Model development for assessing inhibitors impacting Industry 4.0 implementation in Indian manufacturing industries: an integrated ISM-Fuzzy MICMAC approach

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Abstract Industry 4.0 (I4.0) adoption is becoming predominant in manufacturing industries due to its limitless opportunities. Even though companies are interested in adopting digitalization, several perceived barriers stymied them. However, in the interest of its smooth adoption, these perceived barriers must be addressed urgently. This research aims to analyze the broader spectrum of possible barriers that impede the implementation of I4.0 and converge them into the most prominent inhibitors, further assessing these inhibitors to develop contextual relationships among them. A comprehensive literature review and an empirical research-based survey considering a large sample size are used to address the study’s research objectives. Industry and academia experts’ inputs are considered to derive the I4.0 implementation barrier’s current prominence. The interrelationship among extracted twelve significant inhibitors through principle component analysis (PCA) is modeled using interpretive structural modeling (ISM) to manifest each inhibitor’s direct and indirect effect. Fuzzy matriced’ impacts croise’s multiplication applique’e a un classement (MICMAC) analysis is further considered to classify these inhibitors into drivers and dependents. The study depicts inadequate organizational strategies, uncertainty about financial decision making, limited employee readiness, inconsistent legal and government policies, insufficient IT and automation infrastructure as the most prominent driver inhibitors of the I4.0 adoption. An integrated novel PCA-ISM Fuzzy MICMAC model developed in this research paper is unique and used for the first time to establish the hierarchical relationship among I4.0 implementation inhibitors considering the post-COVID-19 scenario. This study offers practical insights and outcomes that will help researchers, decision-makers, and practitioners in unlocking the potential of I4.0 by dealing with its inhibitors efficaciously.

Keywords Industry 4.0 · Sustainability · Inhibitors · Principal component analysis · Interpretive structural modeling · Fuzzy MICMAC · COVID-19

Abbreviations

AHP Analytical hierarchy process
BWM Best worst method
DEMATEL Decision-making trial and evaluation laboratory method
ELECTRE Elimination and choice expressing reality
ICT Information and communication technology
IT Information technology
MCDM Multi-criteria decision-making methods
MMDE Maximum mean de-entropy
SSCM Sustainable supply chain management
TISM Total interpretive structural modeling

1 Introduction

Industry 4.0 (I4.0) is the technological reform of highly cutting-edge manufacturing and sustainable production
practices initiated by Germany in 2011 (Roblek et al. 2016). It can also be referred to as the ‘Fourth Industrial Revolution,’ representing the new organizational paradigm, intelligently controlling the entire industrial value chain. It is evident from the manufacturing companies’ experiences who have already adopted I4.0 partially or fully that I4.0 has tremendous potential to customize products, provide flexibility, achieve cost-effectiveness, improve quality, and increase business operations speed like never before (Ghobakhloo 2020; Ben Wang 2018).

I4.0 aims to converge physical devices (i.e., sensors, actuators, smart machines, various devices, and equipment) with the virtual environment through advanced software and internet networks driven by I4.0 nascent technologies (Bajic et al. 2020). Nevertheless, this will be possible only through seamless convergence, automation, and digitalization of the overall value chain’s horizontal, vertical, and end-to-end business operations (Bhatia and Kumar 2020). The I4.0 nascent technologies like Internet of Things (IoT), Artificial Intelligence (AI), Cyber-Physical System (CPS), Industrial Internet of Things (IIoT), Fog and Edge Computing, Cloud Computing (CC), Augmented and Virtual Reality (AR/VR), Big Data Analytics (BDA), Additive Manufacturing (AM), Robotics, Cobotics, Cyber Security, Semantic Web Technology, Embedded Systems, Simulations, Product Life Cycle Management (PLM), Network Manufacturing (NM). These technologies are helpful for autonomous and intelligent decision-making and integration of manufacturing processes through prediction, maintenance, fault rectification, and end-to-end control of operations in the intelligent factory (Kang et al. 2016; Türkeş et al. 2019; Baicun Wang et al. 2020).

In this pretext, India being one of the fastest developing countries and having understood the I4.0 potential to impact the ways of doing business is now aggressively looking for I4.0 adoption. India’s initiatives like the National Skill Development Mission (2015), followed by a massive change in the education system to make it skills-oriented than just being knowledge-based National Education Policy (2020), establish the urge and passion for imbiding the emerging technologies into every aspect of the business operations. These systematic efforts have been acknowledged by the United Nations Industrial Development Organization (UNIDO), which has put India on the list of ten global front runners who have revolutionized their production systems using advanced digital technologies (UNIDO 2020). Government initiatives like ‘SAMARTH Udyog Bharat 4.0,’ ‘Atmanirbhar Bharat,’ ‘Make in India,’ ‘BharatNet,’ ‘eNAM,’ etc., are just a few out of many other government schemes, which have been designed to meet the objectives of countrywide digitalization. The soul objective remains the same, to promote the local industries to think global and act locally. Indeed, the Indian government is doing everything to facilitate the adoption of new technologies, which will help businesses, in the long run, to produce international quality products and services SAMARTH Udyog Bharat 4.0 (2021). The incredible industrial growth rate in the export sector and the establishment of the ‘Engineering Export Promotion Council’ (EEPC 2020) is now India’s largest foreign exchange earner, accounting for 25% of India’s total product exports. It ultimately demonstrates the Indian government’s strong political will to promote I4.0 practices.

The combined commitment by industry associations, policymakers, and the government has expedited the I4.0 adoption, job creation, productivity enhancement, and competitiveness in Indian manufacturing companies. The industrial ecosystem has never been so conducive as it is today for the adoption of I4.0 technologies. To that effect, the Indian manufacturing industry has made maximum out of these favorable conditions by consistently contributing massively to the nation’s Gross Domestic Product (GDP) (Khanzode et al. 2021; Mehta and Rajan 2017) through its consistent efforts to use advanced technologies. Therefore, India’s digitalization movement has set the base for I4.0 adoption, which is also a top priority of the ‘Make in India’ scheme (Kamble et al. 2018a, b). A glance at a significant increase in India’s information and communication technology (ICT) infrastructure and users is another key indicator of growing digitalization in the country. The highlight of the growth is reflected from the huge expansion of 25% internet users in just one year, i.e., 2019 (23%) to 2020 (48%), targeting to connect 78% of India’s total population (Digital 2020). This rise is expected to touch a new peak post-COVID 19 pandemic scenario.

Even though the government and industry associations have put in the best efforts, except few big businesses, most companies have not yet taken steps to adopt I4.0 in their respective companies. Despite positive experiences and benefits harnessed by companies and strong political will, there is very little acceptance of the I4.0 vision in reality. Past studies have found prominent barriers, like capital investment requirements and unclear cost–benefit analysis of the I4.0 applications (Sony and Aithal 2020), missing clear-cut investment plans, lack of practical change management approach, lack of appropriate skills, lack of support from trade unions, lack of digital leadership, and unclear digital vision (Türkeş et al. 2019) responsible to this low response from the industries. Moreover, inadequate internet connectivity, insufficient data protection, and IT infrastructure converge into extreme challenges, which may create havoc if not attended to at the right time while adopting I4.0 (Khanzode et al. 2021; Luthra and Mangla 2018).

The first mover’s experiences in I4.0 adoption are highly inspiring. Hence, there are high chances I4.0 adoption will prove a game-changer for Indian manufacturing companies. While this is true, the fact remains that I4.0 adoption may not reach its peak in the absence of a robust framework.
to deal with inhibitors. Some research gaps identified by researchers are:

1) Minimal studies discussed the challenges and prospects of imbibing the I4.0 vision (Basi 2017; Bonilla et al. 2018; Müller et al. 2017a) in a specific geographic, political, and business context. As a repercussion of missing clarity about opportunities and challenges, many companies perceived I4.0 negatively, leading to the prolonged, passive, and reluctant approach to implementing I4.0 in India (Luthra and Mangla 2018). This condition has motivated researchers to forward this research agenda passionately.

2) Scarcity in specific research areas persists as very minimal researchers have studied, applied, and analyzed I4.0 barriers through PCA-ISM Fuzzy MICMAC to solve real-time problems, leaving immense scope for research.

3) It is apparent that the respondent’s profile and sample size directly impact the research quality, reliability, and outcomes; this study has considered a sizable sample size.

4) Research published pre COVID-19 time seems irrelevant partially or fully in post-COVID-19 times due to an apparent lack of context to new conditions. The current study is novel, as it judiciously fits the post-COVID-19 needs. The research has considered the intervention of experts in the manufacturing sector as an add-on to demystify the complex relationship among I4.0 inhibitors, especially in the disruptive environment of COVID-19.

For becoming competitive and sustainable in the global market, the manufacturing industries must go beyond simply identifying barriers to I4.0 deployment. So the urgent call necessitates devising the sustained research framework to examine and segregate identified prominent barriers in groups (inhibitors) using statistical approaches. Further, to derive the contextual interrelationships among these groups based on their driving and dependence power to address the research gap. Hence, critically assessing and establishing interrelationships between these inhibitors is pertinent. This study has appropriately responded to all the earlier limitations while designing a properly fitting research methodology. Therefore, the research is a valuable contribution to the novel ideas. This will help to attain confidence among the manufacturing organizations while adopting I4.0.

The proposed robust integrated PCA-ISM Fuzzy MICMAC model in this study systematically addresses the inhibitors and gives a structured way forward to sustainable implementation of the I4.0 vision. The model intends to establish a pathway to developing an ecosystem that will promote the state-of-the-art ICT infrastructure, training, development facilities and customized yet progressive policies. Eventually, this research’s findings will support a systematic and thoughtful approach to adopt I4.0, which will meet the local customer demands and prepare for disruptive global competition (Travaglioni et al. 2020).

In this context, the primary research objectives of this study are,

**RO1:** To identify the crucial I4.0 implementation barriers in manufacturing companies in India.

**RO2:** To converge the barriers into prominent inhibitors for the smooth implementation of I4.0.

**RO3:** To perform an in-depth analysis of contextual interrelationships among these inhibitors based on their significance.

**RO4:** To derive a framework and model for real-time decision-making by policymakers.

This paper has five sections. Section 1 is exclusively dedicated to defining the study’s relevance, context, need, and importance in the current scenario. Section 2 has explored an exhaustive literature review. Section 3 explains the research methodology and elaboration of integrated PCA-ISM Fuzzy MICMAC methodology and model development. Results and discussions are elaborated in Sect. 4. Section 5 highlights conclusions, managerial implications, and contributions to the new knowledge and recommends a pathway to counter post-COVID-19 challenges in the manufacturing industry, and finally, presents future research recommendations.

### 2 Literature review

A systematic literature review is carried out to explore the theoretical background and multiple dimensions of I4.0 adoption in Indian manufacturing industries. This study has extensively used the electronic databases, i.e., ‘SCOPUS,’ ‘Web of Science,’ ‘Google Scholar,’ ‘Elsevier,’ ‘IEEE,’ ‘Emerald,’ ‘Springer’ and ‘Taylor and Francis’, etc., over the year 2010–2021 timespan, to gather 187 research papers. The keywords used to reach pertinent literature relevant to the study are, i.e., ‘Industry 4.0 barriers’, ‘Industry 4.0 drivers’, ‘Industry 4.0 enablers’, ‘Industry 4.0 challenges’, ‘Industry 4.0 inhibitors’, ‘Industry 4.0 risk management’, ‘Industry 4.0 readiness assessment’, ‘Industry 4.0 framework’, ‘Industry 4.0 technologies’, ‘Industry 4.0 and sustainability’, ‘Industry 4.0 and COVID-19’. Non-English language papers, editorials, and magazines have been omitted from the collected corpus. Finally, 137 articles were identified through extensive screening, considering the theme, scope of the underline study, and relevance to the study objectives. The review of these documents led to a sound understanding of the critical nature of impeding barriers hindering the I4.0
propagation in India. It also validated the choice of PCA, ISM, and Fuzzy MICMAC techniques apt to the research problem considered for the study.

2.1 Industry 4.0 implementation in manufacturing

The I4.0 technologies like CPS, IoT, RFID, smart sensors, AI, etc., have brought disruptive changes in manufacturing practices. The physical world’s reconciliation with the virtual environment (Stentoft and Rajkumar 2020) has proved to be most successful in speeding up the overall production cycle and eliminating waste. This integration has also led to legitimate control over the product life cycle, machine-to-machine communication, and data management, giving rise to a self-organizing, self-reliant, and real-time decision-making system at the shop floor, called smart manufacturing (Julian Marius Müller et al. 2018). This smart manufacturing has a massive potential to increase manufacturing productivity and agility, build value opportunities through creative services, enhance product quality, improve sustainability and interconnectivity, and collaborate effectively with stakeholders (Müller et al. 2020). Another aspect of smart manufacturing is big data analytics. The analytics performed on the enormous data collected in real-time from machines improve processes and operations, decrease errors and defect costs, and offer opportunities to optimize resources, reduce waste, and rectify the problems beforehand (Awan et al. 2021; Nara et al. 2021). It has an incredible opportunity to render insights from maintenance practices, manufacturing operations, consumer dynamics, customer purchasing habits, new ways to minimize costs and facilitate more targeted decisions in manufacturing companies to satisfy customized consumer demand (Ghogakhloo 2018; Wang et al. 2016a, b).

2.2 COVID-19 and Industry 4.0 adoption

An unexpected worldwide impact due to the outbreak of pandemic COVID-19 is now evident in all industrial operations, irrespective of the sector, region, and type of ownership (Nicola et al. 2020). Companies with limited resources, specifically micro, small, and medium-scale, and those engaged in long supply chain or mostly dependent on manual operations, are worst hit during the lockdown constraints (Adámek and Meixnerová 2020). Because of a lack of clear directions and vision, several industries have been struggling to cope with I4.0 disruptions since 2011. In this line, some researchers have found that COVID-19 has further worsened the condition, while others believe the pandemic has also bought some opportunities in the sustainable transformation of business functions (Cohen 2020; Narayananamurthy and Tortorella 2021). Thus the substantial evidence around this compels us to believe COVID-19 has expedited the digital revolution in society and industries.

The emergence of sudden infestation of COVID-19 has developed stakeholders’ great interest in I4.0 technologies because of its critical role in containing and mitigating the virus’s adverse repercussions (AlMaadeed 2020; Haleem et al. 2020; Ivanov 2020; Sulkowski 2020). The inspirations theme earlier has become the top agenda accepting the new transition as an only success mantra in the coming time assimilating AI applications, 3D printing, track and trace devices, etc., in day-to-day activities.

The stand-still situation triggered by the coronavirus outbreak has forced manufacturing industries to devise alternate ways of doing business. Advanced intelligent automation is accepted as the most effective tool to acclimatize with new technologies, which unfortunately gave bad time to already hit the job market (Sulkowski 2020). Another lesson learned is to design a fundamentally healthy industry ecosystem by imbibing agility, resilience, flexibility, automation, self-sustenance, and robustness in every industrial operation (Ivanov and Dolgui 2020). However, the digitalization acceptance in just two months is equivalent to two years in a normal course, leading to the fast-tracking application of I4.0 emerging technologies (Narayananamurthy and Tortorella 2021). In light of this, the researchers believe it is necessary to concentrate on the study of barriers/inhibitors and their interrelationships in order to trigger the deployment of I4.0 practices in manufacturing industries, which will be useful in dealing with the situation that emerges during and post COVID-19.

2.3 I4.0 implementation barriers

The emersion of I4.0 has impacted every aspect of consumerism, making it highly demanding. Definitely, first-mover companies have gained the absolute advantage, now leading the respective sectors. This bright side also has dark shades; even though the progression of I4.0 is a proven reality, the accompanying set of barriers cannot be neglected (Rezqianita and Ardi 2020), which justifies the importance of this path showing research on I4.0 barriers. This section is focused on the critical synthesis, analysis, assessment, and application of the existing knowledge and practices, which is used to examine the identified set of barriers the manufacturing industry faces while adopting I4.0.

The exploratory survey-based research on threats and driving forces for introducing I4.0 on 122 top-level Serbian manufacturing companies managers found that human resources with limited expertise and the organization’s minuscule financial capabilities contribute to the most significant obstacles I4.0 adoption. However, resistance to change does not have much effect, as per the opinion of the managers surveyed (Herceg et al. 2020).

Hamada (2019) substantiated in his research on I4.0 adoption through statistical analysis that the decision-makers
need to adopt a positive attitude towards implementing I4.0 by making the right policies to mitigate the shortage of qualified and skilled employees. A similar study conducted in Indonesia highlighted the government’s motivational programs as one of the critical drivers. Moreover, the industry ecosystem, market condition, productivity, and efficiency of the organization, in general, were found to be contributing to the list of I4.0 drivers. As per Rezqianita and Ardi (2020), financial, organizational, government, and technological challenges are equally important and need policymaker’s attention while embarking on the I4.0 implementation.

After identifying the I4.0 drivers, the need for justified and safe ICT infrastructure is imperative to extricate the potential of these drivers. IoT devices, CPS, cloud computing data storage, machine-to-machine communication, etc., running in real-time across integrated internet networks require high-speed seamless broadband internet access, thrusting the need for an efficient network (Akdil et al. 2018; Tupa et al. 2017). This real-time sharing of vast sensitive company data and exchanging information across the entire supply chain network gives rise to cybersecurity challenges and high-speed, low-latency internet bandwidth (Birkel et al. 2019; Caiado et al. 2022; Ivanov 2020). Lack of standardization and benchmarking of business operations is another challenge that technocrats and managers face while digitalizing the industry operations. A distinctly explained and stated set of standards based on dynamic optimization models is a must-have condition to ensure seamless data sharing between external and internal stakeholders like regulatory agencies, production lines, machines, supply chain, and customers throughout the entire value chain (Akdil et al. 2018; De Vries and Van Wassenhove 2020; Terra et al. 2021).

Further, this section describes the 45 barriers considered in the study. The list is an outcome of the meticulous amalgamation of expert opinion and the comprehensive literature review. Table A1 (Appendix) presents a brief description of these barriers.

2.4 Research Tools and Techniques used in past literature

The literature review clearly states that the MCDM techniques, survey, interview method, and statistical tools have been the past researcher’s first choice to analyze the relevant factors, challenges, enablers, barriers, etc., related to I4.0 adoption. Table 1 recapitulates some past studies relevant to the current research problem highlighting research tools used and their contribution to the new knowledge.

The literature review shows that very few studies have focused on identifying a wide spectrum of I4.0 implementation barriers and culminating them in the aptest and significant inhibitors with the most appropriate statistical tool i.e. PCA. Further deriving the interrelationship among these inhibitors using the ISM Fuzzy MICMAC method is the unique contribution of this study to the extant literature. The researchers have attempted to provide a pathway to managers, practitioners, policymakers, and researchers who are working on I4.0 related initiatives and research through the framework developed and findings of this study, which will be useful to them for the successful implementation of I4.0 practices and dealing with the setbacks resulting from the COVID-19 pandemic.

3 Research methodology

A systematic literature review was undertaken in this study to identify the significant barriers impeding the progress of I4.0 implementation. The study first adopted a holistic approach, listing all the 63 barriers identified through an in-depth literature review. Out of 231 respondents, the twenty experts were selected based on their expertise and experience in I4.0 projects and consultancies. These experts were initially provided with a list of 63 barriers to determine the most significant and relevant I4.0 barriers in the context of the present study. The list was further shortened to 45 barriers by applying the principle of ‘mutually exclusive and collectively exhaustive (MECE)’ items through comparative analysis, assessment, and experts’ opinions to avoid repetition and interference. The details of these Forty-five barriers are discussed in earlier Sect. 2.3, and the professional expertise of the twenty experts is discussed below.

1) Industry experts: Eight industry experts confirmed expertise in I4.0 related projects, supply chain management, production planning and control, and manufacturing operations having industrial experience of more than 15 years in their capacity as Director, CEO, Senior Manager, etc. They are mainly associated with the automobile industry, electrical equipment, and appliances manufacturing, textile manufacturing, ammunition hardware manufacturing, plastic industry, furniture manufacturing, and IT and Software.

2) Experts from Academia: Six professors from renowned universities in India who specialized in Industrial, Manufacturing, Electronics Engineering, Management, Information Technology, and Computer Science represented an academic perspective. These academic professionals with over 20 years of expertise in academia have directed numerous industry-institutional collaboration programs and provided I4.0 advisory services.

3) Data Scientists: Two experts contributed with expertise in data analytics and management. These two data scientists have over ten years of experience and now working with well-established industrial organizations in India that are ready to implement I4.0 practices.
| Contributions                                                                 | Outcomes                                                                                                                                                                                                 | Tools used for analysis                                                                 | References                                |
|-----------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|------------------------------------------|
| I4.0 implementation barriers in food supply chain                          | The most prominent barriers are the absence of awareness and customer receptivity, huge financial investment, technological inadequacy, and scarcity of eco-innovation                                                | Rough-DEMATEL                                                                            | Kumar et al. (2022)                      |
| The causality assessment of the I4.0 challenges                             | Technological up-gradation and lack of a policy framework are placed at the top of the trigger category hierarchy. The significant barriers identified are difficult access to credit and resistance to accept change | DEMATEL                                                                                 | Khanzode et al. (2021)                   |
| Challenges arise in sustainable human resource management due to I4.0 disruption | Job security and persistent training facility are the crucial challenges                                                                                                                                     | Fuzzy BWM                                                                               | Agarwal et al. (2021)                    |
| Challenges identification of I4.0                                           | Internet of Things (IoT) and cybersecurity are the most crucial challenges                                                                                                                              | DEMATEL-MMDE-ISM                                                                         | Singh and Bhanot (2020)                  |
| Framework development to surmount SSCM challenges                           | The management, organizational and economic challenges are prominent                                                                                                                                       | BWM-ELECTRE                                                                             | Yadav et al. (2020)                     |
| I4.0 enablers identification and assessment                                 | The support of top management is necessary for any cultural change                                                                                                                                         | ISM MICMAC                                                                              | Devi et al. (2020)                       |
| Contextual relationship development among sustainable functions of I4.0     | I4.0 is adoption impacted by economic sustainability through the business model’s innovation and efficiency                                                                                           | ISM MICMAC                                                                              | Ghoubakloo (2020)                       |
| I4.0 enablers identification                                                | Financial help, cheaper internet, government services, continuing education, and workforce training have been the most effective enablers                                                               | TISM and Fuzzy MICMAC                                                                    | Jain and Ajmera (2020)                   |
| Ranking and clustering of I4.0 barriers                                     | The absence of transparency in cost–benefit analysis followed by unclear knowledge of benefits was the prominent barrier. The inappropriateness of existing machines/equipment in the new layout, missing standards, lack of adequately skilled workforce, lagging IT infrastructure, and limited data security were other most impacting barriers | PCA-Fuzzy AHP-K means                                                                    | Kumar et al. (2020)                     |
| Establishing a causal relationship between I4.0 barriers                   | The most critical barrier is an inadequate digital strategy and resource scarcity. However, the most impacting barriers are missing I4.0 standards, an organized system of government guidelines, and regulations that affect the implementation of I4.0 | Grey DEMATEL                                                                             | Raj et al. (2020)                        |
| Identification and assessment of I4.0 enablers                             | IoT, Big data, and the IoT ecosystem were the most significant enablers                                                                                                                                   | PCA-ISM-DEMATEL                                                                          | Rajput and Singh (2019a)                |
| Established a causal relationship between I4.0 barriers                    | Lack of education, knowledge, and awareness are critical causes that trigger the other barriers, i.e., lack of ICT adoption, lack of perseverance, and lack of qualified employees                                  | Interview and ISM and MICMAC                                                            | Karadayi-Usta (2019)                    |
| Prioritizing the I4.0 challenges                                           | The most significant challenge hindering the implementation of I4.0 is the lack of technological infrastructure                                                                                      | BWM                                                                                    | Moktadir et al. (2018)                  |
| Establish contextual relationships among the I4.0 barriers                  | The company’s legal identity and its ability to enter into a contract without infringing the framework were identified as critical barriers                                                             | ISM and Fuzzy MICMAC                                                                    | Kamble et al. (2018a, b)                |
4) Consultants: Four experts belonged to the consultancy sector. They contributed through their experience in handling I4.0 projects in manufacturing industries of India possess experience of more than 15 years.

An empirical analysis was performed using PCA for the group formation further named as inhibitors and the final selection of barriers in the particular group. Further, an expert panel from Industry and academia (previously identified twenty experts) were consulted to affirm the identified group names (inhibitors) and to comprise barriers to confirm the practical relevance and importance of the barriers affecting the inhibitors to which it belonged. The selected inhibitors were then presented to an expert panel again to gather input for further use of ISM fuzzy MICMAC analysis. This study aimed to provide a robust model that thoroughly addressed the inhibitors and provided a systematic roadmap for the sustainable adoption of I4.0. A mixed-methods research methodology supported this research, and both qualitative and quantitative approaches were used to create a solid theoretical framework. Further, we have discussed an integrated PCA-ISM Fuzzy MICMAC framework developed in this study.

3.1 Integrated PCA-ISM fuzzy MICMAC methodology and model development

The study is profoundly based on empirical data, reflecting its potential to influence the real-time decision-making process. The data is collected online through a structured questionnaire using Google form. Each respondent was asked to rate each I4.0 implementation barrier; a 10 point Likert scale is used to record the perceived level of importance of the particular barrier in achieving the I4.0 implementation, ‘1’ being the lowest importance and ‘10’ being the highest importance. The questionnaire was sent to the 450 prospective respondents, out of which 231 responded (response rate of 51%) after continuous follow-up through phone calls and emails from 15th October 2020 to 15th January 2021. Largely respondents belonged to the categories of industry experts, academicians, consultants, data scientists, etc., responsible for handling the projects related to I4.0 in their respective domains, especially in Indian manufacturing industries. The Demographic Profile of the respondents selected for the study is shown in Table 2.

The sample’s quality is established by relevant demographic factors, such as education, experience, and the respondent’s specialization in the industrial and academic environment. More than 75 percent hold PG and Ph.D. degrees, 90 percent have more than ten years of experience, followed by the uniform representation of all size businesses confirms the respondents’ expertise and competence to produce quality data. The automotive sector’s willingness to adopt I4.0 is noticeable from the data, confirming the previous research findings that this sector has better grasped the opportunities of I4.0 (Mckinsey 2020; Yadav et al. 2020). The software used for data tabulation, pre-processing, visualization, and analysis are SPSS v23, MATLAB 2015, and Microsoft excel. The thumb rule confirmed the sample size adequacy for conducting PCA, i.e., the required sample size should be five times the number of variables considered in the study (Shaukat et al. 2016). The sample size of 231 is finally accepted for carrying out the PCA. Using SPSS v23, the reliability test was performed on the data to measure overall consistency and internal errors, if any. As popularly employed, Cronbach’s Alpha value is used, reflecting how closely a group of items is related to assessing the data set’s reliability. The Cronbach’s Alpha value found to be 0.882 assures data credibility for further analysis (Victor et al. 2018). Figure 1 elaborates on the stepwise research methodology adopted in the study.

3.1.1 Principal component analysis (PCA)

PCA is a dimension reduction technique often used to minimize a large data set’s dimensionality, converting a large dataset of variables into a smaller one without compromising the original dataset information (Jollife and Cadima 2016). A high-dimensional input vector is transformed linearly by PCA into a low-dimensional output containing non-correlated elements (Cao et al. 2003). This multivariate analysis approach is extensively used to reduce dimensionality (S. Kumar et al. 2020). It extracts new orthogonal variables named principal components (PCs), which are the linear combinations of the input variables (Ringnér 2008). These identified PCs retrieve most of the data’s variability with minimal deviation compared to the original data’s total variance (Kumar and Sharma 2015).

Kaiser–Meyer–Olkin (KMO) test is used to measure the appropriateness of factor analysis data. For each variable in the model and the full model, the sampling significance is tested. A varimax rotation is used to maximize the sum of the variance of squared loadings, i.e., correlations among variables and factors, with a maximum of 50 iterations of convergence. The aim is to relate each variable to a maximum of one factor to simplify PCA results (Kumar and Sharma 2015). Bartlett’s test of sphericity confirms that the correlation matrix obtained has an identity matrix with an associated $p$-value < 0.001, indicating PCA can be used (Rajput and Singh 2019b). The KMO value of this dataset is 0.72. The Bartlett test of sphericity approx Chi-Square is 6692.490, the degree of freedom is 990, and the $p$-value is 0.000, which confirms that the sampling data is appropriate for factors extraction (Kaiser 1974). The eigenvalue indicates the variance of each variable in the total sample. Referring to the scree plot Fig. 2, it is evident that twelve
components show the eigenvalues more than one, indicating twelve components can be extracted. These twelve components explain 74% of the variation in the data considered for the study.

Figure 3 depicts the mapping of inhibitors with loaded barriers indicating similar variables (barriers) categories into principal components (inhibitors).

Further, ISM Fuzzy MICMAC is used to develop the ISM model and calculate all the twelve inhibitors’ driving and dependence power.

### 3.1.2 ISM model development

Interpretive structural modeling proposed by Warfield (1974) is an interconnecting framework in which a set of directly and indirectly related elements are mapped into a contextual model to identify and comprehend the complicated relationship between them. A multilevel structural model is developed by considering inputs from twenty I4.0 experts, selected from the sample of 231 respondents, based on their knowledge, experience, and expertise to handle I4.0 projects explained earlier. According to Murry and Hammons (1995), the focus group of twelve experts is adequate for the exploratory study, whereas the current research has chosen twenty, making it robust and precise.

The following stepwise process is adopted for ISM fuzzy MICMAC modeling.

1. **Step 1** Extraction of 12 Inhibitors from 45 barriers using PCA.

   Twelve Inhibitors IH1, IH2, IH3, IH4, IH5, IH6, IH7, IH8, IH9, IH10, IH11, and IH12 derived through PCA are named to reflect eminence of contributing barriers. Refer to Fig. 3 for the names of the inhibitors and their mapping with the contributing barriers.

2. **Step 2** Constructing structural self-interaction matrix (SSIM).

   The SSIM is the base matrix drawn from the inputs received from the 20 experts chosen for the study, as described earlier. The notation used to obtain the SSIM
was A, O, V, and X. These notations indicated the relationship between inhibitors.

Where V = Inhibitor in an ith row will impact the jth column’s inhibitor. A = Inhibitor in an ith row is impacted by inhibitor in the jth column. X = Inhibitor in the ith row and the jth column will impact each other, and O = inhibitor in the ith row and jth column are unrelated.

Both modes of data collection, i.e., online and face-to-face, were used as per the expert’s convenience and availability. Expert data was collected using either of the codes V/A/X/O to reflect the exact relationship between the inhibitors’ pairs. The maximum time–frequency (Mode) value is used as a criterion for formulating the final matrix. The relationship code (V/A/X/O) associated with the mode value is chosen for respectively paired inhibitors. To a large extent, the data compiled was clear and unambiguous. One more round of data collection was carried out for unclear and ambiguous responses where two choices shared the mode value. The obtained SSIM is shown in Table 3.
Step 3 Formulating the reachability matrix.

Table 4 depicts rules to convert the SSIM into a binary matrix by replacing V/A/X/O with zero or one, as shown in Table 5. This binary matrix is named as initial reachability matrix, which is further tested for transitivity by marking the additional pairs based on the assumption, if element 1 is associated with element 2 and element 2 is associated with element 3, then element 1 is associated with element 3 (Qureshi et al. 2008). The MATLAB program is used to test and resolve the transitivity issue, as shown in Table 6.

Step 4 Level partitions.

All inhibitors are partitioned into levels by identifying reachability and antecedent sets. These sets are further defined as the set of the inhibitors themselves and those it may help achieve called reachability, and others may assist in attaining it called the antecedent. Both sets are used to obtain the intersection set, which is used to rank the inhibitors and the reachability matrix. This way, the inhibitor/s whose reachability and intersection sets have the same element/s in iteration 1 is/are identified and given the top rank in the hierarchy. This top-rank inhibitor/s would not help any other inhibitors to achieve higher performance. After the top-level inhibitors are drawn from the total inhibitors, they are eliminated from the further iterations. The process continues until all the inhibitors are ranked and positioned in the hierarchy below the top rank inhibitor/s; refer to Tables 7 and 8.

Step 5 ISM Model Formation.

The structural model is developed to indicate the direct and indirect dependencies between every inhibitor by an arrow referring to the relationships obtained from the final reachability matrix and the level partitions. The ISM model of the I4.0 inhibitor’s interdependencies hierarchy is shown in Fig. 4.

3.1.3 ISM fuzzy MICMAC analysis

The expert’s input received earlier for ISM analysis was binary in nature, i.e., yes–no, true–false, or 1–0. If the relationship is found to exist, it is represented by one or zero without giving much attention to the relationship’s intensity. This is considered a drawback of ISM as the strength of any two inhibitors’ relationships is unclear. The possibilities of strong or weak, stable, or unstable, fragile, or robust relations always existed in all scenarios. ISM does not have any scope for this. Hence ISM fuzzy MICMAC analysis is selected to overcome this drawback. The detailed stepwise approach is explained below.

Step 1: Development of Binary direct reachability matrix (BDRM).

BDRM is the base matrix for ISM fuzzy MICMAC analysis. The initial reachability matrix is re-written by replacing all the diagonal elements with zero to obtain the BDRM, as illustrated in Table 9.

Step 2: Construction of Fuzzy direct reachability matrix (FDRM).

The strength or degree of the relationships is the basis for this analysis. All twenty experts were invited again to rate and record their opinion. This time, the relationship rating between paired inhibitors was on a scale of 0–1 instead of 0 or 1. Experts’ judgment was recorded in terms of the numerical value chosen from the scale given in Table 10. After receiving the data, the rule shown in Table 10 was applied to construct the fuzzy direct reachability matrix shown in Table 11 based on the number of experts in agreement, i.e., saying yes to the relationship.

Step 3: Construction of Fuzzy MICMAC stabilized matrix.

Researchers have used three fuzzy combinations, i.e., max–min, max—product, max—average, to define the intensity of fuzzy indirect relationships from elements i to j. Looking at the strength of the fuzzy relations max–min combination was considered suitable for this study. The selected combination can be further explained as the minimum intensity must be the maximum of all feasible minimal impacts from element i to j. The final fuzzy stabilized matrix is achieved by multiplying the matrices repeatedly. The test of the stabilized matrix attainment is the stable hierarchy of dependence power and driving power.

The basic fuzzy multiplication algorithm was used to multiply two matrices based on the boolean matrix multiplication rule. As per the fuzzy set theory, the product of
two fuzzy matrices is always a fuzzy matrix. The rule is explained below in Eq. (1).

\[ T = U \ast V = \max_n \{ \min(x_{in}, y_{nj}) \} \]  

(1)

Here, \( U = x_{in} \) and \( V = y_{nj} \)

Table 12 shows the Fuzzy MICMAC stabilized matrix developed using the MATLAB program. The driving power was derived by adding all the row entries, and dependence power was derived by adding all the column entries. The strength of the row and column values indicates the impact of the respective inhibitor on the implementation of I4.0. This value, along with the cluster diagram, provides vital information to management while making important decisions. The cluster diagram divides the inhibitors into four segments: autonomous, dependent, linkage, and driver.

### 4 Results and discussions

This research’s primary goal is to establish a model that replicates the prevailing situation and systematically
encourages technocrats and managers to achieve sustained competitive advantage by adopting it. A holistic effort is made to directly-indirectly consider all the prominent barriers impacting I4.0 implementation. The base list included forty-five barriers, which was an outcome of long and intensive engagement with experts followed by a robust literature review. The list was further reduced to twelve inhibitors by PCA. The Inhibitors were named, studying the contributory elements from the base list. Before accepting the names, researchers consulted the experts for validation of the inhibitors’ names.

The PCA outcome was used as an input to develop the ISM model, as shown in Fig. 4, with the main objective to investigate the interdependencies between all the twelve inhibitors. The top-level inhibitors (IH2, IH9, and IH11) depend on the bottom and middle-level inhibitors. Bottom-level inhibitors (IH1, IH5, IH12, IH4, and IH3) drive the middle-level (IH8, IH10, IH7, and IH6) and top-level inhibitors, which must be dealt with priority by the top leadership of the manufacturing companies.

Fuzzy MICMAC analysis was then carried out to categorize these inhibitors in four quadrants, as shown in Table 12 and Fig. 5.

1) Autonomous inhibitors (Segment I)

The 3rd quadrant represents the group of autonomous inhibitors showing weak driving and weak dependence power. Inhibitors contributing to this segment do not

Table 3 Structural self-interaction matrix (SSIM)

| Inhibitors | IH1 | IH2 | IH3 | IH4 | IH5 | IH6 | IH7 | IH8 | IH9 | IH10 | IH11 | IH12 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|
| IH1        | X   | V   | V   | V   | V   | V   | V   | V   | V   | V    | V    | V    |
| IH2        | X   | A   | A   | O   | A   | O   | A   | A   | A   | A    | A    | A    |
| IH3        | X   | X   | A   | O   | V   | O   | V   | V   | V   | V    | V    | V    |
| IH4        | X   | A   | O   | V   | V   | V   | V   | V   | V   | X    | V    | V    |
| IH5        | X   | O   | A   | V   | O   | V   | V   | V   | V   | A    | O    | A    |
| IH6        | X   | V   | V   | V   | V   | V   | V   | V   | V   | A    | V    | A    |
| IH7        | X   | A   | O   | A   | V   | A   | V   | A   | A   | X    | A    | A    |
| IH8        | X   | V   | V   | V   | V   | V   | V   | V   | V   | X    | V    | A    |
| IH9        | X   | A   | A   | O   | A   | V   | A   | A   | A   | X    | A    | A    |
| IH10       | X   | V   | A   | 1   | 1   | 1   | 1   | 1   | 1   | 1    | 1    | 1    |
| IH11       | X   | A   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1    | 1    | 1    |
| IH12       | X   | A   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1    | 1    | 1    |

Table 4 Rules to convert the values in SSIM into zeros and ones

| Sr no | Character in SSIM (V, A, O, X) | Value associate at in reachability matrix (1, 0) |
|-------|--------------------------------|-----------------------------------------------|
| 1     | V                              | 1                                             |
| 2     | A                              | 0                                             |
| 3     | O                              | 0                                             |
| 4     | X                              | 1                                             |

Table 5 Initial reachability matrix

| Inhibitors | IH1 | IH2 | IH3 | IH4 | IH5 | IH6 | IH7 | IH8 | IH9 | IH10 | IH11 | IH12 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|
| IH1        | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1    | 1    | 1    |
| IH2        | 0   | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0    | 0    | 0    |
| IH3        | 0   | 1   | 1   | 1   | 1   | 0   | 0   | 0   | 0   | 0    | 0    | 0    |
| IH4        | 0   | 1   | 1   | 0   | 0   | 1   | 1   | 1   | 1   | 1    | 1    | 1    |
| IH5        | 0   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1    | 1    | 1    |
| IH6        | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 1    | 1    | 1    |
| IH7        | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0    | 0    | 0    |
| IH8        | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0    | 0    | 0    |
| IH9        | 0   | 0   | 0   | 0   | 0   | 1   | 1   | 1   | 1   | 1    | 1    | 1    |
| IH10       | 0   | 0   | 0   | 0   | 0   | 1   | 1   | 1   | 1   | 1    | 0    | 1    |
| IH11       | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 1    | 0    | 1    |
| IH12       | 0   | 0   | 0   | 0   | 0   | 1   | 1   | 1   | 1   | 0    | 1    | 1    |

1) Autonomous inhibitors (Segment I)

The 3rd quadrant represents the group of autonomous inhibitors showing weak driving and weak dependence power. Inhibitors contributing to this segment do not
significantly impact the I4.0 adoption decision-making process as these elements are highly disconnected from the system. The study found none of the inhibitors in this segment, which means all the inhibitors considered in the study are essential and hold a significant role in the I4.0 implementation decision-making process.

2) Dependent inhibitors (Segment II)

The 4th quadrant comprises the inhibitors’ group as a dependent or resultant inhibitor. This group has weak driving and strong dependence power. It has a very high dependence on the other inhibitors in the model, considering the system’s output variable depends on the other input variables. The absence of eco-friendly production (IH2), ineffective customer management (IH9), and ineffective product management (IH11) fall into this segment, confirming that it is a highly driven and dependent inhibitor. This finding is consistent with earlier research (Akdil et al. 2018; Bandara et al. 2019; Kiel et al. 2017; Müller et al. 2018; Preuveneers et al. 2017).

3) Linkage inhibitors (Segment III)

The 1st quadrant constitutes the group of inhibitors with exceptionally high driving power and too high dependence power. This group is highly influential because of its position in the model. It depends on the 2nd quadrant inhibitors and drives the inhibitors of the 4th quadrant, making it a crucial group. This segment consists of incompatible I4.0 implementation standards (IH6), inappropriate data security measures (IH7), inadequate skill development program (IH8), limited I4.0 technology competency and adoption (IH10). It signifies the minor alteration in any of these

| Table 6 Final reachability matrix (Transitivity) |
|-----------------------------------------------|
| Inhibitors | IH1 | IH2 | IH3 | IH4 | IH5 | IH6 | IH7 | IH8 | IH9 | IH10 | IH11 | IH12 |
| IH1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| IH2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IH3 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| IH4 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| IH5 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| IH6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IH7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IH8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IH9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IH10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IH11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| IH12 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| Table 7 Final reachability matrix level partitions for 1st iterations |
|---------------------------------------------------------------|
| I4.0 implementation inhibitors | Reachability | Antecedent | Intersection | Level |
|--------------------------------|---------------|-------------|--------------|-------|
| Iteration I | IH1 | IH1, IH2, IH3, IH4, IH5, IH6, IH7, IH8, IH9, IH10, IH11, IH12 | IH1 | IH1 | IH1 |
| | IH2 | IH2 | IH2 | IH2 | IH2 |
| | IH3 | IH2, IH3, IH4, IH5, IH6, IH7, IH8, IH9, IH10, IH11, IH12 | IH3, IH4, IH5, IH6, IH7, IH8, IH9, IH10, IH11, IH12 | IH3, IH4, IH5, IH6, IH7, IH8, IH9, IH10, IH11, IH12 | IH3, IH4, IH5, IH6, IH7, IH8, IH9, IH10, IH11, IH12 |
| | IH4 | IH4 | IH4 | IH4 | IH4 |
| | IH5 | IH5 | IH5 | IH5 | IH5 |
| | IH6 | IH6 | IH6 | IH6 | IH6 |
| | IH7 | IH7, IH8, IH9, IH10, IH11 | IH7, IH8, IH9, IH10, IH11 | IH7, IH8, IH9, IH10, IH11 | IH7, IH8, IH9, IH10, IH11 | IH7, IH8, IH9, IH10, IH11 |
| | IH8 | IH8 | IH8 | IH8 | IH8 |
| | IH9 | IH9 | IH9 | IH9 | IH9 |
| | IH10 | IH10 | IH10 | IH10 | IH10 |
| | IH11 | IH11 | IH11 | IH11 | IH11 |
| | IH12 | IH12 | IH12 | IH12 | IH12 |
inhibitors will leverage the output effect on the inhibitor. Many studies have validated these findings (Calabrese et al. 2020; Hamada 2019; Herceg et al. 2020; Khan et al. 2020; Preuveneers et al. 2017; Raj et al. 2020; Rezqianita and Ardi 2020; Xu et al. 2018).

4) Driver inhibitors (Segment IV)

The 2nd quadrant consists of inhibitors with too high driving power and extremely low dependence power of the entire system. The findings of the study depict inhibitors as inadequate organizational strategies (IH1), uncertainty about financial decision making (IH5), limited employee readiness (IH12), inconsistent legal and government policies (IH3), insufficient IT and automation infrastructure (IH4) belong to this group. These independent inhibitors influence all other inhibitors and act as significant activators for I4.0 implementation. These inhibitors must be handled carefully by the practitioners, policymakers, and stakeholders and should urgently be treated. These findings also agree with the outcomes of the research studies (Glass et al. 2018; Khan et al. 2020; Luthra and Mangla 2018; Raj et al. 2020; Schroeder et al. 2019).

This study suggests that manufacturing companies should recognize the significance of all these inhibitors and develop

Table 8  Final reachability level partitions for 2nd to 8th iterations

| Code | Reachability | Antecedent | Intersection | Level | Inhibitor |
|------|--------------|------------|--------------|-------|-----------|
| Iteration I |
| IH1 | IH1 IH2 IH3 IH4 IH5 IH6 IH8 IH9 IH10 IH11 IH12 | IH1 | 8 | IH1 | Inadequate organizational strategies |
| IH2 | IH2 | IH1 IH2 IH3 IH4 IH12 | IH2 | 1 | Presence of eco-friendly production |
| IH3 | IH2 IH3 IH4 IH6 IH7 IH8 IH9 IH10 | IH3 | 6 | IH4 ID12 | Inconsistent legal and government policies |
| IH4 | IH1 IH4 IH6 IH9 IH10 | IH1 IH5 IH12 | IH3 IH4 IH12 | Insufficient IT and automation infrastructure |
| IH5 | IH1 IH4 IH5 IH6 IH7 IH9 IH10 | IH1 IH5 IH12 | IH3 IH4 IH12 | Uncertainty about financial decision making |
| IH6 | IH1 IH5 IH12 | IH3 IH4 IH12 | IH3 IH4 IH12 | Incompatible I4.0 implementation standards |
| IH7 | IH1 IH12 | IH1 IH5 IH12 | IH3 IH4 IH12 | Inconsistent I4.0 technology competency and adoption |
| IH8 | IH1 IH3 IH4 IH5 IH6 IH7 IH8 IH9 IH10 IH11 IH12 | IH1 IH3 IH4 IH5 IH6 IH7 IH8 IH9 IH10 IH12 | IH3 IH4 IH12 | Limited employee readiness |
| IH9 | IH1 IH3 IH4 IH5 IH6 IH7 IH8 IH9 IH10 IH11 IH12 | IH1 IH3 IH4 IH5 IH6 IH7 IH8 IH9 IH10 IH11 IH12 | IH3 IH4 IH12 | Limited employee readiness |
| IH10 | IH4 ID12 | IH3 IH4 IH12 | IH3 IH4 IH12 | Limited employee readiness |
| IH11 | IH9 IH11 IH12 | IH3 IH4 IH12 | IH3 IH4 IH12 | Limited employee readiness |
| IH12 | IH1 IH3 IH4 IH6 IH7 IH8 IH9 IH10 IH11 IH12 | IH1 IH3 IH4 IH5 IH6 IH7 IH8 IH9 IH10 IH11 IH12 | IH3 IH4 IH12 | Limited employee readiness |

Fig. 4 ISM model of the I4.0 inhibitors interdependencies hierarchy
organizational policies and strategies to overcome them to rip the benefits of I4.0 implementation. Organizations need to be very keen to select appropriate I4.0 technologies to achieve sustainable growth (Bai et al. 2020; Siltori et al. 2021). Implementation of these technologies, mainly IoT, IIoT, CC, BDA, AM, AR/VR, CPS, Robotics, etc. integrating with humans and machines will help to achieve a flexible, environmentally, socially, and economically sustainable manufacturing system (Fakhar Manesh et al. 2021; Karadayi-Usta 2019; Stentoft and Rajkumar 2020; Wang et al. 2016a, b). Admittedly, every company may not have the liberty to install new or align existing ICT infrastructure due to financial constraints (Singh and Bhanot 2020). The way out could be possible only through well-thought customized strategies at departmental and organizational levels. Here, top management and corporate administration’s role is crucial as the authority to decide which business functions should be held inside the company and what else to outsource. The third-party involvement may be decisive if not consolidated and made legally binding on the service provider against business secrets’ confidentiality and safety (Harikannan et al. 2020; Raj et al. 2020). In response to this, the Indian government has initiated, The Personal Data Protection Bill 2019 and National Cyber Security Policy -2013 (Ministry of Electronics and Information Technology report 2013) to protect the business interests while adopting the

| Inhibitors | IH1 | IH2 | IH3 | IH4 | IH5 | IH6 | IH7 | IH8 | IH9 | IH10 | IH11 | IH12 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|
| IH1        | 0   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1   | 1    | 1    | 1    |
| IH2        | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0    | 0    | 0    |
| IH3        | 0   | 1   | 0   | 1   | 0   | 0   | 1   | 0   | 1   | 1    | 1    | 1    |
| IH4        | 0   | 1   | 1   | 0   | 0   | 0   | 1   | 1   | 1   | 1    | 1    | 1    |
| IH5        | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 0    | 1    | 0    |
| IH6        | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0    | 0    | 0    |
| IH7        | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1    | 0    | 0    |
| IH8        | 0   | 0   | 0   | 0   | 0   | 1   | 1   | 0   | 1   | 1    | 1    | 0    |
| IH9        | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0    | 1    | 0    |
| IH10       | 0   | 0   | 0   | 0   | 0   | 1   | 1   | 0   | 1   | 0    | 1    | 0    |
| IH11       | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 1    | 0    | 0    |
| IH12       | 0   | 0   | 0   | 1   | 0   | 1   | 1   | 0   | 1   | 1    | 1    | 0    |

Table 9 Binary direct reachability matrix (BDRM)

| Inhibitors | IH1 | IH2 | IH3 | IH4 | IH5 | IH6 | IH7 | IH8 | IH9 | IH10 | IH11 | IH12 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|
| IH1        | N   | N   | N   | N   | N   | N   | N   | N   | N   | N    | N    | N    |
| IH2        | N   | N   | N   | N   | N   | N   | N   | N   | N   | N    | N    | N    |
| IH3        | N   | N   | N   | N   | N   | N   | N   | N   | N   | N    | N    | N    |
| IH4        | N   | N   | N   | N   | N   | N   | N   | N   | N   | N    | N    | N    |
| IH5        | N   | N   | N   | N   | N   | N   | N   | N   | N   | N    | N    | N    |
| IH6        | N   | N   | N   | N   | N   | N   | N   | N   | N   | N    | N    | N    |
| IH7        | N   | N   | N   | N   | N   | N   | N   | N   | N   | N    | N    | N    |
| IH8        | N   | N   | N   | N   | N   | N   | N   | N   | N   | N    | N    | N    |
| IH9        | N   | N   | N   | N   | N   | N   | N   | N   | N   | N    | N    | N    |
| IH10       | N   | N   | N   | N   | N   | N   | N   | N   | N   | N    | N    | N    |
| IH11       | N   | N   | N   | N   | N   | N   | N   | N   | N   | N    | N    | N    |
| IH12       | N   | N   | N   | N   | N   | N   | N   | N   | N   | N    | N    | N    |

Table 10 Fuzzy scale to rate the intensity of inhibitors

| Strength | Not important | Very low | low | medium | high | very high | Completely important |
|----------|---------------|----------|-----|--------|------|-----------|----------------------|
| Numerical value | 0 | 0.1 | 0.3 | 0.5 | 0.7 | 0.9 | 1 |
| No. of experts | 0 | 1 to 3 | 4 to 6 | 7 to 9 | 10 to 12 | 13 to 15 | 16 and more |

Table 11 Fuzzy direct reachability matrix

| Inhibitors | IH1 | IH2 | IH3 | IH4 | IH5 | IH6 | IH7 | IH8 | IH9 | IH10 | IH11 | IH12 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|
| IH1        | 0   | 1   | 0.5 | 0.5 | 0.5 | 1   | 1   | 1   | 1   | 1    | 1    | 0.5  |
| IH2        | 0.3 | 0   | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3   | 0.3  | 0.3  |
| IH3        | 0.5 | 1   | 0.7 | 0.5 | 1   | 0.9 | 1   | 1   | 1   | 0.9   | 1    | 0.9  |
| IH4        | 0.5 | 1   | 0.7 | 0.5 | 1   | 0.9 | 1   | 1   | 1   | 0.9   | 1    | 0.9  |
| IH5        | 0.3 | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3   | 0.3  | 0.3  |
| IH6        | 0.3 | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3   | 0.3  | 0.3  |
| IH7        | 0.3 | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3   | 0.3  | 0.3  |
| IH8        | 0.3 | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3   | 0.3  | 0.3  |
| IH9        | 0.3 | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3   | 0.3  | 0.3  |
| IH10       | 0.3 | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3   | 0.3  | 0.3  |
| IH11       | 0.3 | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3   | 0.3  | 0.3  |
| IH12       | 0.5 | 1   | 0.5 | 0.5 | 0.9 | 1   | 1   | 0.9 | 1   | 0.9   | 1    | 0    |
I4.0 vision. Companies may opt to use blockchain technology as it is a more immutable, transparent, and trustworthy platform for business transactions (Leng et al. 2020).

Digital transformation has brought a new edge to traditional manufacturing by making it fast and flexible. Even though this is a fact, companies are struggling because of the dearth of skilled workforce with extensive programming, data analytics, and tech-savvy digital skills to sustain in a digitalization transformation (Birkel et al. 2019). Some companies have started upskilling the existing employees, enabling them to become compliant with the changing demand of humans’ role to survive in I4.0 environment requirements (Neumann et al. 2021). As a result, having a workforce with I4.0 technology competencies and expertise will help to improve employee readiness. In addition, through well-planned training and skill upgrading programs, management encouragement, and instilling encouraging policies to work deployment based on the caliber of the employees, will leverage I4.0 adoption passionately.

The framework developed in this study suggests the interlink between technology competency and technology adoption, cybersecurity and data security measures, and compatible I4.0 standards must be aligned properly as the slightest misalignment or negligence of these inhibitors may derail the ultimate objective of sustainable I4.0 implementation. This may be accomplished by deploying I4.0 competent technology in many activities of modern business models, which will aid in the smooth operation of the business, and many functions performed remotely will boost flexibility and productivity by optimizing the use of organizational resources. Harnessing data security measures to maintain the confidentiality and integrity of a company’s critical credentials adopting an end-to-end encrypted framework increases the company’s top management confidence in welcoming I4.0 adoption with great enthusiasm. The rapid progression of I4.0 can be hastened by well-defined I4.0 standards, which can be established by government initiatives and policymakers’ interventions to build universal I4.0 standards and reference architecture.

Eco-friendly products and product customization are also critical aspects of digital transformation which can be addressed only by reconciling customer expectations, customer buying behavior, product characteristics data in real-time. Thereby, the reuse and recycling of waste material, optimum utilization of resources, conservation of energy, and encouraging circular economy to achieve an eco-friendly production system are challenging and ought to attend immediately (Müller, Dotzauer, et al. 2017b) to reduce the loss of environment.

As mentioned earlier, COVID-19 has impacted all facets of the global industry, and the consumer is no exception. The sudden rise in the customer’s digital literacy proved to be a deciding factor in controlling and mitigating the pandemic evils. The high-speed propagation of online communication related to precautions and care forced the

| Table 12 Fuzzy MICMAC stabilized matrix | Inhibitors | IH1 | IH2 | IH3 | IH4 | IH5 | IH6 | IH7 | IH8 | IH9 | IH10 | IH11 | IH12 | Driving power |
|----------------------------------------|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|---------------|
| IH1                                     | 0.5        | 0.7 | 0.5 | 0.5 | 0.5 | 0.9 | 0.9 | 0.9 | 0.7 | 0.9 | 0.7   | 0.5   | 8.2   |
| IH2                                     | 0.3        | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3   | 0.3   | 3.6   |
| IH3                                     | 0.5        | 0.7 | 0.7 | 0.5 | 0.5 | 0.9 | 0.9 | 0.9 | 0.7 | 0.9 | 0.7   | 0.7   | 8.6   |
| IH4                                     | 0.5        | 0.7 | 0.5 | 0.5 | 0.5 | 0.9 | 0.9 | 0.9 | 0.7 | 0.9 | 0.7   | 0.5   | 8.6   |
| IH5                                     | 0.3        | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.9 | 0.9 | 0.9 | 0.7 | 0.9   | 0.7   | 3.6   |
| IH6                                     | 0.3        | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.9 | 0.9 | 0.9 | 0.7 | 0.9   | 0.7   | 3.6   |
| IH7                                     | 0.3        | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.9 | 0.9 | 0.9 | 0.7 | 0.9   | 0.7   | 3.6   |
| IH8                                     | 0.3        | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.9 | 0.9 | 0.9 | 0.7 | 0.9   | 0.7   | 3.6   |
| IH9                                     | 0.3        | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.9 | 0.9 | 0.9 | 0.7 | 0.9   | 0.7   | 3.6   |
| IH10                                    | 0.3        | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.9 | 0.9 | 0.9 | 0.7 | 0.9   | 0.7   | 3.6   |
| IH11                                    | 0.3        | 0.7 | 0.3 | 0.3 | 0.3 | 0.3 | 0.9 | 0.9 | 0.9 | 0.7 | 0.9   | 0.7   | 8.6   |
| IH12                                    | 0.5        | 0.7 | 0.5 | 0.5 | 0.5 | 0.9 | 0.9 | 0.9 | 0.7 | 0.9 | 0.7   | 0.5   | 8.2   |

Dependence power 4.6 7.2 4.8 4.8 4.8 9 9 9 7.2 9 7.2 4.8 81.4

![Fig. 5 Categorization of I4.0 implementation inhibitors based on driving and dependence power](image-url)
customers to align with national policies to ensure individual safety during COVID-19. The last person in the social chain could be contacted at never before speed, just because of the extreme rise in digitally literate internet users. This could be an excellent base for further creating a sustainable customer service program by every manufacturing organization. This also warned the businesses about the digitalization of customer-focused operations. Design of an online customer interface through the company’s own digital platforms, social networking handles, mobile apps, chatbot interaction, and online chat by a virtual agent to provide customized assistance (Chung et al. 2020) and to facilitate their participation in the process of eco-friendly and digital product customization, guided by the customer’s personalized needs (Coreynen et al. 2017) could be the real game-changer in post-COVID 19. Here the role of behavioral economics, predictive analytics, AI, ML could be two-fold. Firstly, it can help to predict the needs and requirements of the customer intelligently. Secondly, it will help the customer to track the product at every manufacturing and distribution stage until it is home delivered (Akdil et al. 2018). These provisions are expected to enhance the experience, stimulating the customer to make favorable buying decisions. Manufacturing companies’ sustainability is assessed by their agility, productivity, customer responsiveness, and emphasis on product quality and regulatory controls; hence, customer satisfaction in any business’s success needs no further elaboration (Wang et al. 2017).

5 Conclusions, study contribution, implications, and future recommendations

The innumerable opportunities I4.0 has bought to the doorsteps of companies have gained a high level of attention from policymakers, manufacturing sectors, and academic researchers in the past few years. As a result of this, new knowledge from very recent years is prominently seen in the current high-quality literature review. It is apparent from most of the research articles that I4.0 is soon going to be the topmost agenda for most companies because of its ability to make business competitive and sustainable in the long run. It has created an urgency for enterprises. PCA is a widely accepted and trusted tool used to extract the most uncorrelated and unique twelve components, i.e., inhibitors from identified forty-five barriers. The interrelationship among these inhibitors was analyzed using ISM integrated with Fuzzy MICMAC analysis. The proposed robust framework will aid management, researchers working on I4.0 implementation research, and project managers in defining strategies and plans to prioritize I4.0 implementation inhibitors according to their significant importance to expedite I4.0 implementation in their respective domains is the distinct credit of this study. The study’s contribution to the theory and coping with post-COVID-19 challenges managerial and policymakers implications are addressed further in this section.

5.1 Contribution to the theory

Despite gaining a vast interest in I4.0, it is noticed that there is still a dearth of comprehensive studies. Indian manufacturing companies are still crawling and struggling on the way to implement I4.0, demanding more elaborative, indepth analyses and structured frameworks to assess the barriers constraining open-hearted welcome to I4.0 (S. Kumar et al. 2020; Luthra and Mangla 2018). This study has tried to uncover a wider ambit of prospective forty-five barriers impacting I4.0 adoption and categorized them into twelve inhibitors to ease dealing with the individual. The study has also developed the conceptual model, which provides the base for designing solutions to overcoming these inhibitors. The ISM with fuzzy MICMAC model divided the inhibitors into four segments. The inhibitors belonging to the independent category must be attended at utmost urgency, i.e., it revealed to be most overriding because of its less dependence and high driving power grabbed policymakers’ attention. Similarly, the inhibitors in the dependent category should not be disregarded.

After being integrated with Fuzzy MICMAC, the study proves that the ISM model ascertained the developed model’s reliability. This research will act as a base to direct academicians and policymakers to devise their way forward by prioritizing the most significant inhibitors. Also, conquering the driver inhibitors through well-thought organizational and strategic management planning, coordination, collaboration, and adoption of government’s legal and financial policies is expected to speed up the adoption of I4.0 in manufacturing companies.

5.2 Study contribution to mitigating post-COVID-19 challenges in manufacturing industry

In the view of a crisis like COVID-19, the role of I4.0 becomes even more crucial. Many companies faced operational challenges in providing efficient services (Haleem et al. 2020), while others have already achieved milestones in using emerging technologies to sustain their business. Similarly, few have deferred I4.0 adoption plans that required higher capital expenditure due to the unclear or long-term payback periods. In contrast, others have considered this as an opportunity to build on their capacity and capability. Although the pandemic outbreak has already caused major demand losses and disruption in the
manufacturing industries due to the unavailability of goods, human resources, and buyers (Ivanov and Dolgui 2020). India’s manufacturing companies are committed to making a strong comeback with government support and built-in resilience.

Nevertheless, Digital technologies can help mitigate the impact in a variety of ways, including increased employee protection, operational performance, asset productivity, and product quality. The slowdown is short-term; the post-COVID-19 propagation of I4.0 will be much faster as the digitalization wave has already reached every aspect of the business proving its worth for adoption (Mckinsey 2020). This study’s findings can guide the safe and secured I4.0 adoption in India’s manufacturing industry by adopting interconnected, intelligent, smart, and flexible manufacturing systems. Incorporating the latest advanced sensors, big data analytics, controllers, cyber-physical system integration, IoT devices, cloud manufacturing, and the embedded system will steer the manufacturing industries to become sustainable in global competition. These new digital automation progressions facilitate the decentralization of manufacturing operations and promote technological responsiveness towards maintaining social distancing during production activities.

5.3 Managerial and policymakers and researchers’ implications

This research offers a couple of ramifications for managers and policymakers. Identifying the prospective I4.0 implementation inhibitors at the initial stage reduces risks and potential setbacks. This facilitates the policymakers and practitioners to make wise decisions at the right time to prevent any adverse effect on the success of I4.0. Most of the studies in the literature reported the frameworks with a limited number of barriers. This research has considered 45 barriers leaving no scope for any omissions. The ISM Fuzzy MICMAC model has significantly contributed to validating and further refining the findings. The critical assessment of each quadrant (Fig. 5) could be a path showing knowledge to managers. It will direct managers, practitioners, and policymakers to reach a high standard of excellence in managing integrated, innovation-driven production processes to deliver intelligent products in high quality and quantity for the right consumer and at the right cost (Gunasekaran et al. 2019). Policymakers may refer to the manifested PCA-ISM Fuzzy MICMAC framework to elucidate the inhibitors’ interconnectedness to formulating an action plan to imbibe digital transformation policies for their organization. I4.0 implementation has immense potential to improve economic performance. Safe and environment-friendly processes through the digital transformation of the manufacturing system will respond to real-time demands is another attraction of I4.0. It will eventually lead to efficient resource allocation, adequate digital infrastructure and network management, and highly effective coordination and collaboration among all value chain elements (Chromjakova and Bata 2017; Stock and Seliger 2016). It encourages the critical consensus on the overall repercussions of inhibitors rendering the managers, policymakers, and academic researchers enough base to formulate strategies, a roadmap for the successful implementation of I4.0.

5.4 Limitations and future research direction

This research work is carried out in the Indian context; the inhibitors identified may not have real significance with other under-developed, developing, or developed country conditions. A similar study may be conducted further to investigate the relevance of the inhibitors in the respective countries. These inhibitors’ interrelationships may also be impacted by the experts’ profile, national policies, and industrial development in that country. In this study, academicians and industry experts’ assigned weights to the inhibitors to develop the ISM fuzzy MICMAC model are purely based on their judgment. Personal biases and subjective assessment may differ from person to person can influence the result. It is recommended to use other MCDM techniques to explore these inhibitors’ causes and dependencies. The insights gained from this study could be the potential foundation to derive causal dependencies of other prospective inhibitors that may have been taken into account in this study. Also, Structural Equation Modeling may be deployed to validate the developed model statistically and empirically. The study may be extended to analyze the broader ambit of enablers of I4.0 to usher the other side of it. It is proposed to conduct more survey-based empirical studies to examine and validate this study outcome for different sectors.

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Declarations

Conflict of interest There is no conflict of financial or non-financial interests between the authors.

Ethical approval No experiments on humans or animals were conducted as a part of this study. The questionnaire served to the respondents, and the methodology used to conduct the study was approved before implementing it.

Informed consent Respondents were given to understand the research objectives and implications before filling out the questionnaire. Informed consent from the respondent was received before filling out the questionnaire.

Appendix

See Table 13.
| Code | Name of barrier                                                                 | Description                                                                                                                                                                                                 | References                                                                                                                                 |
|------|---------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| B1   | Scarcity of high-speed internet communication network infrastructure              | Unstable, unreliable, and uneven internet connectivity and infrastructure hinder real-time communication between different manufacturing functions, leading to chaos in implementing I4.0                                                                 | Glass et al. (2018); Leitão et al. (2016); Luthra and Mangla (2018); Waibel et al. (2017); Zhou et al. (2016)                              |
| B2   | Lack of legal framework and policies                                             | The nonexistence of the legal/regulatory framework jeopardizes I4.0 adoption                                                                                                                                 | Calabrese et al. (2020); Kiel et al. (2017); Luthra and Mangla (2018); Müller et al. (2017b)                                            |
| B3   | Lack of data exchange and transfer protocols                                     | Industries are reluctant to adopt emerging information technologies interface due to a lack of data exchange and transfer standards                                                                             | Kumar et al. (2020); Luthra and Mangla (2018)                                                                                             |
| B4   | High competitive pressures to change                                             | Responding to the highly competitive pressure to change is the most challenging task to address                                                                                                               | Machado et al. (2019); (Terra et al. 2021)                                                                                            |
| B5   | Lack of personnel training and development                                       | No I4.0 compliant skills and competencies nurtured at the university level right from the teaching–learning framework. It also lacked proper training and development policies at the organizational level | Karadayi-Usta (2019)                                                                                                                       |
| B6   | Lack of energy-efficient and eco-friendly production system                      | The absence of policies and strategies regarding remanufacturing, energy-efficient waste management, and eco-friendly production systems is crucial                                                              | Herrmann et al. (2014); Kiel et al. (2017); Müller et al. (2017a)                                                                       |
| B7   | Lack of data security measures                                                   | The safety and security of the data generated at every juncture is a big concern as the data flows through the entire connected network                                                                              | Lee and Lee (2015); Oesterreich and Teuteberg (2016); Xu et al. (2018)                                                                     |
| B8   | Complex network system                                                           | A complicated networking facility is required for providing seamless data connectivity among sensors and wireless technologies                                                                               | Calabrese et al. (2020); Elkhodr et al. (2016); Kang et al. (2016); Liao et al. (2017)                                                   |
| B9   | A complex integration of IT and OT                                               | Information technology (IT) integration with operational technology (OT) is of the highest importance during the adoption of IoT, even though it is complicated                                              | Moktadir et al. (2018); Lee et al. (2015); Lu (2017)                                                                                     |
| B10  | Legal and contractual certainty is missing                                       | There is a lack of legal and contractual regulations on data protection for online data transfer and processing                                                                                               | Kamble et al. (2018b); Müller et al. (2017b); Schröder (2016); Singh and Bhanot (2020)                                                    |
| B11  | Lack of global standards                                                         | Local and global standards in operations at all levels are vital in safeguarding manufacturers’ and consumers’ interests                                                                                       | Chen (2017); Glass et al. (2018); Raj et al. (2019); Schröder (2016)                                                                     |
| B12  | Limited skilled leaders                                                          | Digital leadership competent to handle the dynamics of the organization’s capacity and capability is crucial                                                                                                 | Horváth and Szabó (2019); Rezqianita and Ardí (2020); Terra et al. (2021)                                                                |
| B13  | Limited human–robot interaction                                                  | Robot, Cabot, and human’s enhanced coordination and collaboration are most important to achieving high-quality manufacturing functions                                                                         | Rajput and Singh (2019b)                                                                                                                   |
| B14  | Lack of employee reorganization                                                  | Upskilling and reorganizing the existing employees’ roles and responsibilities in different age brackets is challenging                                                                                     | Ghobakhloo (2018); Horváth and Szabó (2019); Machado et al. (2019)                                                                       |
| B15  | High investment in I4.0 implementation                                           | High capital investment is almost inevitable while adopting the I4.0 practices                                                                                                                                 | Herceg et al. (2020); Kache and Seuring (2017); Singh and Bhanot (2020)                                                                     |
| B16  | Difficulties in identifying peculiar customer requirements as a result of their increased collaboration and involvement | Interpretation of customer feedback is challenging because of the unstructured approach adopted by the individual                                                                                           | Kiel et al. (2017)                                                                                                                         |
| Code | Name of barrier                                                                 | Description                                                                                                                                                                                                 | References                                                        |
|------|-------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------|
| B17  | Limited infrastructure standardization                                        | Infrastructure with an advanced technical specification that will accommodate heterogeneous devices and machines into the network is an essential part of an automated I4.0 system. Infrastructure standardization can allow users without much difficulty to handle it anonymously | Rajput and Singh (2019b); Leitão et al. (2016)                     |
| B18  | Lack of legislation                                                            | Government initiative by passing legislation (law) will take care of legal barriers that hinder the industry’s empowerment                                                                                     | Calabrese et al. (2020); Kamble et al. (2018a); Kiel et al. (2017); Caiado et al. (2022) |
| B19  | The clarity in standards towards I4.0 is missing                               | The right set of yardsticks are a must to achieve sustainable growth. The focus group in an organization should set the right priorities toward it                                                              | Calabrese et al. (2020); Schroeder et al. (2019)                  |
| B20  | Company’s poor digital operations, vision, and strategy                        | I4.0’s vision and strategy should be based on the substantial digital transformation supported by a clear and visionary idea of developing sustainability                                                          | Erol et al. (2016); Luthra and Mangla (2018)                       |
| B21  | Lack of assimilation of wireless technologies and standards in IIoT             | The co-existance of old technologies, I4.0’s intelligent wireless systems, and new IIoT devices lead to the most complicated system design. This makes communication technologies difficult to handle | Khan et al. (2020)                                               |
| B22  | Lack of readiness for innovation                                               | The resistance of managers, staff to imaginative embrace and innovative solutions to new challenges is a concern                                                                                             | Müller et al. (2017b); Theorin et al. (2017)                       |
| B23  | Inadequate research and development on I4.0 adoption                           | A systematic and scientific research-oriented approach based on conceptual and practical knowledge and experience is essential for sustainable I4.0 adoption                                                     | Luthra and Mangla (2018)                                         |
| B24  | Lack of intelligent decision-making system and negotiation mechanism           | For the machine to become an intelligent entity in the value creation chain, it should possess the ability to generate data and continuously learn from it. In the absence of a well-crafted mechanism, this could be very challenging | Fatorachian and Kazemi (2018); Kumar et al. (2020); Vaidya et al. (2018) |
| B25  | Lack of automation system virtualization                                       | Making the system available to all concerns virtually by combining a solid network of sensors, data transfer, and providing real-time visibility of the system is very challenging      | Babiceanu and Seker (2016); Rajput and Singh (2019a)              |
| B26  | Inadequate government funding and policies                                     | The government’s intervention by providing definite guidelines, financial assistance, training programs, etc., will be the deciding factor in times to come                                                                 | Ghadge et al. (2020); Wang et al. (2016a, b)                      |
| B27  | Lack of standardized communication protocols for data interfaces              | The unavailability of standardized communication protocols to avoid inter-firm and intra-firm coordination and management challenges need to tackle carefully                                                                 | Kiel et al. (2017)                                               |
| B28  | Resistance to new business models acceptance                                   | The new insights gained from the data will only be worthwhile if the organization has the asset of smart data scientists who could perform the detailed analytics fitting to the new business model’s need | Khan et al. (2017); Saucedo-Martínez et al. (2018)               |
### Table 13 (continued)

| Code | Name of barrier                                      | Description                                                                                                                                                                                                 | References                                                                                     |
|------|------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| B29  | Lack of CPS modeling and integration                | A customized and structured model that will deal with real-time data seamlessly is a must to connect the physical and virtual worlds                                                                             | Rajput and Singh (2019a)                                                                        |
| B30  | Lack of developing or sourcing qualified employees  | Customized, progressive training and development programs and reliable sourcing of employees are essential in driving the company                                                                              | Kamble et al. (2018b); Stentoft and Rajkumar (2020)                                           |
| B31  | Internet censorship issues                          | Many organizations can control access to specific internet content, depending upon the perceived relevance to the business. This censorship may adversely impact the performance of search engine applications, photo sharing apps, and other services, disturbing the flux of meaningful information | Aceto et al. (2019); Caiado et al. (2022)                                                      |
| B32  | Inadequate maturity and integration of necessary technologies | Underdeveloped, developed technologies and their integration with others are chaotic and troublesome and pose security, privacy, and standards issues  | Glass et al. (2018); Moktadir et al. (2018); Lee and Lee (2015); Raj et al. (2019)              |
| B33  | The emergence of IoT specific operating systems      | The tiny size, high performance, reliability, and sensitivity of IoT devices to the connecting devices demand specific operating systems that specialists need to take up                                                | Javed et al. (2018); Khan et al. (2020); Zikria et al. (2019)                                   |
| B34  | Concerns of job security and redundancy             | The company should address this to consider the socio-cultural and socio-economic balance before it leads to negative perception                                                                              | Fatorachian and Kazemi (2018); Kache and Seuring (2017)                                        |
| B35  | Uncertain return on investments                      | The lack of trusted models and standard practices for the value and risk consensus, return on investment limits infrastructure investment, weakens the technical capabilities, and creates barriers to harnessing the benefits of I4.0 | Schroeder et al. (2019)                                                                        |
| B36  | Limited product personalization                      | The customization of the products and services, guided by the company’s capability and market demand, must be addressed carefully. Firms must devise ways and means to deal with minimum to extreme customization to meet the market demand. ‘One Size’ batch production is a significant challenge | Calabrese et al. (2020); Müller et al. (2018)                                                  |
| B37  | Lack of semantic interoperability                    | Semantic interoperability handled properly to integrate and communicate different devices with machines efficiently and effectively without impacting the self and system’s overall performance is a big concern | Elkhodr et al. (2016); Rajput and Singh, (2019a)                                               |
| B38  | Lack of government’s infrastructure                  | The government’s role in making available and constructing common-use I4.0 compliant infrastructure to achieve better quality production is decisive and vital                                         | Rezqianita and Ardi (2020)                                                                     |
| B39  | Lack of knowledge about I4.0 vision                  | Detailed I4.0 fundamentals and models must be discussed and deliberated on general platforms to bring clarity and specificity to the approach                                                            | Cimini et al. (2017); Hofmann and Rüssch (2017)                                                 |
| Code | Name of barrier                                      | Description                                                                                                                                  | References                                      |
|------|-----------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|
| B40  | Problems related to coordination and collaboration | To achieve co-operation and collaboration with suppliers and customers, a robust communication mechanism with high hardware and software compatibility with requisite technical infrastructure, standardization of interfaces, and data consistency is required | Lee et al. (2014); Luthra and Mangla (2018)   |
| B41  | Challenges in technology up-gradation               | Smart and intelligent automation leads to creating an end-to-end digitalization of a company. To attain this, the up-gradation of the current technical infrastructure is necessary | Yang et al. (2018)                            |
| B42  | Lack of experts                                     | A multidisciplinary focus group comprising experts from different domains, practitioners, and consultants who understand the I4.0 implications can help create a sustainable and viable framework | Almada-Lobo (2016); Ghadge et al. (2020); Hermann et al. (2016); Hofmann and Rüsch (2017) |
| B43  | Scarcity of efficient and resilient big data analytics technologies | To achieve intended results from the huge volume of data efficiently, the company must have specialists and adequate real-time big data analytics capabilities for handling and analyzing the data produced by IIoT devices | Khan et al. (2020); Caiado et al. (2022)       |
| B44  | Incompetent digital culture                         | Digital transformation of the overall business environment is the essential requirement of I4.0 adoption                                        | Schuh et al. (2020)                           |
| B45  | Lack of managers and employees’ competences         | Unavailability of digital resources and virtual platforms for training to improve technological competencies and skills hinders achieving the I4.0 aims, objectives, and goals          | Horváth and Szabó (2019)                      |
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