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Analysis and Evaluation of Roadblocks Hindering Lean-Green and Industry 4.0 Practices in Indian Manufacturing Industries

Rimalini Gadekar, Government Polytechnic, Gondia, India*
Bijan Sarkar, Jadavpur University, Kolkata, India
Ashish Gadekar, Amity Institute of Higher Education, Amity University, Mauritius

ABSTRACT

This research is focused on the identification, assessment, analysis, and evaluation of the impact of the most prominent out of many roadblocks impeding the implementation of Lean-Green and I4.0 practices in manufacturing industries. The research methodology is underpinned by an extensive literature review with expert interventions to make it comprehensive and far-reaching. Further, this exploratory research to address the broad objectives is based on a large sample size, which is validated statistically and empirically for its aptness. A combination of widely used statistical methods is used to converge, assess, analyze, and evaluate the impact of each roadblock individually and in the group on I4.0 implementation in industry. The study prominently depicts lack of organizational leadership, unclear waste management practices, and missing environment-friendly practices as the most prominent roadblocks hindering the progression of Lean-Green and I4.0 adoption. The novel PCA-ISM Fuzzy MICMAC integrated model developed in this research makes this article unique.

KEYWORDS

COVID-19, First Mover Advantage, Fuzzy MICMAC, Growth, Industry 4.0, Inhibitors, Interpretive Structural Modeling, Principal Component Analysis, Sustainability

1. INTRODUCTION

It is evident from the experience of manufacturing companies though few, who have already adopted I4.0 practices partially or fully, that I4.0 has tremendous potential to bring operational excellence in terms of increased speed, flexibility, reliability, quality, and reduced cost like never before (Ben Wang, 2018). Basically, it provides data-driven smart solutions to the existing and futuristic complex problems by converging and controlling physical devices (i.e., sensors, actuators, smart machines, various devices, and equipment) seamlessly with the help of emerging technologies like the Internet of Things (IoT), Big Data Analytics (BDA) and customized software solutions (Bajic et al., 2020). Further

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*Corresponding Author

to this, the sustainable effect of this convergence to the whole value chain can be experienced only by expanding the automation and digitalization to overall business operations (Bhatia & Kumar, 2020). Here, the main objective of this convergence is to create a smart factory where every manufacturing process will be intelligent and autonomous, which on its own will be able to make smart decisions regarding manipulating capacity, capability, maintenance, without much human intervention (Kang et al., 2016; Türkeş et al., 2019; Baicun Wang et al., 2020).

In this pretext, having realized the I4.0's immense potential to transform the industrial operations into smart and sustainable operations, Indian Manufacturing industries, under the guidance and support of the Indian government through various schemes, are embracing digitalization and smart practices aggressively. The government's key initiatives like the national skill development mission (2015) and National Education Policy (2020) reflect the urgency and urge to prepare a favorable and sustainable environment conducive to all kinds of local and international businesses operations in India.

It is highly encouraged that lean thinking coupled with I4.0 practices eliminate waste in processes and logistics at various stages of operations increases production flexibility (Pinto et al., 2019). Lean production and lean tools should be employed successfully and efficiently to realize the benefits of I4.0 (Tortorella et al., 2021). I4.0 technologies can enhance the adoption process of green production (Dev et al., 2020) ultimately leverage the I4.0 advancements. Green technologies are observed as one of the crucial pillars of I4.0, which helps promote environment-friendly production and processes and reduce wastages (Vrchota et al., 2020). Although I4.0, as reflected through earlier literature, has tremendous scope to achieve sustainable manufacturing, there are still a lot of hidden opportunities to explore its full strength by incorporating lean-green practices in manufacturing while approaching I4.0 adoption. It paves a new way to explore the synergy between lean-green and I4.0 (Nedjwa et al., 2022) to unpack the new dimensions of sustainability to adopt I4.0.

Even though the Indian government is taking many initiatives, barring a few industries and associations, others have not yet gathered confidence and trust in the proposed smart practices. The apprehension is mainly because of the missing knowledge and assessment of the perceived barriers in lean-green and I4.0. In this realm, proposed comprehensive research, which is robust and based on a large dataset, intended to analyze and evaluate barriers of lean-green and I4.0. Further grouping them in the most significant roadblocks and deriving interconnect among them becomes highly relevant to clear the myths, ambiguities, and apprehensions regarding implementing the I4.0 vision focusing on its relevance to lean and green concepts.

The primary objectives of this study are listed below:

RO1: To recognize and explore the key barriers of I4.0 implementation considering lean and green practices.
RO2: To explore the connection among these barriers through extracted roadblocks of lean-green and I4.0 practices.
RO3: To perform qualitative and quantitative analysis of roadblocks and explore contextual interrelationships and significance to decision-makers.
RO4: To derive a robust, sustainable, and comprehensive framework and model for I4.0 implementation in industries.

The findings of this study will help managers, policymakers, decision-makers to devise their plans and actions for overcoming the adverse impact of Lean-Green and I4.0 adoption roadblocks for emphasizing sustainable manufacturing in Indian manufacturing industries. This paper is divided into six sections. Section 1 establishes the ground by clearly defining the current context's importance, need, and relevance. Section 2 link the existing knowledge to proposed research culminating in an exhaustive literature review. Section 3 explains the research methodology focused on the integrated Principal Component Analysis-Interpretive Structural Modeling (PCA-ISM) Fuzzy Matriced' Impacts Croise's Multiplication Applique'e a' un Classement (MICMAC) approach followed section 4 is dedicated to results and discussions. Further, Section 5 focuses on recommendation, conclusion, contribution to literature, and implications to decision-makers in the manufacturing industry to meet post-COVID challenges. Finally, section 6 presents future research recommendations.

2. LITERATURE REVIEW

A robust literature review explores different key aspects of the implementation of I4.0 in the Indian Manufacturing industry. Research documents listed in the databases, i.e., "SCOPUS", "Web of Science", "Google Scholar", published by the esteemed publishers known for their high-quality publications, i.e. "Elsevier", "IEEE", "Emerald", "Springer" and "Taylor and Francis", during the span of 2010 to February 2022 have been considered as a source of knowledge. In the beginning, 209 relevant research papers are collected using "Industry 4.0 AND barriers", "Industry 4.0 drivers OR Industry 4.0 enablers", "Industry 4.0 drivers AND Industry 4.0 enablers", "Industry 4.0 challenges"," Industry 4.0 inhibitors", "Industry 4.0 challenges OR Industry 4.0 inhibitors", "Industry 4.0 technologies", "Industry 4.0 AND lean manufacturing", "Industry 4.0 AND green manufacturing", "Industry 4.0 AND COVID-19 AND sustainability".

Further, the database is filtered to exclude non-English language papers, editorials, and magazines. Finally, the literature review is based on highly relevant 132 articles. Undoubtedly this set of articles nicely exposed the critical traits of each roadblock obstructing the smooth propagation of I4.0 in the Indian manufacturing industry. Nevertheless, this literature review also validated the research methodology, sampling technique, and choice of the PCA, ISM, and Fuzzy MICMAC techniques considered to analyze, assess, and evaluate the role of each roadblock and finally formulate the model.

2.1. Lean-Green and Industry 4.0 Implementation in Manufacturing

This study aims to explore the role of Lean-Green manufacturing practices on I4.0 implementation in Indian Manufacturing companies. As evident from the past studies, Lean manufacturing mainly targets the continuous elimination of waste from the business operations in a systematic manner (Bhattacharya et al., 2019). Over the past few decades, because of the uncontrolled use of fossil fuels and the negligent approach of the industries, the earth's climate has suffered extreme setbacks. This led to the rise of the green manufacturing concept and its implementation in operation management. The detailed analysis depicts lots of similarities at the level of organizational leadership, change management, and effective resource management. However, organizations may have to go through a trade-off situation because of the different generic focuses while implementing these concepts. Green manufacturing's importance has arisen because Lean manufacturing concepts do not include environmental issues (Siegel et al., 2019). More recently, the Green manufacturing concept has been accepted by industries as an initiative to control the negative impact caused by manufacturing activities. In a nutshell Lean-Green concept focuses mainly on reducing effects on the natural environment by reducing energy consumption, waste material, and emissions.

The role of emerging technologies like Artificial Intelligence (AI), Robotics, Cyber-Physical Systems (CPS), IoT, Radio Frequency Identification (RFID), smart sensors,, have undoubtedly made a significant impact on the end-to-end operations in the manufacturing industry. This is evident from the high degree of flexibility, speed, and effective control of the waste that companies have attained as an outcome of perfect reconciliation between the company's physical and virtual environments (Gadekar et al., 2022b; Stentoft & Rajkumar, 2020). This amalgamation has also led to significant control on the overall product life cycle, data management system, machine to machine, and machine to human communications. This has given rise to a highly resilient, agile, self-organizing, self-reliant, and real-time data-based decision-making system at the shop floor, called smart manufacturing (Julian Marius Müller et al., 2018). In addition to this smart manufacturing also has the potential to massively improve upon the quality, agility, productivity, interconnectivity leading to sustainability, creation of value opportunities, and collaboration with stakeholders (Gadekar et al., 2022c; Müller et al., 2020).

BDA is another key aspect of smart manufacturing (G. Wang et al., 2016) which successfully deals with volume, variety, velocity, and veracity of the enormous data in real-time to improve processes and operations precision and accuracy. Hence creates opportunities to reduce errors, defects, cost, waste and ideal time, optimize resources, and increase system predictability culminating in an increase in return of investment (Awan et al., 2021).

2.2. COVID-19 and Industry 4.0 Adoption

Pandemic has affected all business sectors worldwide, irrespective of location, economic development, technological advancement, business size, and ownership (Nicola et al., 2020). Amongst all of them, the worst hit is small-medium, small and micro companies whose most of the functions except core function are outsourced because of the limited resources, automation, and expertise (Nicola et al., 2020). Even though the I4.0 philosophy was introduced a decade before in 2011, many companies are still at the critical points because of the lack of clear direction, hence struggling to match the high pace of digitalization and customer expectations (Narayanamurthy & Tortorella, 2021). Two schools of thought evolved during this pandemic and lockdown conditions. One section firmly believes that pandemic has toppled all the development plans and ruined the established businesses' position in the market, while the other section feels the pandemic has brought a plethora of opportunities to build sustainable business functions (Cohen, 2020; Gadekar et al., 2022a; Narayanamurthy & Tortorella, 2021). The lesson is well learned; we need a robust, self-sustained, and fundamentally strong ecosystem that will be agile, flexible, and resilient to mitigate all the external pressures (Ivanov & Dolgui, 2020). All said and done, and the fact can not be denied, the pandemic has expedited the digital revolution in society and industries exponentially. This leaves the scope for researchers to work on the relationship between Lean-Green and I4.0. As mentioned in earlier studies, Lean-Green practices make the environment a better place to live through centering waste reduction. This can further add to dealing successfully with the health challenges in society and devise solutions to fight the viruses like Covid-19 and others.

2.3. Lean-Green and I4.0 Implementation Barriers

One more thing happened during the past decade, and especially last few years, the consumer has become more aware and educated than earlier, for which the credit goes to the massive digitalization and use of emerging technologies. Today's consumer is smart and far more demanding than ever. In this regard, all those companies who recognized the opportunity and imbibed the changes in company operations to serve the smart consumer gained the absolute advantage and now successfully leading the respective sectors. Like any other transformation, technological development is also facing challenges from the company's internal and external environment. Even though it has many advantages, because of limited evidence of the brighter side, the progression of I4.0 has not yet picked up the speed. Hence, the researcher felt the urgency to investigate the barriers (Gadekar et al., 2022c; Rezqianita & Ardi, 2020) of Lean-Green and I4.0 in a consolidated manner by conducting thorough individual barrier analysis, assessment, and evaluation, which justifies the relevance and importance of this study in the present context. The researcher first identified the barriers impeding the Lean-Green and I4.0 adoption and converged them in prospective roadblocks hindering the I4.0 adoption in the manufacturing industry and then examined them by conducting critical synthesis, analysis, assessment, and application based on the existing knowledge and practices. As an outcome of this exercise and meticulous amalgamation of expert opinion and the comprehensive literature review mutually exclusive yet collectively exhaustive list of 54 barriers was identified. The final barriers presented below are considered appropriate for the study. Details are given in Table 1a.

B01: Inadequate research and development facilities to support I4.0 requirements.
B02: Lack of data transfer protocols from machine to machine and other devices.
B03: Lack of competence in an organization to produce environment friendly products.

Table 1a. Summary of Lean-Green and I4.0 Barriers considered by earlier researchers in past studies and expert suggestions

Code	New	Barriers explained	References
R01	B01	Inadequate research and development facilities to support I4.0 requirements	Schuh et al. (2020); Khan et al. (2020)
R01	B07	Lack of measures to minimize and manage the waste, meaning environmental depletions.	Suggested by Focus Group
R01	B08	Lack of support to technology transfer, due to innovation and identification of operational needs.	Moktadir et al. (2018); Lee et al. (2015); Lu (2017)
R01	B15	Resistance to change and acceptance of new business model	Suggested by Focus Group
R01	B23	Lack of lean technology and operational excellence due to skills deficiency.	Kiel et al. (2017)
R01	B33	Lack of data based intelligent decision-making system	Suggested by Focus Group
R02	B21	Concerns of job security and redundancy due to intelligent automations	Fatorachian and Kazemi (2018); Kache and Seuring (2017)
R02	B36	Lack of workforce retention, upskilling and training policy, leading to psychological breakdown among the employees	Kamble et al. (2018b); Stentoft and Rajkumar (2020)
R02	B44	Lack of employee skills recognition and reallocation of the jobs fitting to their competencies	Ghobakhloo (2018); Horváth and Szabó (2019); Machado et al.(2019)
R02	B48	Inadequate and incomplete communication about the policy changes leading to unnecessary strain on the workforce	Almada-Lobo (2016); Ghadge et al.(2020); Hermann et al. (2016); Hofmann and Rüsch (2017)
R02	B52	Lack of employees' readiness for research and innovation, due to excessive workload or interest.	Müller et al. (2017b); Theorin et al. (2017)
R03	B05	Lack of Government vision and inability to bring supportive regulations.	Kamble et al. (2018b); Müller et al. (2017b); Schröder (2016); Singh and Bhanot (2020)
R03	B35	Lack of government support to raise green infrastructure	Rezqianita and Ardi (2020)
R03	B41	Lack of government support to start green business	Calabrese et al. (2020)
R03	B47	Lack of government funding for conducive green business policies	Ghadge et al. (2020); Calabrese et al. (2020)
R03	B49	Lack of supporting research to develop Green product in an organization	Wang et al., (2016)
R03	B54	Lack of green product lifecycle design competency in an organization	Calabrese et al. (2020); Kamble et al. (2018a); Kiel et al. (2017)
R04	B03	Lack of competence in an organization to produce environment friendly products	Müller et al. (2017a)
R04	B10	Lack of environmental pollution control advanced measures and inadequate mechanism to enforce existing measures	Hofmann and Rüsch (2017)
R04	B17	Lack of energy consumption monitoring mechanism	Suggested by Focus Group
R04	B25	Lack of energy-efficient and eco-friendly production system	Herrmann et al. (2014)
R05	B22	Lack of investments to be made in lean manufacturing machines	Schroeder et al. (2019)
R05	B37	Lack of risk management tools for Lean manufacturing investments	Machado et al. (2019)

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Table 1a. Continued

Code	New	Barriers explained	References
R05	B45	Uncertainty about return on waste management technology investments	Schroeder et al. (2019)
R05	B53	Lack of financial resources to buy the advanced supportive infrastructure	Herceg et al. (2020); Kache and Seuring (2017); Singh and Bhanot (2020)
R06	B04	Lack focused training and development facilities for lean skills development.	Suggested by Focus Group
R06	B11	Incompetent culture to support waste management training and skills	Cimini et al. (2017)
R06	B18	Lack of competent lean trainer to drive effective training programs	Horváth and Szabó (2019)
R06	B26	Overlooking the importance of continuous training and skill upgradation requirements	Karadayi-Usta (2019)
R06	B30	Lack of clarity about carbon footprints reduction and climate change hazards.	Luthra and Mangla (2018)
R07	B12	lack of digital leadership and vision is most harmful for any organizational growth	Erol et al. (2016); Luthra and Mangla (2018)
R07	B31	Lack of awareness of strategic importance of I4.0 and Green practices	Glass et al.(2018); Moktadir et al. (2018); Lee and Lee (2015); Raj et al. (2019)
R07	B39	Lack of coordination and collaboration among business functionalities may lead to the collapse of projects	Lee et al. (2014); Luthra and Mangla (2018)
R08	B19	Lack of data management policies limit the effective accessibility to data at crucial junctures.	Calabrese et al. (2020); Elkhodr et al.(2016); Kang et al. (2016); Liao et al. (2017)
R08	B42	Lack of appropriate data security measures brings vulnerability to knowledge management	Lee and Lee (2015); Oesterreich and Teuteberg (2016); Xu et al. (2018)
R08	B51	Too much or nothing Internet censorship leads to communication and seamless data transfer issue	Aceto et al.(2019)
R09	B27	Lack of technology innovation, integration and deployment in company	Yang et al. (2018)
R09	B28	Lack of effective and job intensive network system,	Khan et al. (2020)
R09	B50	Lack of system virtualization leading to free and flawless access to company operations	Rajput and Singh (2019a)
R10	B14	Lack of constant tracking of inventory in stock leading to formation of bottleneck situations	Suggested by Focus Group
R10	B29	Inadequate green capabilities for deepening customer relationships	Kiel et al.(2017)
R10	B46	Difficulties in identifying peculiar green customer requirements because of lack of market research and lack of communication with customers.	Müller et al. (2017b) Suggested by Focus Group
R11	B02	Lack of data transfer protocols from machine to machine and other devices	Kumar et al. (2020); Luthra and Mangla (2018)
R11	B09	Lack of protocols for data interfaces, leading to clutters and improper data management in the organization.	Kiel et al. (2017)
R11	B16	Lack of wireless technological standards in IIoT leading to poor communication among the machines to machine and men to machine	Suggested by Focus Group
R11	B24	Absence of benchmarks and standard in operations	Calabrese et al. (2020)

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Table 1a. Continued

Code	New	Barriers explained	References
R11	B34	Lack of global standards for comparing the product characteristics	Chen (2017); Glass et al. (2018); Schröder (2016)
R12	B06	Lack of greenness and environment friendly approach	Müller et al. (2017a)
R12	B13	Lack of repairability due to the complex product organization	Suggested by Focus Group
R12	B20	Lack of green product awareness among the customers and consumers	Hofmann and Rüsch (2017)
R12	B32	Lack of reusability of the products due to refilling and recharging limitations	Raj et al. (2019)
R12	B38	Lack of disposal plan as to limit the environmental degradation.	Rezqianita and Ardi (2020)
R12	B40	Lack of data sharing capability due to the product inefficiency to collect and transfer the data in the system	Calabrese et al. (2020); Müller et al. (2018)
R12	B43	Lack of capacity to incorporate green product development strategies because of low awareness or lack of will.	Ghadge et al. (2020);

Table 1b. List of the variables and its definitions used in the study

Code	Roadblock Title	Definition	Source
R01	Lean Process Management	Make the processes efficient by controlling the 7 wastes	(Mora et al., 2017)
R02	Social impact and employee readiness	Fear of losing job due to excessive automation, leading to negative perception of emerging technology.	(Kamble, Gunasekaran, & Sharma, 2018)
R03	Government and legal support to green business	Government support required to raise infrastructure and pass legislation to protect the green business interests	(King & Lenox, 2011)
R04	Environment friendliness	Minimal harm to the environment during product life cycle.	(G Yadav et al., 2020)
R05	Economic impact of Lean practices	Capital investment is required to bring in technology transfer.	(A. Kumar, 2014)
R06	Training and upskilling	Existing manpower needs to be upskilled and trained for future job profile	(Sindhwani et al., 2019)
R07	Organizational performance	Effective and efficient utilisation of resources in strategic manner increases the productivity of the organisation	(Rothenberg et al., 2001)
R08	Data management	Data driven decisions are less prone to failures. Effective data analytics and management is key for dynamic decision making,	(Leong et al., 2019)
R09	Technological and IT infrastructure	Robust and sustainable IT infrastructure is key to organisational better planning, more effective coordination, and digitalisation	(G Yadav et al., 2020)
R10	Green Customer management	Customer interested in consuming green products, should be recognised, and appreciated by maintaining strong business relations.	(Mittal et al., 2014)
R11	I4.0 standards	Business operations must be benchmarked with new competitive standards aligned to the consumer expectations	(Kamble, Gunasekaran, & Sharma, 2018)
R12	Green product management	Environment friendliness of the products should be assured after ensuring every aspect, as to avoid any greenwashing incidences.	(Dashore & Sohani, 2008)

B04: Lack focused training and development facilities for lean skills development.
B05: Lack of Government vision and inability to bring supportive regulations.
B06: Lack of greenness and environment friendly approach.
B07: Lack of measures to minimize and manage the waste, meaning environmental depletions.
B08: Lack of support to technology transfer, due to innovation and identification of operational needs.
B09: Lack of protocols for data interfaces, leading to clutters and improper data management in the organization.
B10: Lack of environmental pollution control advanced measures and inadequate mechanism to enforce existing measures.
B11: Incompetent culture to support waste management training and skills.
B12: lack of digital leadership and vision is most harmful for any organizational growth.
B13: Lack of repairability due to the complex product organization.
B14: Lack of constant tracking of inventory in stock leading to formation of bottleneck situations.
B15: Resistance to change and acceptance of new business model.
B16: Lack of wireless technological standards in IIoT leading to poor communication among the machines to machine and men to machine.
B17: Lack of energy consumption monitoring mechanism.
B18: Lack of competent lean trainer to drive effective training programs.
B19: Lack of data management policies limit the effective accessibility to data at crucial junctures.
B20: Lack of green product awareness among the customers and consumers.
B21: Concerns of job security and redundancy due to intelligent automations.
B22: Lack of investments to be made in lean manufacturing machines.
B23: Lack of lean technology and operational excellence due to skills deficiency.
B24: Absence of benchmarks and standard in operations.
B25: Lack of energy-efficient and eco-friendly production system.
B26: Overlooking the importance of continuous training and skill upgradation requirements.
B27: Lack of technology innovation, integration and deployment in company.
B28: Lack of effective and job intensive network system.
B29: Inadequate green capabilities for deepening customer relationships.
B30: Lack of clarity about carbon footprints reduction and climate change hazards.
B31: Lack of awareness of strategic importance of I4.0 and Green practices.
B32: Lack of reusability of the products due to refilling and recharging limitations.
B33: Lack of data based intelligent decision-making system.
B34: Lack of global standards for comparing the product characteristics.
B35: Lack of government support to raise green infrastructure.
B36: Lack of workforce retention, upskilling and training policy, leading to psychological breakdown among the employees.
B37: Lack of risk management tools for Lean manufacturing investments.
B38: Lack of disposal plan as to limit the environmental degradation.
B39: Lack of coordination and collaboration among business functionalities may lead to the collapse of projects.
B40: Lack of data sharing capability due to the product inefficiency to collect and transfer the data in the system.
B41: Lack of government support to start green business.
B42: Lack of appropriate data security measures brings vulnerability to knowledge management.
B43: Lack of capacity to incorporate green product development strategies because of low awareness or lack of will.
B44: Lack of employee skills recognition and reallocation of the jobs fitting to their competencies.
B45: Uncertainty about return on waste management technology investments.

B46: Difficulties in identifying peculiar green customer requirements because of lack of market research and lack of communication with customers.
B47: Lack of government funding for conducive green business policies.
B48: Inadequate and incomplete communication about the policy changes leading to unnecessary strain on the workforce.
B49: Lack of supporting research to develop Green product in an organization.
B50: Lack of system virtualization leading to free and flawless access to company operations.
B51: Too much or nothing Internet censorship leads to communication and seamless data transfer issue.
B52: Lack of employees' readiness for research and innovation, due to excessive workload or interest.
B53: Lack of financial resources to buy the advanced supportive infrastructure.
B54: Lack of green product lifecycle design competency in an organization.

2.4. Research Tools and Techniques

It is highly evident from the past studies that the majority of the researchers in the past have used the survey and interview as a tool to collect the data relevant to roadblocks, challenges, enablers, related to I4.0 adoption and then used MCDM techniques and statistical tools to analyze the same.

Table 2 summarizes the research tools and techniques used by the past researchers and confirms the appropriateness of the chosen instrument in the current research study.

2.5. Research Gap

According to all those large scales and few medium-large scale companies, who have already accepted the I4.0 vision in their business operations, I4.0 adoption has contributed immensely

Table 2. Recapitulation of tools used for analysis in past literature

Tools used for analysis	Contributions	Reference
BWM.	Ranked the I4.0 challenges according to their importance	Moktadir et al. (2018)
ISM and Fuzzy MICMAC.	Explored the contextual relationship among the I4.0 barriers.	(Kamble, Gunasekaran, & Sharma, 2018)
PCA-ISM-DEMATEL	Identified and assessed the I4.0 enablers	Rajput and Singh (2019a)
Interview and ISM and MICMAC	Assessed the causal relationship among I4.0 barriers	Karadayi-Usta (2019)
DEMATEL-MMDE-ISM	Identified the challenges encountered during I4.0 implementation	Singh and Bhanot (2020)
BWM-ELECTRE	Identified the SSCM challenges and developed the framework to surmount it	Yadav et al. (2020)
ISM MICMAC	Identified and assessed the I4.0 enablers	Devi K et al. (2020)
ISM MICMAC	Explored the contextual relationship among the I4.0 sustainable functions	Ghobakhloo (2020)
TISM and Fuzzy MICMAC.	Identified and evaluated the I4.0 enablers	Jain and Ajmera (2020)
PCA-Fuzzy AHP-K means	Ranked and categorized the I4.0 barrier into clusters	Kumar et al. (2020)
Grey DEMATEL	Assessed the causal relationship among I4.0 barriers	Raj et al. (2020)
DEMATEL	Cause and effect relationship is assessed for I4.0 challenges	Khanzode et al. (2021)

in attaining operational excellence and overall organizational sustainability. In a nutshell, the first mover's experiences inspire others to follow the path. Hence, there are high chances I4.0 adoption will positively impact Indian manufacturing companies in times to come. Although this seems possible, the fact remains that environmental, financial, and operational sustainability can not be attained without a robust framework for dealing with the barriers and roadblocks for these new advancements. The researcher found the following research gap while going through past literature:

1. Not many studies considered area-specific barriers and roadblocks of I4.0 adoption (Basl, 2017; Bonilla et al., 2018; Gadekar et al., 2022d; Müller et al., 2017a) in the context of location, politics, culture, and ways of doing business considering Leen-Green perspective (Dev et al., 2020; Gadekar et al., 2020; Tortorella et al., 2021).
2. Minimum studies have reflected on the I4.0 barrier's analysis and application using PCA-ISM Fuzzy MICMAC to solve real-time problems.
3. The majority of the researchers have avoided considering the large sample size for the study (Gadekar et al., 2021).
4. There is limited or no relevance of the studies published pre COVID-19 time to the post-COVID new normal conditions.

The research methodology used in this study is designed to address the limitations of earlier studies and discover new opportunities and growth avenues.

3. RESEARCH METHODOLOGY

This empirical research is profoundly based on robust primary data, expert intervention, and well-established conceptual framework, making it highly relevant to the current competitive business environment. By all means, the findings of this study have the potential to impact the real-world decision-making process positively. In the pretext of rising external pressure and the evolution of technology, companies are in search of sustainable solutions to complex business problems, which will ensure retention of the existing and acquisition of new market share without compromising on customer satisfaction and competitive advantage.

The sampling technique used here is convenience purposive snowball to justify the collection of highly appropriate and quality data. A structured questionnaire using Google Forms was served to prospective respondents. To record the perceived importance of barriers with precision and accuracy, a 10-point Likert Scale is used, where the value 10 represents the highest importance and value 1, the lowest. This exhaustive questionnaire is sent to prospective 557 respondents, out of which 40% responded (231), as an outcome of continuous follow-up from 15th November 2020 to 15th May 2021. The sample profile includes the professionals largely from industry, consultants, freelancers, researchers, data analysts, scientists, and academicians who have been handling I4.0 projects either in the past or present, especially in Indian manufacturing industries. The highlights of the sample spectrum considered in this study are shown below in Table 3.

It is a proven fact now the respondent's knowledge and experience in the topic considered for the research is very significant in producing precise and accurate data and results. Hence, the analysis started first by looking into the demographic data. To a large extent, the sample profile confirms that the data is most appropriate for the study based on the respondent's education, expertise, and experience. The automotive sector's top position in the list of most aggressive sectors, as seen in the demographic data, confirms the earlier studies' findings (Mckinsey, 2020; Yadav et al., 2020) that this sector is willing to adopt the I4.0 vision and be the first to harness the opportunities. This sector has already adopted Lean-Green practices in their companies.

Table 3. Respondent's profile

Dimensions	Respondent's Description	Frequency	Percent
Educational Qualification	Diploma and AMIE	17	7%
	Graduate	59	26%
	Masters	96	42%
	PG Diploma MIS	28	12%
	PhD and D Lit	31	13%
Work Experience	Less than 10	24	10%
	11 to 20	95	41%
	21 to 30	89	39%
	More than 30	23	10%
Industry Sector	Automotive Industry	53	23%
	Higher Education	51	22%
	Other Industries (less than 5)	32	14%
	IT and Software Industry	25	11%
	Metals and Machinery Industry	22	10%
	Electrical and Electronic Equipment Manufacturing Industry	18	8%
	Consultancy Services	15	6%
	Textile Industry	9	4%
	Food and Beverages Industry	6	3%
Ownership	Multinational Corporation	43	19%
	Private	145	63%
	Public/ Government	43	19%
Annual Turnover	1 to 10 Crore	27	12%
	10 to 75 Crore	37	16%
	75 to 300 Crore	63	27%
	300 to 500 Crore	54	23%
	More than 500 Crore	50	22%

The sample size is one of the strengths of this research. Hence its adequacy for conducting PCA and other tests is confirmed and validated beforehand using the thumb rule i.e. it should be five times the total number of variables (Shaukat et al., 2016). Subsequently, PCA is carried out to converge the 54 barriers into 12 groups (variables). These 12 groups are named after due deliberation and considering relevant references from the literature review to encompass the role of every element in a true sense and considered as variables for further analysis as shown in Table 1b.

Data analysis is carried out using SPSS v23. The data credibility and appropriateness are well established by Cronbach's alpha value, to be 0.882 (Victor et al., 2018). Further, this section elaborated detailing of an integrated PCA-ISM Fuzzy MICMAC methodology and model development. Fig. 1 Highlights the systematic and scientific approach adopted in this study.

Figure 1. Research Methodology

3.1. Principal Component Analysis (PCA)

Analyzing large data sets with many attributes may be cumbersome and ambiguous at points. In such situations, statistical techniques like PCA helps to reduce the data dimensionality without compromising the information contained in the original dataset (Jollife & Cadima, 2016). This technique linearly transforms the existing high-dimensional vector into a low-dimensional vector containing non-correlated elements (Cao et al., 2003). This approach is the researcher's favorite to reduce dimensionality (S. Kumar et al., 2020). It excerpts new orthogonal variables called principal

Table 4. Summary of Lean-Green and I4.0 barriers considered for the study as PCA outcome

Code	Roadblock Title	Barrier Code	Barrier Title	Loading factor
R01	Lean Process Management	B01	Inadequate research and development facilities to support I4.0 requirements	0.681
		B07	Lack of measures to minimize waste	0.867
		B08	Lack of support to technology transfer	0.774
		B15	Resistance to acceptance of new business model	0.763
		B23	Lack of lean technology and operational excellence	0.849
		B33	Lack of data based intelligent decision-making system	0.773
R02	Social impact and employee readiness	B21	Concerns of job security and redundancy	0.93
		B36	Lack of workforce retention policy, due to job disruption	0.845
		B44	Lack of employee reorganization according to their competencies	0.923
		B48	Unnecessary strain on the workforce	0.834
		B52	Lack of employees' readiness for innovation	0.929
R03	Government and legal support to green business	B05	Lack of Government vision	0.577
		B35	Lack of government support to raise green infrastructure	0.845
		B41	Lack of government support to start green business	0.611
		B47	Lack of government funding for green business policies	0.851
		B49	Lack of supporting research to develop Green product	0.857
		B54	Lack of green product lifecycle design competency	0.878
R04	Environment friendliness	B03	Lack of competence to produce environment friendly products	0.794
		B10	Lack of environmental pollution control measures	0.688
		B17	Lack of energy consumption monitoring mechanism	0.736
		B25	Lack of energy-efficient and eco-friendly production system	0.787
R05	Economic impact of Lean practices	B22	Lack of investments to be made in lean manufacturing machines	0.945
		B37	Lack of risk management tools for Lean manufacturing investments	0.767
		B45	Uncertainty about return on waste management technology investments	0.939
		B53	Lack of financial resources	0.945
R06	Training and upskilling	B04	Lack lean focused training and development facilities	0.64
		B11	Incompetent culture to support waste management training and skills	0.708
		B18	Lack of competent lean trainer to drive training programs	0.707
		B26	Continuous training and skill up-gradation requirements	0.671
		B30	Lack of clarity about carbon footprints reduction	0.738
R07	Organizational performance	B12	lack of digital leadership and vision	0.646
		B31	Lack of awareness of strategic importance of I4.0	0.616
		B39	Lack of coordination and collaboration	0.618
R08	Data management	B19	Lack of data management policies	0.869
		B42	Lack of data security measures	0.873
		B51	Internet censorship issue	0.873

continued on following page

Table 4. Continued

Code	Roadblock Title	Barrier Code	Barrier Title	Loading factor
R09	Technological and IT infrastructure	B27	Lack of technology integration	0.624
		B28	Lack of effective network system	0.6
		B50	Lack of system virtualization	0.62
R10	Green Customer management	B14	Lack of constant tracking of inventory in stock	0.556
		B29	Inadequate green capabilities for deepening customer relationships	0.686
		B46	Difficulties in identifying peculiar green customer requirements	0.689
R11	I4.0 standards	B02	Lack of data transfer protocols	0.725
		B09	ack of protocols for data interfaces	0.8
		B16	Lack of wireless technological standards in IIoT	0.809
		B24	Absence of benchmarks	0.737
		B34	Lack of global standards	0.718
R12	Green product management	B06	Lack of greenness	0.674
		B13	Lack of repairability	0.764
		B20	Lack of green product awareness	0.882
		B32	Lack of reusability	0.81
		B38	Lack of disposal plan	0.763
		B40	Lack of data sharing capability	0.751
		B43	Lack of capacity to incorporate Green product development strategies	0.847

components (PCs), which are the linear combinations of the input variables (Ringnér, 2008). New PCs withhold original data's variance with minimal deviation in the process, which is important to note here (S. Kumar & Sharma, 2015).

The selection of the barriers considered in this study has adopted a holistic approach. In the beginning, based on the literature review and subsequent brainstorming sessions, a list of 75 barriers is prepared. After this, in the presence of experts, the principle of 'mutually exclusive and collectively exhaustive (MECE) and literature review input is applied to all 75 barriers to finally curtailed the list into 54 barriers. Each barrier went through comparative analysis and in-depth assessment to avoid any repetition and interference as discussed. Finally, 54 barriers were selected for this study.

The most preferred test to assess the adequacy of factor analysis is Kaiser-Meyer-Olkin (KMO) test. The sampling relevance is determined for every variable in the model as well as the overall model using this test. With a maximum of 50 cycles of convergence, a varimax rotation is employed to maximize the summation of the variance of squared loadings, i.e., the relationship between variables and factors. Each variable should be related to no more than one factor to streamline the PCA outcome (S. Kumar & Sharma, 2015). The KMO value identified in this study is 0.819. Bartlett's test of sphericity verifies that the derived correlation matrix does have an identity matrix with a corresponding p-value < 0.001, indicating that PCA can be employed (Rajput & Singh, 2019b). In this study, the Bartletts test of sphericity, the Chi-Square value is 18228.90, the degree of freedom value is 1485, and the p-value is 0.000, confirming that the sampling data is adequate for factor exploration (Kaiser, 1974). The eigenvalue infers the variance of each variable in the overall sample. These twelve variables as described below account for 79.7 percent of the variation in the data used in the study.

R01 - Lean Process Management: A Lean process improvement methodology called continuous improvement gives teams the disciplined approach they need to maintain improvement as their top goal. Effective Lean process improvement initiatives require that every aspect of the organization be open to and willing to change.

R02 - Social impact and employee readiness: Fear of losing your work due to overuse of automation, which results in a poor impression of new technology. An increasing body of research, particularly in the business and psychology fields, aims to establish a causal relationship between workplace variables and employees' openness to change.

R03 - Government and legal support to green business: Government support is necessary to improve infrastructure and enact regulations to safeguard the interests of green businesses. Governments must take the lead, but there is a dearth of national and international leadership, along with economic, political, and regulatory barriers that are slowing development.

R04 - Environment friendliness: Minimal environmental damage during the course of a product's life is the main aim of the environment friendly production. Environmentally friendliness is the phrase most frequently used to describe products that support eco-friendly living or methods for saving resources like water and energy. Eco-friendly products also reduce their impact on contamination of the air, water, and land. By paying more attention to how you use resources, you can develop eco-friendly habits or behaviours.

R05 - Economic impact of Lean practices: Technology transfer requires a financial investment. Lean management is a powerful tool that businesses in the fourth industrial revolution may use to discover distinctive solutions to their own distinctive difficulties. On the other hand, businesses around the world are becoming increasingly aware of their critical need to attain economic sustainability.

R06 - Training and upskilling: It is necessary to upskill and train current employees for future job profiles. Corporate executives are aware of the high cost of staff turnover. Employers invest in their workers in much more ways than just paying salary. They also spend money on their recruitment, orientation, and development. Upskilling training might be economical in this situation.

R07 - Organizational performance: The capacity of an organization to achieve its objectives and maximize results is known as organizational performance. The productivity of the organization is increased by the strategic and effective use of resources. Organizational performance in the modern workforce is the capacity of a business to meet objectives in a context of ongoing change.

R08 - Data management: Decisions based on data are less likely to go wrong. Dynamic decision-making requires effective data analytics and management. Data management is the process of ingesting, storing, organizing, and managing the data produced and gathered by an organization. A key component of implementing IT systems that power business applications and deliver analytical data to support operational decision-making and strategic planning by corporate executives, business managers, and other end users is effective data management.

R09 - Technological and IT infrastructure: Digitalization, better organizational planning, and more effective coordination all depend on a strong and sustainable IT infrastructure. The collective elements required for the operation and management of enterprise IT services and IT environments are referred to collectively as "information technology infrastructure," or "IT infrastructure."

R10 - Green Customer management: Strong commercial ties should be maintained in order to recognize and value customers that prefer to consume green products. Consumer demand for goods and services that were produced in an environmentally responsible manner, including one that involves recycling and protecting the planet's resources, is known as "green consumerism."

R11 - I4.0 standards: By using the same connectivity standards across all of your devices, you can make sure that they all communicate with one another and work together. You might be using a combination of new and used equipment from several sources, like many other manufacturers. Setting up connectivity standards makes real-time networking seamless and maintains the efficiency of your factory's processes. Businesses must evaluate their operations to new competitive benchmarks that reflect consumer expectations.

R12 - Green product management: To prevent instances of "greenwashing," it is important to guarantee the products' environmental friendliness after checking all its components. Although product recycling and the development of eco-friendly items are essential, the key to efficient sustainability management entails a thorough monitoring of the manufacturing company's whole product supply chain. This includes implementing cutting-edge technology and expertise that not only increase productivity but also save internal expenses by outsourcing some business operations.

Table 2 and Table 4 show the 12 principal components (roadblocks) and similar elements (barriers) contributing to each. Further, these 12 PCs are analyzed and assessed by applying ISM Fuzzy MICMAC. First, based on the inter-relationship among each roadblock, the ISM model is developed and then, by calculating roadblocks' driving and dependence power, distributed them into four quadrants.

3.2. Interpretive Structural Modeling (ISM) Model Development

An exploratory study is impacted positively by the more significant number of experts. As suggested by Murry and Hammons (1995), a focus group of 12 experts is considered adequate to reflect the expert's involvement in the research comprehensively. Since the 1980s, ISM has been a well-accepted framework to scientifically present complicated relationships among the set of directly or indirectly related elements Warfield (1974). Thereby evolved contextual model is accepted by decision-makers to comprehend the relationship and prioritize arising actions, if any, to deal with critical roadblocks. This study is based on the large focus group size of 20 experts who contributed actively by virtue of their educational qualification, experience, expertise, and robust sample size, as mentioned earlier of 231 respondents. The expert's profile is given below:

1. **Industry experts:** Ten industry experts in their capacity as General Manager, CEO, CFO, COO, Director, and Senior Manager belonging to manufacturing, textile, furniture, and IT services, confirmed their involvement in delivering I4.0 related projects in the last three years.
2. **Experts from Academia:** Four senior professors specializing in manufacturing, logistics, and emerging technologies represented an academic perspective.
3. **Data Scientists:** Two data analysts and scientists presented a perspective highlighting the importance of having data management strategies in place in every industry.
4. **Consultants:** Four independent experts gave consultancy experience in handling I4.0 projects.

The stepwise process adopted for ISM fuzzy MICMAC modeling is presented below:

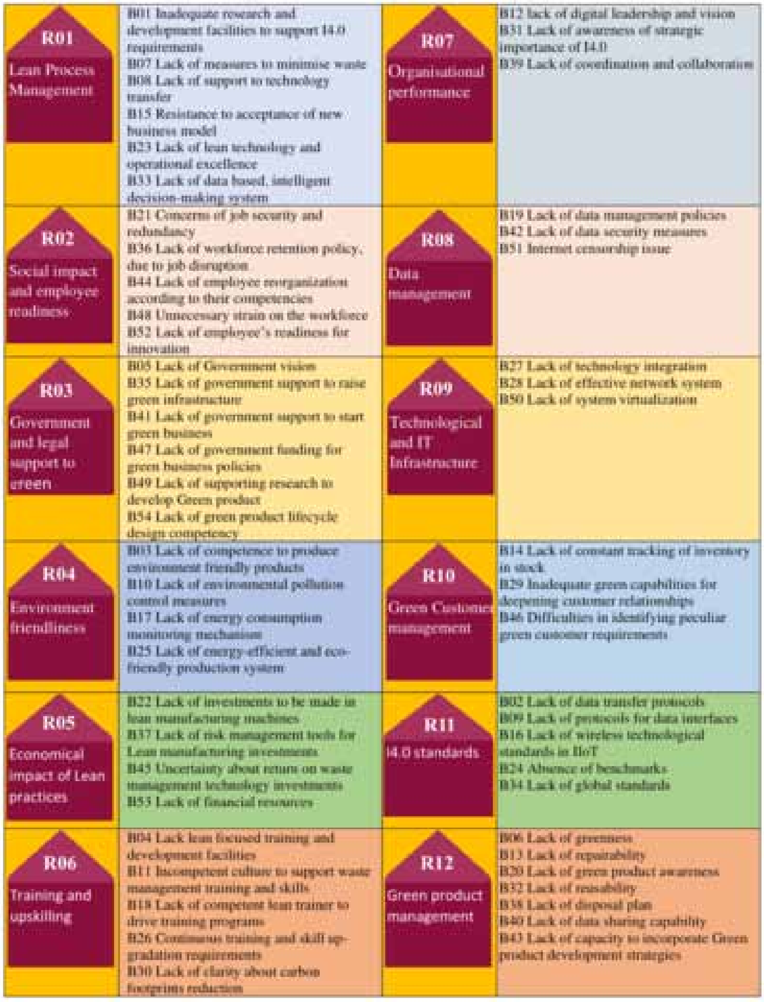
Step 1: Extraction of 12 roadblocks from 54 barriers using PCA.

Twelve roadblocks R01, R02, R03, R04, R05, R06, R06, R07, R08, R09, R10, R11 and R12 derived using PCA are named to reflect the essence of each of the contributing barriers. Refer to Fig. 2 for more details.

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

The primary inputs given from the focus group of 20 experts are used to formulate SSIM. The direction of the relationship between each pair of roadblocks is indicated using notation as A, O, V, and X where:

Figure 2. 12 principal components (roadblocks) and similar elements (barriers) contributing to each



V= Reflect the impact of a roadblock in the i^{th} row on a roadblock in a j^{th} column
A= Reflect roadblock in the i^{th} row is impacted by a roadblock in a j^{th} column
X= Reflect mutual impact among roadblock in the i^{th} row and j^{th} column
O= Reflect roadblock in the i^{th} row and j^{th} column are not related

Before the data collection started, researchers engaged with experts to explain the coding and establish the ambit and scope of each roadblock. This step ensured the uniform perception of each roadblock and smoothened the data collection process. Experts are allowed to respond either online or face-to-face, depending upon their convenience and availability. The data regarding the roadblock's relationship is recorded using the earlier explained codes V/A/X/O. Mode (maximum time-frequency) value is used to formulate SSIM. Barring a few, most of the mode values were unique. Hence, to a large extent, the data is clear and unambiguous. The experts are consulted again to resolve any ambiguities, where two choices share the mode value. The obtained SSIM is shown in Table 5.

Step 3: Formulating the reachability matrix.

Table 5. Structural self-interaction matrix (SSIM)

Roadblock	R01	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12
R01	X	V	V	V	X	V	V	V	V	V	V	V
R02	A	X	A	A	A	V	A	A	O	A	A	A
R03	A	V	X	X	A	V	O	V	V	V	V	V
R04	A	V	X	X	A	O	V	V	V	V	V	X
R05	X	V	V	V	X	V	V	V	V	V	V	V
R06	A	A	A	O	A	X	O	A	V	A	V	O
R07	A	V	O	A	A	O	X	A	O	A	V	A
R08	A	V	A	A	A	V	V	X	V	V	V	A
R09	A	O	A	A	A	A	O	A	X	A	A	O
R10	A	V	A	A	A	V	V	A	V	X	V	A
R11	A	V	A	A	A	A	A	A	V	A	X	A
R12	A	V	A	X	A	O	V	V	O	V	V	X

Table 6 depicts rules used to formulate binary matrix, which subsequently is named as initial reachability matrix, from the SSIM replacing V/A/X/O with zero or one. Further, this initial reachability matrix is tested for transitivity based on the assumption if roadblock 1 is associated with roadblock 2 and roadblock 2 is associated with roadblock 3; in that case, roadblock 1 is associated with roadblock 3 (Qureshi et al., 2008). This approach ensures due importance to the indirect relationships among the roadblocks making the approach comprehensive. The transitivity issue is resolved using the MATLAB program, as shown in Table 7.

Step 4: Level partitions.

The building of the ISM model starts from the top and flows to the bottom. First-level elements do not impact or drive any other elements, but it is considered as the model's outcome. All the roadblocks are partitioned initially into two sets, namely reachability and antecedents set. Reachability set helps to achieve, while antecedent assists in attaining the impact. Common elements in both sets form another set called intersection set, which has a key role in allowing the position of each roadblock in the model by ranking them. After this level, the partition is carried out by identifying the common roadblock in the intersection and reachability sets. The roadblock identified in the first iteration is allotted the top position in the model. This top position roadblock in total is impacted directly or indirectly by all the other roadblocks but does not impact any other roadblock. Once a roadblock is

Table 6. Rules to convert the notations by binary numbers (0 and 1)

Sr No	Binary number replacing the notation in Reachability Matrix (1, 0)	Notations used in SSIM to collect the data (V, A, O, X)
1	1	V
2	0	A
3	0	O
4	1	X

Table 7. Final reachability matrix (Transitivity)

Roadblock	R01	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12
R01	1	1	1	1	1	1	1	1	1	1	1	1
R02	0	1	0	0	0	1	0	0	1	0	1	0
R03	0	1	1	1	0	1	1	1	1	1	1	1
R04	0	1	1	1	0	1	1	1	1	1	1	1
R05	1	1	1	1	1	1	1	1	1	1	1	1
R06	0	1	0	0	0	1	0	0	1	0	1	0
R07	0	1	0	0	0	1	1	0	1	0	1	0
R08	0	1	0	0	0	1	1	1	1	1	1	0
R09	0	0	0	0	0	0	0	0	1	0	0	0
R10	0	1	0	0	0	1	1	0	1	1	1	0
R11	0	1	0	0	0	1	0	0	1	0	1	0
R12	0	1	1	1	0	1	1	1	1	1	1	1

allotted the rank, it is withdrawn from the subsequent iterations. The process continues till the last roadblock is allotted the rank Table 8.

Step 5: ISM Model Formation.

The ISM model, as explained earlier, shows the relationship among roadblocks in terms of their direct and indirect dependence. The direction of the arrow from the roadblock means the said roadblock is impacting the targeted roadblock. The base for the ISM is drawn from the final reachability matrix

Table 8. Final reachability level partitions for 1st to 7th iterations

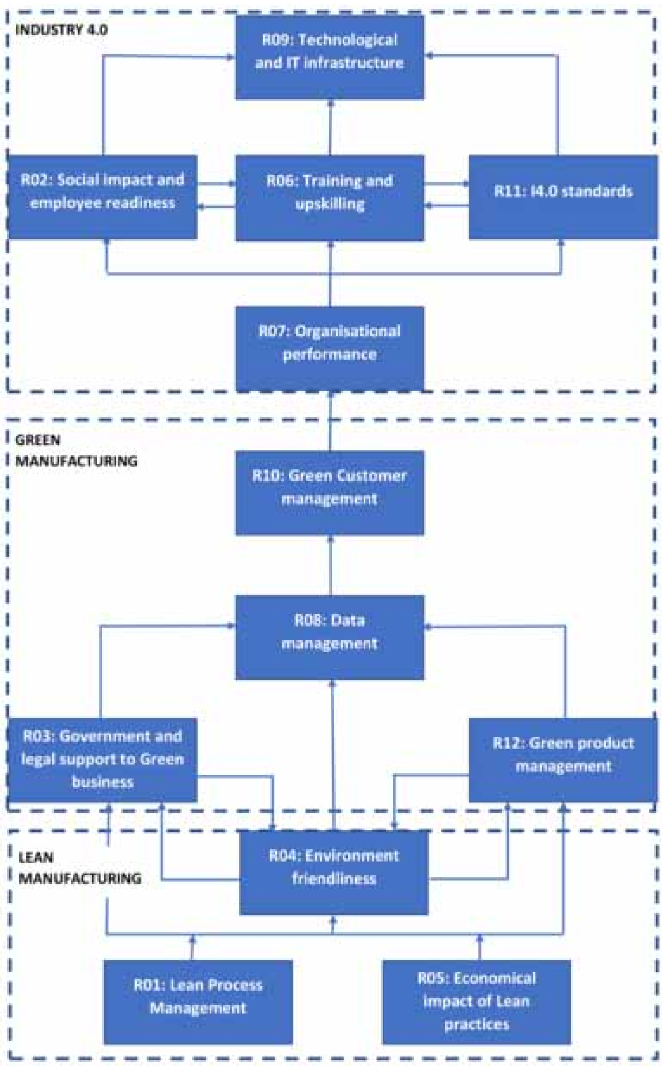
Roadblock No.	Reachability	Antecedent (Transposed)	Intersection	Level
R01	R01, R05	R01, R05	R01, R05	Level 7
R02	R02, R06, R11	R01, R02, R03, R04, R05, R06, R07, R08, R10, R11, R12	R02, R06, R11	Level 2
R03	R03, R04, R12	R01, R03, R04, R05, R12	R03, R04, R12	Level 6
R04	R03, R04, R12	R01, R03, R04, R05, R12	R03, R04, R12	Level 6
R05	R01, R05	R01, R05	R01, R05	Level 7
R06	R02, R06, R11	R01, R02, R03, R04, R05, R06, R07, R08, R10, R11, R12	R02, R06, R11	Level 2
R07	R07	R01, R03, R04, R05, R07, R08, R10, R12	R07	Level 3
R08	R08	R01, R03, R04, R05, R08, R12	R08	Level 5
R09	R09	R01, R02, R03, R04, R05, R06, R07, R08, R09, R10, R11, R12	R09	Level 1
R10	R10	R01, R03, R04, R05, R08, R10, R12	R10	Level 4
R11	R02, R06, R11	R01, R02, R03, R04, R05, R06, R07, R08, R10, R11, R12	R02, R06, R11	Level 2
R12	R03, R04, R12	R01, R03, R04, R05, R12	R03, R04, R12	Level 6

and the level partitions, explained earlier. The ISM model obtained in this study showing the I4.0 roadblock's interdependencies hierarchy is shown in Fig. 3.

3.3. ISM Fuzzy MICMAC Analysis

Even though ISM analysis is widely accepted for presenting direct-indirect dependencies of elements, the binary data used for model formulation pose a major limitation. In a real-world scenario, the relationship among the roadblocks can not be expressed just by using yes-no, true-false,1-0, or any other dichotomous scale. Hence to understand the strength of the relationship clearly in terms of how strong or weak, stable or unstable, fragile or robust the relationship is, measuring scale must have more data points. Since ISM does not have the scope of adopting scales other than binary scales, the researcher decided to overcome ISM drawback by using ISM fuzzy MICMAC analysis. The stepwise approach is explained below.

Figure 3. ISM model showing the 14.0 roadblock's interdependencies hierarchy



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

The base matrix BDRM to be used for ISM fuzzy MICMAC analysis is constructed by replacing all the diagonal elements with zero in the initial reachability matrix and re-writing it.

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

The focus group is approached again to rate the strength of the relationship, this time not on the scale of 0 or 1 but on the scale of 0 to 1. The numerical scale shown in Table 9 is used to record experts' judgment on the strength of the relationship between the pair of roadblocks. Further fuzzy direct reachability matrix is formulated applying the rule shown in Table 9 and in Table 10 based on experts' frequency in agreement, i.e., saying yes.

Step 3: Construction of Fuzzy MICMAC stabilized matrix.

In the past, researchers used three fuzzy combinations, i.e., max-min, max – product, max – average, to analyze the intensity of fuzzy indirect relationships from element i to j. For this study, the max-min combination is considered suitable, considering the strength of the fuzzy relation. 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 matrices are repeatedly multiplied till a final fuzzy

Table 9. Fuzzy scale to rate the intensity of roadblock relationships

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
Frequency of Experts	0	1 to 3	4 to 6	7 to 9	10 to 12	13 to 15	16 and more

Table 10. Fuzzy direct reachability matrix

Roadblock	R01	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12
R01	0	1	0.5	0.5	0.5	1	1	1	1	1	1	0.5
R02	0.3	0	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
R03	0.5	1	0	0.7	0.5	1	0.9	1	1	1	1	0.5
R04	0.5	1	0.7	0	0.5	1	1	1	0.9	1	0.9	0.7
R05	0.5	1	0.5	0.5	0	0.9	1	1	1	1	1	0.5
R06	0.3	0.7	0.3	0.3	0.3	0	0.7	0.9	0.7	0.7	0.7	0.3
R07	0.3	0.7	0.3	0.3	0.3	0.9	0	0.9	0.7	0.9	0.7	0.3
R08	0.3	0.7	0.3	0.3	0.3	0.7	0.9	0	0.7	0.7	0.7	0.3
R09	0.3	0.1	0.3	0.3	0.3	0.3	0.3	0.3	0	0.3	0.1	0.3
R10	0.3	0.7	0.3	0.3	0.3	0.9	0.7	0.9	0.7	0	0.7	0.3
R11	0.3	0.1	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0	0.3
R12	0.5	1	0.5	0.5	0.9	1	1	0.9	1	0.9	1	0

stabilized matrix is achieved. The final fuzzy stabilized matrix is achieved by repeatedly multiplying the matrices until the stable hierarchy of dependence and driving power is attained.

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

$$T = U * V = \max n\left[\min\left(x_{in}, y_{nj}\right)\right] \tag{1}$$

where:

$$U = x_{in} \text{ and } V = y_{nj}$$

A MATLAB program is used to formulate the Fuzzy MICMAC stabilized matrix, as shown in Table 10. The summation of all the row entries represents the driving power, while of columns represent the dependence power as shown in Table 11. The magnitude of the values indicates the intensity of the impact of the respective roadblock on the implementation of I4.0. Further, a cluster diagram is developed, which divides the roadblocks into four clusters: autonomous, dependent, linkage, and driver based on these values. This cluster diagram, along with the earlier calculated value, provides vital information to management while making important decisions. The cluster diagram as shown in Fig 4, divides the roadblocks into four segments: autonomous, dependent, linkage, and driver.

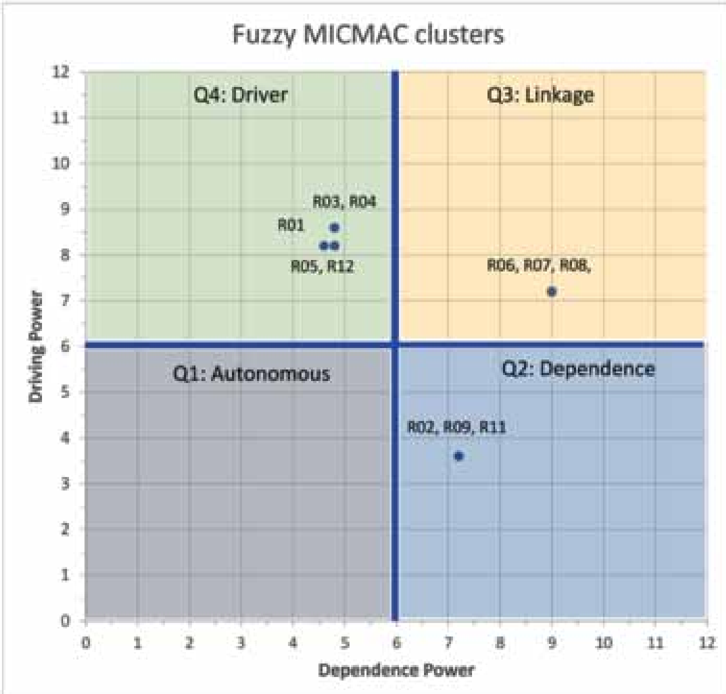
4. RESULTS AND DISCUSSIONS

The primary goal of this research is to develop a model which will replicate the real-world situation as it is and allow the decision-makers to understand the relative importance of each roadblock while embarking on the journey to adopt the I4.0 vision. A robust approach is adopted while listing the

Table 11. Fuzzy MICMAC stabilized matrix

Roadblock	R01	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12	Driving
R01	0.5	0.7	0.5	0.50	0.5	0.9	0.9	0.9	0.7	0.9	0.70	0.5	8.2
R02	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
R03	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
R04	0.5	0.7	0.5	0.7	0.7	0.9	0.9	0.9	0.7	0.9	0.7	0.5	8.6
R05	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
R06	0.3	0.7	0.3	0.3	0.3	0.9	0.9	0.9	0.7	0.9	0.7	0.3	7.2
R07	0.3	0.7	0.3	0.3	0.3	0.9	0.9	0.9	0.7	0.9	0.7	0.3	7.2
R08	0.3	0.7	0.3	0.3	0.3	0.9	0.9	0.9	0.7	0.9	0.7	0.3	7.2
R09	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
R10	0.3	0.7	0.3	0.3	0.3	0.9	0.9	0.9	0.7	0.9	0.7	0.3	7.2
R11	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
R12	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	4.6	7.2	4.8	4.8	4.8	9	9	9	7.2	9	7.2	4.8	

Figure 4. Cluster diagram, divides the roadblocks into four segments: Autonomous, dependent, linkage, and driver



barriers to cover every bit of the hindrances, causing the delay in I4.0 adoption considering the Lean-Green approaches. The first list of 54 barriers is an outcome of rigorous extra mile effort by researchers, which further is converged into prominent 12 roadblocks using the PCA approach. These are named after due consultation and considering all the contributory elements from the first list.

In the next stage, the ISM model is formulated using the outcome of PCA, as shown in Fig. 3. As it is evident from the hierarchy, the model has three segments top, middle, and bottom showing the interdependencies between all the twelve roadblocks. The top-level roadblocks (R09, R02, R06, R11, and R07) representing mainly as responsible for attaining I4.0 adoption depends on the bottom-level roadblocks representing Lean Manufacturing and middle-level roadblocks representing Green Manufacturing. Lean Manufacturing roadblocks (R01, R05, and R04) drive the Green Manufacturing (R10, R08, R03, and R12) and indirectly I4.0 adoption roadblocks, which must be dealt with priority as to attain organizational sustainability. After this, Fuzzy MICMAC analysis is applied to categorize all the 12 roadblocks into four quadrants, as shown in Fig. 4 explained above.

Autonomous roadblocks shown in the 1st quadrant represent the set of highly disconnected roadblocks having weak driving and dependence power, signifying negligible impact on the I4.0 adoption decision-making process. None of the 12 roadblocks is placed in this quadrant, which strengthens the claim that all the roadblocks play a vital role in the I4.0 implementation decision-making process.

Dependent roadblocks reflected in the 2nd quadrant possess weak driving and strong dependence power making them highly dependent on other roadblocks in the model. The Social Impact and employee readiness (R02), Technological and IT infrastructure (R09), and I4.0 standards (R11) belong to this quadrant, confirming that it is a highly driven and dependent roadblock. 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).

Linkage roadblocks are shown in the 3rd quadrant roadblocks possess exceptionally high driving power high dependence power making them highly influential in the model. By virtue of its position depends on the 2nd quadrant and drives the 4th quadrant roadblocks, making it a crucial group. This segment consists of Training and upskilling (R06), Organizational performance (R07), Data management (R08), and Green Customer management (R10) roadblocks. It signifies the minor alteration in any of these roadblocks will leverage the output effect on the roadblocks. Many studies have validated these findings (Calabrese et al., 2020; Dev et al., 2020; Hamada, 2019; Rezqianita & Ardi, 2020).

Driver roadblocks represented in the 4th quadrant roadblocks possess too high driving power and extremely low dependence power. These are independent roadblocks that lay a foundation of growth in an organization. The findings of the study depict roadblocks as Lean Process Management (R01), government and legal support to green business (R03), Environment friendliness R04), Economical impact of Lean practices(R05), and Green product management (R12) belong to this group. These roadblocks must be attended to carefully and urgently. These findings also agree with the outcomes of the number of research studies (Glass et al., 2018; Khan et al., 2020; Luthra & Mangla, 2018; Raj et al., 2020; Schroeder et al., 2019).

In the midst of extensive digitalization, the customer has become more aware and demanding. Companies should frequently engage in market research to reconcile customer expectations with company capability. Data-based decision-making shows very good results in waste management, energy conservation, optimum utilization of resources, and encouraging the implementation of eco-friendly business practices (J. Müller, Dotzauer, et al., 2017).

This study suggests that manufacturing companies, instead of avoiding the use of emerging technologies, better develop sustainable policies and practices to overcome the perceived adverse impact on business operations. The right choice of technology is key to achieving sustainable growth (Bai et al., 2020; Siltori et al., 2021). Emerging technologies, mainly IoT, IIoT, CC, BDA, AM, AR/VR, CPS, Robotics, undoubtedly have the potential to achieve a flexible, environmentally, socially, and economically sustainable manufacturing system (Fakhar Manesh et al., 2021; Karadayi-Usta, 2019; Stentoft and Rajkumar, 2020; S. Wang et al., 2016). Admittedly, every company may not have the capacity to spend on technology up-gradation due to financial constraints (Singh & Bhanot, 2020). The way out could be to start thoughtfully at the department level and then scale it at the organizational levels.

5. CONCLUSION, STUDY CONTRIBUTION, AND MANAGERIAL IMPLICATIONS

It is evident from past studies that companies are eager to adopt I4.0 practices. The findings show organizational sustainability can be achieved by systematically adopting lean, green, and I4.0 vision. I4.0 is gaining high-level attention from policymakers, manufacturing sectors, and academic researchers than ever before due to its potential to positively impact all sector business operations. As a result of this, new knowledge from very recent years is prominently seen in the current high-quality literature review. The PCA, followed by the ISM Fuzzy MICMAC approach in this study, systematically investigated the role of each roadblock in I4.0 adoption in the Indian manufacturing industry. The study's contribution to the theory and managerial and policymakers' implications are addressed further in this section.

5.1. Contribution to the Theory

The study has also developed the conceptual model based on 12 prominent roadblocks, which provides the base for designing solutions to overcoming these roadblocks. This research, based on PCA followed by the ISM Fuzzy MICMAC approach, will act as a base to direct academicians and policymakers to devise their way forward by prioritizing the most significant roadblocks. The findings are expected to speed up the adoption of I4.0 in manufacturing companies.

5.2. Managerial and Policymakers and Researchers' Implications

This research is based on a strong conceptual framework, robust sample size, and large size focus group, which validates the findings in itself. The ISM Fuzzy MICMAC model clearly establishes the role of each roadblock in forwarding the I4.0 adoption. This research has considered 54 barriers leaving no scope for any omissions. It will direct managers, practitioners, and policymakers to reach a high standard of excellence in managing integrated, innovation-driven production processes at the right cost (Gunasekaran et al., 2019).

6. LIMITATIONS AND FUTURE RESEARCH DIRECTION

The roadblocks' interrelationships are tended to change with the place, focus group profile, local industrial development, and government policies. This research work is carried out in the Indian context; hence the roadblocks identified may not have real significance with other under-developed, developing, or developed country conditions. Considering the pandemic and its aftermath effects it would be wise to try different combinations and compositions of the inhibitors and study its effect. Such study can also be conducted in service industry (e.g. Aviation and Tourism) in future to understand the inhibitor's impact and prevent adversities.

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ABBREVIATIONS

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
TISM: Total Interpretive Structural Modeling

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APPENDIX

Questionnaire One

Roadblock importance data from company perspective is collected using following questionnaire. Total of 231 respondent's data is finally accepted for Principal Component Analysis.

Dear Sir/Madam,

Rate the Lean-Green and I4.0 barriers based on your knowledge, experience, and expertise in this field. The rating should be reflection of the importance, implication, and relevance of each barrier to the company's mission to become sustainable in times to come. Use the scale 1-10 to express the intensity of the following barriers holding your company from implementing I4.0 vision and practices. Here 1 represents least existence and 10 highest existences.

Table 12.

Barrier Code	Barrier Title	Use 1 to 10 scale
B01	Inadequate research and development facilities to support I4.0 requirements	
B02	Lack of data transfer protocols	
B03	Lack of competence to produce environment friendly products	
B04	Lack lean focused training and development facilities	
B05	Lack of Government vision	
B06	Lack of greenness	
B07	Lack of measures to minimize waste	
B08	Lack of support to technology transfer	
B09	ack of protocols for data interfaces	
B10	Lack of environmental pollution control measures	
B11	Incompetent culture to support waste management training and skills	
B12	lack of digital leadership and vision	
B13	Lack of repairability	
B14	Lack of constant tracking of inventory in stock	
B15	Resistance to acceptance of new business model	
B16	Lack of wireless technological standards in IIoT	
B17	Lack of energy consumption monitoring mechanism	
B18	Lack of competent lean trainer to drive training programs	
B19	Lack of data management policies	
B20	Lack of green product awareness	
B21	Concerns of job security and redundancy	
B22	Lack of investments to be made in lean manufacturing machines	
B23	Lack of lean technology and operational excellence	
B24	Lack of benchmarks	
B25	Lack of energy-efficient and eco-friendly production system	

continued on following page

Table 12. Continued

Barrier Code	Barrier Title	Use 1 to 10 scale
B26	Continuous training and skill upgradation requirements	
B27	Lack of technology integration	
B28	Lack of effective network system	
B29	Inadequate green capabilities for deepening customer relationships	
B30	Lack of clarity about carbon footprints reduction	
B31	Lack of awareness of strategic importance of I4.0	
B32	Lack of reusability	
B33	Lack of data based intelligent decision-making system	
B34	Lack of global standards	
B35	Lack of government support to raise green infrastructure	
B36	Lack of workforce retention policy, due to job disruption	
B37	Lack of risk management tools for Lean manufacturing investments	
B38	Lack of disposal plan	
B39	Lack of coordination and collaboration	
B40	Lack of data sharing capability	
B41	Lack of government support to start green business	
B42	Lack of data security measures	
B43	Lack of capacity to incorporate green product development strategies	
B44	Lack of employee reorganization according to their competencies	
B45	Uncertainty about return on waste management technology investments	
B46	Difficulties in identifying peculiar green customer requirements	
B47	Lack of government funding for green business policies	
B48	Unnecessary strain on the workforce	
B49	Lack of supporting research to develop green product	
B50	Lack of system virtualization	
B51	Internet censorship issue	
B52	Lack of employees' readiness for innovation	
B53	Lack of financial resources	
B54	Lack of green product lifecycle design competency	

Questionnaire Two

Roadblock importance data from company perspective is collected using following questionnaire. Total of 20 Expert's data is finally accepted for ISM.

Dear Expert,

Rate the Lean-Green and I4.0 roadblock based on your knowledge, experience, and expertise in this field. The rating should be reflection of the importance, implication, and relevance of each barrier to the company's mission to become sustainable in times to come. Use the scale points V, A, X and O to indicate the relationship direction where:

V= Reflect the impact of a roadblock in the i^{th} row on a roadblock in a j^{th} column
A= Reflect roadblock in the i^{th} row is impacted by a roadblock in a j^{th} column
X= Reflect mutual impact among roadblock in the i^{th} row and j^{th} column
O= Reflect roadblock in the i^{th} row and j^{th} column are not related

Table 13.

Code	Roadblock Title
R01	Lean Process Management
R02	Social impact and employee readiness
R03	Government and legal support to green business
R04	Environment friendliness
R05	Economic impact of Lean practices
R06	Training and upskilling
R07	Organizational performance
R08	Data management
R09	Technological and IT infrastructure
R10	Green Customer management
R11	I4.0 standards
R12	Green product management

Table 14.

Roadblock	R01	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12
R01	X											
R02	X	X										
R03	X	X	X									
R04	X	X	X	X								
R05	X	X	X	X	X							
R06	X	X	X	X	X	X						
R07	X	X	X	X	X	X	X					
R08	X	X	X	X	X	X	X	X				
R09	X	X	X	X	X	X	X	X	X			
R10	X	X	X	X	X	X	X	X	X	X		
R11	X	X	X	X	X	X	X	X	X	X	X	
R12	X	X	X	X	X	X	X	X	X	X	X	X

Questionnaire Three

Roadblock degree of importance data from company perspective is collected using following questionnaire. Total of 20 Expert's data is finally accepted for ISM.

Dear Expert,

Rate the Lean-Green and I4.0 roadblock based on your knowledge, experience, and expertise in the field of manufacturing engineering. The rating should be reflection of the importance, implication, and relevance of each barrier to the company's mission to become sustainable in times to come. Use the scale 0 to 1, where 0 represents weak and 1 strong. Use the numerical value from the scale below to indicate the relationship strength.

Table 15.

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

Table 16.

Code	Roadblock Title
R01	Lean Process Management
R02	Social impact and employee readiness
R03	Government and legal support to green business
R04	Environment friendliness
R05	Economic impact of Lean practices
R06	Training and upskilling
R07	Organizational performance
R08	Data management
R09	Technological and IT infrastructure
R10	Green Customer management
R11	I4.0 standards
R12	Green product management

Table 17.

Roadblock	R01	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12
R01	0											
R02		0										
R03			0									
R04				0								
R05					0							
R06						0						
R07							0					
R08								0				
R09									0			
R10										0		
R11											0	
R12												0

Rimalini Ashish Gadekar is a Mechanical Engineering lecturer at Government Polytechnic, Gondia, Maharashtra, and Research Scholar at Jadavpur University Kolkata. She has earned her Bachelor's Degree in Production Engineering from SGGS Nanded and Master's Degree in Mechanical Engineering (Production and Manufacturing) from the Department of Production Engineering, Maharaja Sayajirao University Vadodara. She is an accomplished academician who is a passionate researcher also. She has to her credit high-quality research articles published in the indexed journal of international repute. She is currently working on the Industry 4.0 implementation projects. Her specific interest is on a people-centric approach while implementing Industry 4.0. Her other research areas are smart manufacturing, Operations research, and production engineering. She has the life membership pf ISTE and IIIE.

Bijan Sarkar is a renowned professor working in the department of Production Engineering at Jadavpur University Kolkata. His fields of specialization are Tribology, Reliability, Terotechnology, Operations Management, Operations Research, Project Management, Soft Computing, Management Development Programme. He has taught Operations Management, Project Management, Plant & Maintenance Engineering, Intelligent Manufacturing Systems, Quantitative Theories in Management, Reliability Engineering, Productivity & Quality Management, Analysis & Synthesis of Mechanisms, and Tribology teaching career. His research area is Project & Operations Management, Reliability analysis of Engineering Systems, Productivity Management, Soft Computing Applications, Manufacturing Domains Constraint Management, Grievance Analysis & control. He has published 12 papers in conference 138 papers in journals and guided 30 PhDs and 17 Masters Thesis. He has also received six awards.

Ashish Gadekar is a Professor and Dean in Faculty of Management at AMITY Mauritius. His area of interest in research is Industry 4.0 and Education 4.0. While in the class he strongly believes, research-based teaching-learning has no substitution. He has been a successful consultant, trainer and mentor to corporate leaders, over and above his excellence in teaching at higher education level in the last 22 years. He has been on the editorial board as well as reviewer's board of reputed international journals, also publishing few as an editor in chief in past years. He has published more than 40 research papers in reputed international journals and conferences.