Kumar, R., Singh, R.K. and Dwivedi, Y.K. (2020), "Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: analysis of challenges", *Journal of Cleaner Production*, Vol. 275, p. 124063, doi: 10.1016/j.jclepro.2020.124063.

Kumar, V., Vrat, P. and Shankar, R. (2023b), "MCDM model to rank the performance outcomes in the implementation of industry 4.0", *Benchmarking: An International Journal*, doi: 10.1108/BIJ-04-2022-0273.

Kusiak, A. (2018), "Smart manufacturing", *International Journal of Production Research*, Vol. 56 Nos 1/2, pp. 508-517, doi: 10.1080/00207543.2017.1351644.

Lee, I. and Lee, K. (2015), "The Internet of Things (IoT): applications, investments, and challenges for enterprises", *Business Horizons*, Vol. 58 No. 4, pp. 431-440, doi: 10.1016/j.bushor.2015.03.008.

Majumdar, A., Garg, H. and Jain, R. (2021), "Managing the barriers of Industry 4.0 adoption and implementation in textile and clothing industry: interpretive structural model and triple helix framework", *Computers in Industry*, Vol. 125, p. 103372, doi: 10.1016/j.compind.2020.103372.

Masood, T. and Sonntag, P. (2020), "Industry 4.0: adoption challenges and benefits for SMEs", *Computers in Industry*, Vol. 121, p. 103261, doi: 10.1016/j.compind.2020.103261.

Melaka Malaysia and Ahmed, E.M. (2020), "Covid19-Implications on ISDB member countries sustainable digital economies", *International Journal of Innovation and Knowledge Management in Middle East and North Africa*, Vol. 8 Nos 1/2, pp. 11-37, doi: 10.47556/J.IJIKMMENA.8.1.2020.2.

Modrak, V., Soltysova, Z. and Poklemba, R. (2019), "Mapping requirements and roadmap definition for introducing I 4.0 in SME environment", in Hloch, S., Klichová, D., Krolczyk, G.M., Chattopadhyaya, S. and Ruppenthalová, L. (Eds), *Advances in Manufacturing Engineering and Materials*, Springer International Publishing, Cham, pp. 183-194, doi: 10.1007/978-3-319-99353-9_20.

Müller, J.M., Buliga, O. and Voigt, K.-I. (2018), "Fortune favors the prepared: how SMEs approach business model innovations in industry 4.0", *Technological Forecasting and Social Change*, Vol. 132, pp. 2-17, doi: 10.1016/j.techfore.2017.12.019.

Nimawat, D. and Gidwani, B.D. (2021), "Identification of cause and effect relationships among barriers of industry 4.0 using decision-making trial and evaluation laboratory method", *Benchmarking: An International Journal*, Vol. 28 No. 8, pp. 2407-2431, doi: 10.1108/BIJ-08-2020-0429.

Oesterreich, T.D. and Teuteberg, F. (2016), "Understanding the implications of digitisation and automation in the context of industry 4.0: a triangulation approach and elements of a research agenda for the construction industry", *Computers in Industry*, Vol. 83, pp. 121-139, doi: 10.1016/j.compind.2016.09.006.

Orzes, G., Rauch, E., Bednar, S. and Poklemba, R. (2018), "Industry 4.0 implementation barriers in small and medium sized enterprises: a focus group study", *2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, pp. 1348-1352, doi: 10.1109/IEEM.2018.8607477.

Parida, B., Sunand Dash, S. and Sharma, D. (2021), "Role of culture-specific rights, responsibilities and duties in industry 4.0: comparing Indic and Western perspectives", *Benchmarking: An International Journal*, Vol. 28 No. 5, pp. 1543-1557, doi: 10.1108/BIJ-05-2020-0257.

Petrillo, A., Felice, F.D., Cioffi, R. and Zomparelli, F. (2018), "Fourth industrial revolution: current practices, challenges, and opportunities", in Petrillo, A., Cioffi, R. and Felice, F.D. (Eds), *Digital Transformation in Smart Manufacturing*, InTech, doi: 10.5772/intechopen.72304.

Pfaff, Y.M., Birkel, H. and Hartmann, E. (2023), "Supply chain governance in the context of industry 4.0: Investigating implications of real-life implementations from a multi-tier perspective", *International Journal of Production Economics*, Vol. 260, p. 108862, doi: 10.1016/j.ijpe.2023.108862.

Rad, F.F., Oghazi, P., Palmié, M., Chirumalla, K., Pashkevich, N., Patel, P.C. and Sattari, S. (2022), "Industry 4.0 and supply chain performance: a systematic literature review of the benefits, challenges, and critical success factors of 11 core technologies", *Industrial Marketing Management*, Vol. 105, pp. 268-293, doi: 10.1016/j.indmarman.2022.06.009.

Raj, A., Dwivedi, G., Sharma, A., Lopes De Sousa Jabbour, A.B. and Rajak, S. (2020), "Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: an inter-country comparative perspective", *International Journal of Production Economics*, Vol. 224, p. 107546, doi: 10.1016/j.ijpe.2019.107546.

Rajput, S. and Singh, S.P. (2019), "Identifying industry 4.0 IoT enablers by integrated PCA-ISM-DEMATEL approach", *Management Decision*, Vol. 57 No. 8, pp. 1784-1817, doi: 10.1108/MD-04-2018-0378.

Ravi, V. and Shankar, R. (2005), "Analysis of interactions among the barriers of reverse logistics", *Technological Forecasting and Social Change*, Vol. 72 No. 8, pp. 1011-1029, doi: 10.1016/j.techfore.2004.07.002.

Rocha, C., Quandt, C., Deschamps, F., Philbin, S. and Cruzara, G. (2023), "Collaborations for digital transformation: case studies of Industry 4.0 in Brazil", *IEEE Transactions on Engineering Management*, Vol. 70 No. 7, pp. 2404-2418, doi: 10.1109/TEM.2021.3061396.

Ronaghi, M.H. (2022), "Toward a model for assessing smart hospital readiness within the industry 4.0 paradigm", *Journal of Science and Technology Policy Management*, doi: 10.1108/JSTPM-09-2021-0130.

Sachdeva, N., Shrivastava, A.K. and Chauhan, A. (2021), "Modeling supplier selection in the era of industry 4.0", *Benchmarking: An International Journal*, Vol. 28 No. 5, pp. 1809-1836, doi: 10.1108/BIJ-12-2018-0441.

Sharma, M., Sehrawat, R., Giannakis, M. and Dwivedi, Y.K. (2023), "Learnings from industry 4.0 for transitioning towards industry 4.0+: challenges and solutions for Indian pharmaceutical sector", *Annals of Operations Research*, doi: 10.1007/s10479-023-05391-6.

Shukla, M. and Shankar, R. (2022), "Modeling of critical success factors for adoption of smart manufacturing system in Indian SMEs: an integrated approach", *OPSEARCH*, Vol. 59 No. 4, pp. 1271-1303, doi: 10.1007/s12597-021-00566-w.

Sundarakani, B., Kamran, R., Maheshwari, P. and Jain, V. (2021), "Designing a hybrid cloud for a supply chain network of Industry 4.0: a theoretical framework", *Benchmarking: An International Journal*, Vol. 28 No. 5, pp. 1524-1542, doi: 10.1108/BIJ-04-2018-0109.

Surucu-Balci, E., Iris, Ç. and Balci, G. (2024), "Digital information in Maritime supply chains with blockchain and cloud platforms: supply chain capabilities, barriers, and research opportunities", *Technological Forecasting and Social Change*, Vol. 198, p. 122978, doi: 10.1016/j.techfore.2023.122978.

Tieng, K., Jeenanunta, C., Chea, P. and Rittippant, N. (2022), "Roles of customers in upgrading manufacturing firm technological capabilities toward industry 4.0", *Engineering Management Journal*, Vol. 34 No. 2, pp. 329-340, doi: 10.1080/10429247.2021.1922219.

Tripathi, S. and Gupta, M. (2021a), "A holistic model for global industry 4.0 readiness assessment", *Benchmarking: An International Journal*, Vol. 28 No. 10, pp. 3006-3039, doi: 10.1108/BIJ-07-2020-0354.

Vern, P., Panghal, A., Mor, R.S., Kamble, S.S., Islam, M.S. and Khan, S.A.R. (2023), "Influential barriers to blockchain technology implementation in agri-food supply chain", *Operations Management Research*, Vol. 16 No. 3, pp. 1206-1219, doi: 10.1007/s12063-023-00388-7.

Wang, Q. and Shang, J. (2023), "Analysis of the quality improvement path of supply chain management under the background of industry 4.0", *International Journal of Technology Management*, Vol. 91 Nos 1/2, p. 1, doi: 10.1504/IJTM.2023.127854.

Xia, H., Wang, Y., Jasimuddin, S., Zhang, J.Z. and Thomas, A. (2023), "A big-data-driven matching model based on deep reinforcement learning for cotton blending", *International Journal of Production Research*, Vol. 61 No. 22, pp. 7573-7591, doi: 10.1080/00207543.2022.2153942.

Xu, L.D., Xu, E.L. and Li, L. (2018), "Industry 4.0: state of the art and future trends", *International Journal of Production Research*, Vol. 56 No. 8, pp. 2941-2962, doi: 10.1080/00207543.2018.1444806.

Yadav, V., Jain, R., Mittal, M.L., Panwar, A. and Sharma, M.K. (2019), "An appraisal on barriers to implement lean in SMEs", *Journal of Manufacturing Technology Management*, Vol. 30 No. 1, pp. 195-212, doi: 10.1108/JMTM-12-2017-0262.

Zhang, Q., Abdullah, A.R., Chong, C.W. and Ali, M.H. (2023), "Analysis on the production technology innovation and management path of industrial enterprises under the trend of industry 4.0", *International Journal of Technology Management*, Vol. 91 Nos 1/2, p. 53, doi: 10.1504/IJTM.2023.127857.

Further reading

Abdirad, M. and Krishnan, K. (2021), "Industry 4.0 in logistics and supply chain management: a systematic literature review", *Engineering Management Journal*, Vol. 33 No. 3, pp. 187-201, doi: 10.1080/10429247.2020.1783935.

Ganguly, S. (2020), "Informality and structural change: evidences from microenterprises in India's unorganised manufacturing sector", *Journal of Small Business and Enterprise Development*, Vol. 28 No. 1, pp. 22-44, doi: 10.1108/JSBED-11-2019-0377.

Kumar, A. and Dixit, G. (2018), "An analysis of barriers affecting the implementation of e-waste management practices in India: a novel ISM-DEMATEL approach", *Sustainable Production and Consumption*, Vol. 14, pp. 36-52, doi: 10.1016/j.spc.2018.01.002.

Mantok, S., Sekhon, H., Sahi, G.K. and Jones, P. (2019), "Entrepreneurial orientation and the mediating role of organisational learning amongst Indian S-SMEs", *Journal of Small Business and Enterprise Development*, Vol. 26 No. 5, pp. 641-660, doi: 10.1108/JSBED-07-2018-0215.

Tripathi, S. and Gupta, M. (2021b), "Identification of challenges and their solution for smart supply chains in Industry 4.0 scenario: a neutrosophic DEMATEL approach", *International Journal of Logistics Systems and Management*, Vol. 40 No. 1, p. 70, doi: 10.1504/IJLSM.2021.117691.

Corresponding author

Vinod Yadav can be contacted at: vinod.ydv2008@gmail.com