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Inhibitors of Industry 4.0 and Circular Economy in Manufacturing Industry Supply Chains

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ABSTRACT

Circular economy (CE) and Industry 4.0 (I4.0) are clearly gaining popularity around the world because to their ability to integrate breakthrough technology with unique circular production and business models. This study conducted a systematic literature review, followed by expert intervention, to identify the 16 inhibitors hindering the implementation of a combination of CE practices and I4.0 technologies in the manufacturing industry supply chain. This paper has used ISM, Fuzzy MICMAC, and Fuzzy AHP approach to analyse the interrelationship among inhibitors and highlight the most critical of them. The findings of the paper suggest 'missing competitive leadership and 'lack of capital' are the most critical inhibitors, hindering the implementation of I4.0 and CE approach, depriving the manufacturing sector from enormous incentives. This one-of-a-kind original research paper is a holistic attempt to highlight the key elements of manufacturing and production supply chain. The results of the study will help the SCM companies to devise the strategies for achieving excellence.

KEYWORDS

Circular Economy, Competitive Leadership, Inhibitors, Supply Chain Management, Sustainability

INTRODUCTION

Globally the products and services storage and distribution are still a big challenge. Every year food loss worth 2.6 trillion USD is registered, which could have fed more than 8 million hungry people. The alarming thing is that most of these losses, approximately 14% are on account of poor Supply Chain Management (SCM). Hence, with the growing crises, the manufacturing companies are looking for solutions to control this situation by relying on Industry 4.0 (I4.0) and Circular Economy (CE) practices. It is evident from the market that emerging technologies have enhanced the performance in many other sectors. An effective and innovative SCM helps to meet the demand and supply, leading to higher customer satisfaction (Chandrasekaran & Raghuram, 2014; Hu and Li., 2022). As evident from the trends, customers are becoming more demanding in this dynamic world, thereby adding an onus on the companies to adopt a niche approach in value creation and distribution (Handayati et al., 2015; Khan & Haleem, 2021). A well-guided collaborative effort by creating an alliance with the manufacturers, producers, and distributors is found to be a reliable way to sustainable digitalization

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(Fu et al., 2017). Since its evolution in 2011, I4.0 smart technologies like Virtual Reality (VR), Cyber-Physical System (CPS), Industrial Internet of Things (IIoT), Cloud Computing (CC), Data analytics have made a significant impact on all spheres of business (Lasi et al., 2014; Oesterreich & Teuteberg, 2016). The improvement is visible in the quality, environment friendliness, production cycle, and product life cycle (Bai et al., 2020; Moeuf et al., 2018; Tortorella & Fettermann, 2018). Nevertheless, the technology also has empowered the companies to achieve excellence in maintaining transparency, visibility, and flexibility at every point of the supply chain (SC), leveraging the global influence and operational excellence (Hofmann & Rüsch, 2017). Now the decisions are based on real-time data, allowing decision-makers a crystal clear understanding of the problem (Casado-Vara et al., 2018), making the decisions more viable and trackable (Bai et al., 2020; Banerjee, 2019).

CE promotes the optimum use of the resources by emphasizing appropriate methods of recycling, reuse, and recovery (Luttenberger, 2020). This approach gives rise to the high level of operational efficacy and effectiveness in converting the age-old business models into more competitive and progressive models (Geissdoerfer et al., 2017; Ghisellini et al., 2016; Lopes de Sousa Jabbour et al., 2018; Rajput & Singh, 2021). The net realization of the benefits is also governed by the degree of customization and company agility (Lakatos et al., 2021; T. T. Pham et al., 2019).

The impact of CE is much visible in the SC, dedicated to the redistribution of refurbished, recycled, repaired goods for reuse or return (T. T. Pham et al., 2019). CE implementation is a collaborative effort among customers, manufacturers, regulators, and suppliers. Once it receives the right technology support, this integration can shape the efficient and environment-friendly business practices that are bound to lead to sustainable development (De Corato, 2020). Another benefit of CE is that it allows process visibility, reliability, viability, and traceability link no other methods provide, but there is a cost associated with this in terms of capital, social, environmental, and economic challenges, which at points may burden the company (Kamble et al., 2020). India is known for its massive manufacturing and production capacities, making it one of the largest contributors to the global economy. This is also forcing the nation to adopt sustainable CE practices (Mangla et al., 2020).

Despite a plethora of advantages of I4.0 and CE adoption, companies look passive in the absence of a lucid framework to deal with the inhibitors. As a result, enormous resources are still being wasted every year, mainly due to improper management practices, lack of will, and halfhearted adoption of technology by unskilled employees (Chauhan et al., 2020). Although CE is one of the proven and very well accepted tools over decades for controlling waste and achieving sustainable development goals, mostly neglected.

Also, in this context, past researchers though very limited, have highlighted the possible impact of I4.0-CE in India on the industries like automotive industry (G. Yadav et al., 2020), risk management (Yazdani et al., 2019), and IT (G. Yadav et al., 2020). Owing to this, researchers realized the significance of conducting research on exploring I4.0-CE inhibitors impacting manufacturing companies and their interrelationships to facilitate their smooth progression and acquire a competitive advantage. Thus, this research is pertinent to exploring the relationship between sustainability and I4.0-CE in India.

The Research Aims to Accomplish The Following Objectives

RO1: Explore Industry 4.0 and CE key linkages, challenges, and advantages that makes it viable in the Production and Manufacturing Supply Chain (PMSC).

RO2: Explore the microscopic and macroscopic barriers impacting and impeding the adoption of I4.0-CE in PMSC.

RO3: Evolve and validate the Interpretive Structural Modeling (ISM)- Matriced' Impacts Croise´s Multiplication Applique´e a UN Classement MICMAC-Fuzzy Analytical Hierarchical Process (FAHP) model to appropriately prioritize the inhibitors based on their critical nature and importance to PMSC.

The manuscript ahead is organized as follows: Section 2 explains the current status of knowledge in I4.0, PMSC, and CE and different theories and models used in the past. Further, section 3 elaborates research methodology, including sampling, data collection, analysis, interpretation, and findings. Section 4 is devoted to the discussion on findings, study implications to stakeholders, and unique contribution to the new knowledge. Finally, conclusions and limitations of the study are presented in section 5.

CONCEPTUAL BACKGROUND

A comprehensive literature review of the published articles in the indexed journals have been carried out to receive a profound understanding regarding the I4.0, CE, I4.0-CE, and technology impact on PMSC. The search was limited to the English language academic literature, reports, reviews, and research articles, published in high-impact factor journals by the most sought-after publishers like Taylor and Francis, Elsevier, Bentham, Science Direct. The literature review is mainly based on the articles published from 2015 to 2020 to ensure the most recent development is taken into consideration while creating the solution to the research problem. The search was carried out by using the keywords 'Industry 4.0 challenges' OR 'Industry 4.0 recognition' OR 'Industry 4.0 implementation' AND 'circular market' and 'production and manufacturing supply chain' OR 'production supply chain' OR 'manufacturing supply chain.' After doing the preliminary screening as to avoid any irrelevant literature, duplicates, or out of context data, the 131 high potential documents were selected, which were further assessed for appropriateness, considering abstract, methodology, and statistical tools used, leading to the final count to highly relevant 56 papers. The reviewed literature is further divided into five subsections as (1) Industry 4.0 in PMSC (2) Industry 4.0 and CE (3) Industry 4.0 and CE Impact on PMSC (4) Industry 4.0 and CE inhibitors for PMSC and (5) Tools and techniques.

Industry 4.0 in Production and Manufacturing Supply Chain

The impact of the disruptive changes brought by I4.0 in the SC and logistic industry is now visible in terms of the increased flexibility and speed of the operations (Long et al., 2019). Adopting a new digital business model to incorporate the variety, volume, velocity, and veracity of the demand has suddenly taken the top position in the new agenda (Xu et al., 2018). There is a certain gain in this approach, subject to successful identification and mitigation of Socio-economic, legal and ethical, and technological obstacles without compromising business growth (Long et al., 2019). Unfortunately, the PMSC industry is very sensitive to many local and global uncertainties (Lezoche et al., 2020). Acceptance of the right technology and methodology while modifying the existing process, products and countering environment-related concerns could be one of the ways to control the uncertainty and expedite the transition (V. S. Yadav et al., 2020; Yang et al., 2021).

Industry 4.0 and Circular Economy

Right since the year 2011, I4.0 has grabbed attention from all walks of life and business sectors (Liboni et al., 2018). To a large extent, the same is true with CE as production, and the manufacturing sector has shown eagerness to adopt these technologies right since the beginning as it has proved its worth in other sectors (Ghobakhloo, 2020). I4.0-CE's ability to impart operational excellence in different business functions has drawn the attention of many companies in such a short span of time (Liao et al., 2017). This has also helped to estimate the utility of the chain of supplies (Tseng et al., 2019) and deployment of the CE measures in terms of reusability, recycling, and remanufacturing to remain productive (Rajput & Singh 2019). In a nutshell, the companies where I4.0 and CE are accepted for implementation reported continuous improvement in the performance standards of processes and operations (Lopes de Sousa Jabbour et al., 2018; Nascimento et al., 2019). The companies have also found, the collaborative approach to exchange expertise and adoptive programs created scope for more success and benefits (Tortorella et al., 2020). Empirical data-based research conducted by G. Yadav et al. (2020) reported 28 inhibitors obstructing the implementation of I4.0 and CE; the study further established the inter-relationship between these inhibitors to evolve a model. Another study by Brozzi et al. (2020) reported that companies do not see any sustainable benefits from implementing I4.0 as they do not have direction.

Industry 4.0 and Circular Economy Impact on Production and Manufacturing Supply Chain

Traditionally the product life cycle study was limited till the ownership was transferred to the customer. This approach did not address the product disposal issues, leaving space for environmental deterioration through the unfriendly disposal of the product (Corvellec et al., 2021). In this context, the research published by Tseng et al. (2019) suggested the product life cycle should be studied under CE so that the ecological aspect of the product disposal is identified and resolved. This way, the amalgamation of I4.0 and CE will boost efficient and effective utilization of the chain of supplies Yazdani et al. (2019). Moreover, other researchers like Belaud et al. (2019) also reported the improvement in waste management and sustainability as an effect of implementing I4.0 and CE simultaneously. This is also substantiated by Chauhan et al. (2020), who emphasized the rise in effectiveness of SC after adopting I4.0-CE.

Industry 4.0 and Circular Economy Inhibitors for Production and Manufacturing Supply Chain

The sectoral growth is led by the unique and special technology adoption that meets the micro-level needs of the specific processes (Mangla et al., 2019). The production and manufacturing sector is being vast in terms of the variety of products, local conditions, local needs, and demands, always focused on using indigenously developed technologies without compromising the environment (Alcayaga et al., 2019). Emerging technologies like IoT, IIoT, big data, data analytics have already been accepted by most of the SMEs in European countries (Luthra & Mangla, 2018). SMEs need simple yet robust technologies as the volume of the business is small. Kirchherr et al.(2018) explained 18 critical challenges faced by PMSC in implementing the I4.0 and CE, namely operational, strategic, technical, ethical, and legal threats, Lack of global standards and guidelines for data exchange, Lack of government willingness, support, strategies, and financial restrictions. Out of all those highest important are cultural, technical, business, and regulatory problems hindering the implementation of the CE (Liboni et al., 2018).-

Based on the literature review and discussion with experts, this study has considered Cultural, Economic, Technological (Rajput & Singh 2019) and Legal & Government policies as the most critical inhibitors hindering the adoption of I4.0 and CE.

Research Tools and Techniques

Past studies have chosen tools and techniques to address problems based on the appropriateness of the tool, proficiency level in using the tool, and reliability. The extracts from the literature review are listed in Table 1, which includes I4.0 and CE tools and techniques used by past researchers.

Findings of the Literature Review

It has been found from the literature review that CE and I4.0 together are more effective as it provides a strong conceptual foundation to create a real-time solution. The study also revealed that many researchers in the past have only addressed the pre-COVID 19 conditions to create a solution that is obvious. This establishes the need for the study to devise solutions to meet post COVID-19 challenges. There is a growing need to conduct research to assess the effects of I4.0 and CE on the supply chain (Luthra & Mangla, 2018; Raut et al., 2019) as the introduction of I4.0 and CE could open doors to new opportunities and ways of problem-solving capability. The convergence of I4.0 principles and CE's strong ability to cut waste gives rise to big hopes for the PMSC industry (G. Yadav et al., 2020). The global PMSC sector is witnessing inclusive changes for good, defined as smart (Luttenberger, 2020). These smart practices

Table 1. Research tools identified through literature review

References	Purpose	Research theme	Tools, Techniques
Long et al. (2016)	Inhibitor identification	Technological innovation in smart agriculture	Interviews, thematic analysis
Liboni et al., (2018)	For getting trends and challenges	I4.0, environment protection & safety	Interviews, “soft system methodology (SSM).”
Kirchherr et al. (2018); Corvellec et al. (2021)	Inhibitor identification	CE	Semi-structured interviews, survey
Luthra & Mangla, (2018)	Challenge identification and prioritization	I4.0, sustainability	AHP, Expert opinion, Explanatory factor analysis
Rajput & Singh (2019)	Development of contextual relation	I4.0, CE	ISM
Luthra & Mangla, (2018)	Challenge identification, inter-relation, and priority establishment	Supply chain management	Expert input, “Graph theory and matrix approach (GTMA).”
Ghobakhloo (2020)	Function identification, inter-relation, and priority establishment	I4.0 and sustainability	ISM
Sehnem et al. (2020)	Challenge identification	CE.	Case Study
Joshi et al. (2020)	Challenge identification, inter-relation, and priority establishment	CE, SC	Delphi Method, ISM
Yazdani et al. (2019)	Driver identification	CE, SC	Failure mode and effect analysis, Stepwise Weight Assessment Ratio Analysis,
G. Yadav et al. (2020)	Framework development (challenges and solution measure identification)	I4.0, CE, sustainable supply chain	Elimination and Choice Expressing Reality, Best Worst Method
Joshi et al.(2020)	Factor identification	SC, sustainability	Semi-structured interview, “principal component analysis (PCA)”
V. S. Yadav et al. (2020)	Inhibitor identification	SC, blockchain	Delphi, ISM, Fuzzy-MICMAC

need to be studied for justified applications and scaling before applying in the industry (Alcayaga et al., 2019) provide future guidance for researchers working in the field of the supply chain. The research focused on identifying, assessing, and analyzing the inhibitors using empirical and theoretical approaches will help decision-makers create their strategies based on importance to the business.

The above analysis states the importance of identifying and investigating the inhibitors relevant to I4.0 and CE for PMSC in the developing manufacturing sector. The model thus developed and validated in this research paper demonstrates the interrelation, degree of importance, and degree of relevance each inhibitor has in the overall adoption of I4.0 and CE. However, before embarking on the adoption of the I4.0-CE approach, the manufacturing industries must assess their current status, potential, and capability and clearly define the road map considering their actual maturity level in regards to I4.0-CE practices in which the company is currently engaged.

RESEARCH METHODOLOGY

The final list of inhibitors is derived from an extensive literature review and a focused group discussion. These inhibitors were then fed to the ISM model to develop the hierarchical model. ISM is preferred over other models as it clearly depicts the direction and order of interrelationship between the criteria, using simple notations. Thereby ISM model is the preferred choice for useful industrial decision-making applications. The figure below shows the step-wise approach followed in this study to finally evolve the structural model and validation. Moreover, MICMAC analysis is also used to cluster the identified inhibitors based on individual inhibitors' driving and dependency power (Kumar et al., 2022). However, to mitigate the limitation of the ISM, as it does not measure the degree of relationship, thoughtfully Fuzzy AHP is applied. The outcome thus is validated using Fuzzy AHP. The research methodology is divided into three phases, as explained further and shown in **Figure 1.**

1. I4.0-CE inhibitors are identified through focused group discussion, and data is collected.
2. An Interpretive Structural Model is developed to investigate the relationships between inhibitors and Fuzzy MICMAC to cluster the inhibitors
3. Apply the Fuzzy AHP method to validate the developed model for the significance of the inhibitors.

Phase 1

Delphi method is one of the choicest approaches used to gather qualitative data from a focused group. Delphi method is an organized, iterative, and systemic approach that enables experts from various fields to register their opinion on the subject matter (Linstone et al., 2002). The Delphi method also allows the experts to contribute through their widespread experience and knowledge without compromising data loss or confidentiality (Green & Price, 2000; Tersine & Riggs,1976). Other than ISM (Singh et al., 2013), past researchers have also used Multicriteria Decision Making (MCDM) methods like the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Decision Making Trial and Evaluation Laboratory (DEMATEL), to highlight the interrelationship between the criteria (Awan et al., 2021; T. Y. Pham et al., 2017), which is also based on Delphi method. It is observed that the Delphi method approach is very successful where experience and expertise can add value in understanding the ground reality, especially in the manufacturing sector (Ahmad & Wong, 2019; Pacurariu et al., 2021).

The experts who actively participated in this research belong to the case company (Automotive Manufacturing situated in Nagpur, India) and other industries, academia, consultancies, and regulatory bodies. These experts were interviewed more than once for receiving inputs and validating findings. These experts hold a high reputation and recognition by virtue of broad domain knowledge, experience, positions in respective organizations, and professional accomplishments. A total of sixteen inhibitors are considered for the study, which includes nine from the literature review and seven from experts. Table 2 shows the 16 experts' inputs. The professional profile of experts is given below:

1) Industry experts: Six experts from industry hold the top position in their capacity as Director, CEO, Senior Manager, etc. confirmed expertise in CE-I4.0 related projects and manufacturing operations. These experts mainly belong to Supply Chain Management, Manufacturing, Logistic, Real Estate, Automobile, Textile, Plastic industry.
2) Experts from Academia: Six Professors and Dean from renowned Autonomous Institutions and Universities in India who specialized in Lean Manufacturing, Green Manufacturing, Waste Management, Business Engineering and Management, Information Technology, and Computer Science represented an academic perspective.
3) Data Scientists: Two experts from the field of Data Analytics and Data Scientists were taken on board to bring the data perspective.
4) Consultants: Two consultants contributed to the inhibitors identification process through their varied exposure and experience in handling I4.0 projects.

Figure 1. Roadmap of the research methodology adopted

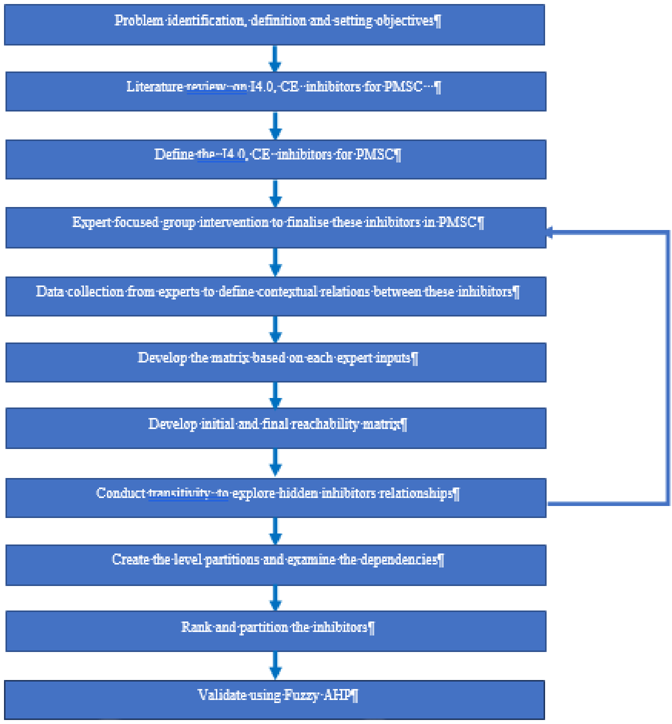


Table 2. SSIM (Self Structural Interaction Matrix)

Inhibitors	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16
I1	X	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V
I2		X	A	A	A	O	A	A	O	A	A	A	O	A	A	A
I3			X	X	A	V	O	V	V	V	V	V	V	V	V	V
I4				X	A	O	V	V	V	V	V	X	V	V	V	X
I5					X	V	V	V	V	V	V	V	V	V	V	V
I6						X	O	A	V	A	V	O	V	A	V	O
I7							X	A	O	A	V	A	O	A	V	A
I8								X	V	V	V	A	V	V	V	A
I9									X	A	A	O	A	A	O	A
I10										X	V	A	A	V	V	A
I11											X	A	A	A	A	A
I12												X	A	O	V	V
I13													X	A	A	O
I14														X	V	A
I15															X	A
I16																X

Phase II

ISM is a well-known method for converting hazy, poorly expressed cognitive models of systems into visual, well-defined models (Warfield, 1974), used extensively to describe the interrelationship between the criteria/attributes/factors.

Following steps are performed while developing the ISM model:

Step 1: Identify the inhibitors to address the research problem.
Step 2: Construct the pairwise relationship matrix based on experts' feedback.
Step 3: Develop the structural self-interaction matrix (SSIM) based on the contextual relationship between inhibitors.

The X_{ij} value reflects the direction of the relationship between i^{th} row on j^{th} column criteria.

Following symbols are used to denote the direction of the relationship.

V: i^{th} criteria advance j^{th} criteria
A: i^{th} criteria is impacted by j^{th} criteria
X: i^{th} criteria and j^{th} criteria has a two-way relationship.
O: i^{th} criteria and j^{th} criteria does not have any relationship

The mode value of each paired relationship is used to finally draw the SSIM. In the case of a tie, the process is repeated till only one key value is obtained.

Step 4: Formulate Initial reachability matrix (IRM) by replacing V, A X, and O with 1 or 0 (V=1, A=0, X=1, O=0)
Step 5: Remove transitivity, i.e., if 'a' is associated with 'b' and 'b' is associated with 'c', then 'a' is associated with 'c'.
Step 6: Calculate the final reachability matrix using Boolean set theory multiplication and addition.
Step 7: Perform the level partition by grouping all the criteria in the row having value 1 as Reachability Set (RS) and in the column as Antecedent Set (AS), and the final attribute reachability matrix. Then the crossroads are set by selecting the same elements in AS and RS. The criteria having the same value in RS and Intersection Set (IS) took the top position in the hierarchy and were removed from the list while carrying out the next iteration, as shown in Table 3.
Step 8: Create the digraph from the final reachability matrix.

The element with the top rank is put on the top, followed by the next rank elements. This process is carried out till the last element is ranked. Elements can then be divided into four clusters using Fuzzy MICMAC according to driving and dependency force. Each inhibitor's driving and dependence power is calculated by summing the particular row and column, respectively. The fuzzy MICMAC diagram is plotted by considering driving power on the x-axis and dependence power on the y-axis.

Phase III

Fuzzy AHP

Satty (1980) proposed the first AHP method, which is now widely used to calculate criteria weights (Zavadskas et al., 2015; Zavadskas & Podvezko, 2016). Decision-makers express their opinions in the linguistic form in real-life settings. AHP employs a crisp number, which is insufficient and imperfect due to decision-makers' judgment's ambiguity and fuzziness. Fuzzy logic is used to address this shortcoming of AHP in pairwise comparison processes (Buckley, 1985; Nădăban et al., 2016).

The steps for Fuzzy AHP (FAHP) by Geometric Mean (Ayhan, 2013; Elomda et al., 2013; Wu et al., 2009), are as follows:

Step 1: Create a fuzzy pairwise comparison matrix.

Each linguistic expression used to highlight the pairwise comparison of criteria is translated into comparable triangular fuzzy numbers using Table 4.

Table 3. ISM level partition

Reachability	Antecedent (Transposed)	Intersection	Level
I1 I2 I3 I4 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16	I1	I1	
I2	I1 I2 I3 I4 I5 I12 I16	I2	Level 1
I2 I3 I4 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16	I1 I3 I4 I5 I12 I16	I3 I4 I12 I16	
I2 I3 I4 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16	I1 I3 I4 I5 I12 I16	I3 I4 I12 I16	
I2 I3 I4 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16	I1 I5	I5	
I6 I9 I11 I13 I15	I1 I3 I4 I5 I6 I8 I10 I12 I14 I16	I6	
I7 I9 I11 I13 I15	I1 I3 I4 I5 I7 I8 I10 I12 I14 I16	I7	
I6 I7 I8 I9 I10 I11 I13 I14 I15	I1 I3 I4 I5 I8 I12 I16	I8	
I9 I13	I1 I3 I4 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16	I9 I13	Level 1
I6 I7 I9 I10 I11 I13 I14 I15	I1 I3 I4 I5 I8 I10 I12 I14 I16	I10 I14	
I9 I11 I13 I15	I1 I3 I4 I5 I6 I7 I8 I10 I11 I12 I14 I15 I16	I11 I15	
I2 I3 I4 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16	I1 I3 I4 I5 I12 I16	I3 I4 I12 I16	
I9 I13	I1 I3 I4 I5 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16	I9 I13	
I6 I7 I9 I10 I11 I13 I14 I15	I1 I3 I4 I5 I8 I10 I12 I14 I16	I10 I14	
I9 I11 I13 I15	I1 I3 I4 I5 I6 I7 I8 I10 I11 I12 I14 I15 I16	I11 I15	
I2 I3 I4 I6 I7 I8 I9 I10 I11 I12 I13 I14 I15 I16	I1 I3 I4 I5 I12 I16	I3 I4 I12 I16	

Table 4. Linguistic Scales and Corresponding Triangular Fuzzy Number

The fuzzy scale of relative importance for pairwise comparison matrix for criteria		
Term	**Crisp Number**	**Fuzzy number**
Equal (E)	1	1,1,1
Moderate(M)	3	2,3,4
Strong(S)	5	4,5,6
Very Strong (VS)	7	6,7,8
Extremely Strong (ES)	9	9,9,9
Intermediate values (IV)	2,4,6,8	(1,2,3),(3,4,5),(5,6,7), (7,8,9)

Step 2: For each criterion, the geometric mean of fuzzy comparison values is calculated (Ayhan, 2013; Elomda et al., 2013; Wu et al., 2009).
Step 3: Each criterion's fuzzy weight is determined.
Step 4: The acquired fuzzy weights are fuzzy numbers that must be defuzzified using any of the several defuzzification methods, including the linguistic approach, the Centroid Method (COA Method), the Graded Mean Integration Representation (GMIR) method, and the Median or Signed-distance or Area of Compensation method.
Step 5: A consistency check should be performed for the choice of weights of the criteria given by the decision-makers to show the validity of weight allotment. The consistency ratio (CR) should not exceed 0.1 (Ayhan, 2013; Haq & Kannan, 2006). When the consistency check on the weights acquired by FAHP is less than 0.1, the weights are deemed legitimate.

In this study, the initially pairwise relation matrix is formulated considering the importance of attributes on each criterion. When an attribute has no impact on another, the assigned value should be zero (Saaty &Vargas, 2013). Followed by this fuzzy AHP is used to address the expert's inputs to the fullest and establish the importance of each criterion.

Case Illustration

The case organization selected for this study is one of the automotive manufacturing companies situated in Central India, one of the leading vehicle manufacturers established in the pre-independence era. Since then, the company has gone through many ups and downs, and even the name has also changed. The name of the case company is not disclosed as to maintain secrecy and avoid any kind of breach of data privacy, which may harm the commercial interest of the business, leading to market loss. Overall, the company booked USD 10 billion profit in 2021 by employing 250,000 professionals. The company is registered on the Indian and US stock exchange and faces fierce competition from local and international competitors. Based on the clues received from the inhouse and external sources, the case company firmly believes that the time has come to revamp and review the traditional approach. This business transformation intends to achieve higher customer satisfaction and suppliers and vendors' trust by improving speed, flexibility, reliability, quality, and cost of the business operations.

Data Analysis

The data gathered from experts and literature review was examined in three steps.

Stage 1: The group of experts from multiple disciplines and domain areas is one of the strengths of this research. As explained earlier, these experts are currently engaged in the I4.0-CE projects. One of the expert selection criteria was the volume of relevant experience and expertise in I4.0 and CE practices impacting the supply chain. By virtue of their vast experience and expertise, these experts contributed the data on the perceived interrelationship of criteria. This helped to draw the conceptual framework.

Stage 2: A structured questionnaire based on the criteria identified through collective efforts of experts and researchers as explained in phase I and II is designed to capture the data for the ISM model and Fuzzy MICMAC. The format used for collecting data was appropriately designed to match the ISM model and Fuzzy MICMAC requirements. Table 5 presents the ISM Model ranking based on each criterion's driving and dependence power.

Table 5. Inhibitor ranking based on the driving and dependence power.

Item	Dependence	Driving	Quadrant	Rank	Title
I1	6	11	Driver	8	Missing competitive leadership (MCL)
I2	9.2	4.8	Dependent	1	Lack of ICT infrastructure (LII)
I3	6.2	11.6	Driver	6	Lack of policies and protocol (LPP)
I4	6.2	11.4	Driver	6	Limited CE Awareness (LCA)
I5	6.2	11	Driver	7	Lack of capital (LC)
I6	11.4	9.8	Linkage	3	Limited digital skills among employees (LDE)
I7	11.4	9.8	Linkage	3	Missing political will (MPW)
I8	11.4	9.8	Linkage	5	Reluctance to adopt change (RAC)
I9	9.2	4.8	Dependent	1	Missing government support (MGS)
I10	11.4	9.8	Linkage	4	Limited I4.0 awareness (LIA)
I11	9.2	4.8	Dependent	2	Missing training and development (MTD)
I12	6.2	11	Driver	6	Missing standards and framework (MSF)
I13	9.2	4.8	Dependent	1	Limited technology adoption (LTA)
I14	11.4	9.8	Linkage	4	Limited motivation (LM)
I15	9.2	4.8	Dependent	2	Missing data security policy (MDP
I16	6.2	11	Driver	6	Missing sustainability standards (MSS)

Stage 3: One more questionnaire was designed to collect the data to calculate the relative criteria using the Fuzzy AHP method. As explained in phase III, the Fuzzy scales are used to define the hierarchy of inhibitor.

An ISM Model is presented with 16 inhibitors clearly reflecting the hierarchy and direction of interrelationship, which the case company is advised to consider while I4.0-CE adoption. The ISM model developed in phase two is shown in **Figure 2.** The direction of the arrow distinctly demonstrates the hierarchical relationship between the criteria. This diagram is known as a digraph.

Figure 3 shows the division of the criteria based on the dependence and driving power of each into four clusters. The MICMAC analysis shows that the criteria belonging to a specific cluster have similar relationships and behavior as their driving and dependence power matches. Therefore, the approach of the FAHP is employed to priorities the selected inhibitors, as the ISM cannot achieve this (Chang et al., 2013).

Table 6. Fuzzy scales for defining the strength of inhibitor

Strength	No	Very low	low	medium	high	very high	complete
Numerical Value	0	0.1	0.3	0.5	0.7	0.9	1
Experts	0	1 to 3	4 to 6	7 to 9	10 to 12	13 to 15	16 to 18

DISCUSSION

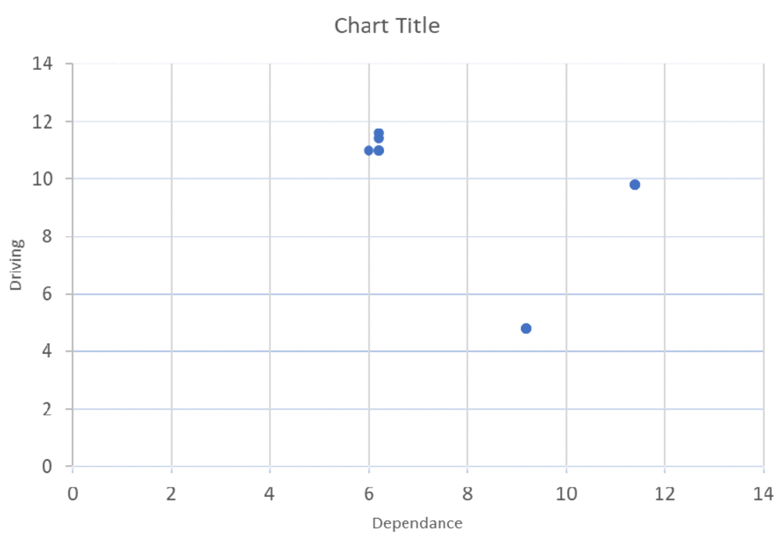
This research adds to the body of knowledge by providing fresh theoretical insights as well as practical ramifications. The study is based on the strong foundation raised by expert intervention and robust literature review. A total of 16 criteria was selected for this study applying the rule of exclusivity and mutually exhaustivity. Each criterion is formulated based on the initial data collected from the experts. The findings are then validated using ISM-Fuzzy MICMAC and Fuzzy AHP. The division of criteria into four clusters gives the right context to each criterion based on its driving and dependence power. The lower-level criteria are causes as they are likely to heavily impact other criteria, and top-level are effects.

As shown in **Figure 2**, Lack of capital (LC) and Missing competitive leadership (MCL) are the bottom level criteria having a very high capacity to influence others and Lack of ICT infrastructure (LII), Missing government support (MGS), Limited digital skills among employees (LDE) are the top-level inhibitors with very high-level dependence on others.

This study primarily aims to explore the linkage between I4.0 and CE, identify the inhibitors, hinder the progression and adoption in PMSC and finally evolve the model for smooth adoption, using ISM, Fuzzy MICMAC and Fuzzy AHP, methods. The robust literature review established the strong linkage between I4.0 and CE and identified 9 prominent inhibitors hindering the I4.0-CE progression. Rest 7 inhibitors evolved from the experts' intervention. This study is based on a total of 16 inhibitors. To begin with, ISM and Fuzzy MICMAC methods were used to develop a combined model, where the interrelationship and commonalities among all the inhibitors were systematically presented and contextualized. ISM model data and additional experts' inputs were used as a base for Fuzzy MICMAC analysis. This model output was validated using Fuzzy AHP. All three methods complemented the findings. According to the ISM ranking, Fuzzy MICMAC clustering and FAHP weights Missing competitive leadership (MCL), Lack of policies and protocol (LPP), Limited CE Awareness (LCA), Lack of capital (LC), Limited digital skills among employees (LDE), Missing Standards and framework (MSF), Missing sustainability standards (MSS) are the most important driving inhibitors, which should be all-time attended which accounts for whoopingly high weightage

Figure 2. The ISM model highlighting the hierarchical dependency

Figure 3. Fuzzy MICMAC analysis



of 63.35%. Next, the linkage group constitutes inhibitors Missing political will (MPW), Reluctance to adopt change (RAC), Limited I4.0 awareness (LIA), and Limited motivation (LM), which accounts for 23% weightage. Lastly, the dependent group, which accounts for 13.8%, constitutes of inhibitors, Lack of ICT infrastructure (LII), Missing government support (MGS), Missing training and Development (MTD), Limited technology adoption (LTA), Missing data security policy (MDP). The findings state, constituents of the dependent group are not triggering change but are highly dependent on the other two groups for initiation as they serve as a solid foundation for the entire hierarchy. The Fuzzy MICMAC analysis further substantiated the ISM findings. The inhibitors are distributed into four clusters considering the individual driving power and dependent power. Each cluster depicts the unique behavior and response pattern by virtue of its place in the model.

Autonomous Inhibitors

These inhibitors are described as those with less capacity to trigger changes or respond to any triggered changes by other constructs. This fundamental property makes them less important constructs and sidelines them from focus areas. These inhibitors are neither impacted nor make any impact on other sets of inhibitors, showing the characteristics that they are out of sync with the rest of the system. The inhibitors in this cluster are frequently separated from the system since they have little influence over the implementation process. None of the inhibitors have fallen in this category in the current study.

Dependent Inhibitors

These are explained as weak drivers causing minimal change but found to be highly sensitive to any impact caused by other constructs. These inhibitors are found on the top of the ISM model. Dependent or resulting inhibitors are located at the bottom right corner of the graph and consist of weak driving and strong reliance power. In the current study, five inhibitors are found to be present in this quadrant. They are I2: Lack of ICT infrastructure (LII), I9: Missing government support (MGS), I11: Missing training and development (MTD), I13: Limited technology adoption (LTA), I15: Missing data security policy (MDP).

Linkage Inhibitors

These inhibitors have characteristics exactly opposite to autonomous inhibitors. They possess very high dependence and driving powers. This high sensitivity nature makes them highly unstable and critical amongst all the inhibitors. However, if these inhibitors are not attended in a timely manner may have serious implications on the overall system stability and productivity. They have a lot of power and are at the top-right corner of the graph, which means they are unstable. A minor change in these inhibitors may have a rapid impact on other inhibitors while also having a feedback effect on themselves.

Moreover, it modifies their output to the system. In this study, the inhibitors, I6: Limited digital skills among employees (LDE), I7: Missing political will (MPW), I8: Reluctance to adopt change (RAC), I10: Limited I4.0 awareness (LIA), I14: Limited motivation (LM) fell under this category. This finding should make an important contribution to the field of knowledge as these linkage inhibitors have a strong feedback effect (Chang et al., 2013); hence while implementing the I4.0 and CE, these inhibitors must be given due importance.

Independent Inhibitors

This set of inhibitors demands prominent attention at all levels. These inhibitors are responsible for any trigger. Missing these inhibitors from the radar means allowing instability and high turbulence in the system. Undoubtedly these inhibitors should be closely monitored by the decision-makers.

The inhibitors in this cluster are strong drivers having minimal or no dependence on other inhibitors. These inhibitors are placed at the top-left zone of the graph, with strong driving and weak, dependent power; they act as initiators in the graph and assist, facilitate, and drive other initiators. These initiators aid and lay a strong foundation in successfully implementing other inhibitors. In the present study following inhibitors were found to be present in this category I1: Missing competitive leadership (MCL), I3: Lack of policies and protocol (LPP), I4: Limited CE awareness (LCA), I5: Lack of capital (LC), I12: Missing standards and framework (MSF), I16: Missing sustainability standards (MSS)

The result of the ISM-Fuzzy MICMAC analysis showed a similar pattern to reflect the relationships among the inhibitors.

Furthermore, using FAHP utilizing the Geometric Mean technique, criteria weights are determined to assign weights to the chosen criteria. Another round of in-depth conversations with experts is used to create the pairwise comparison matrix between the criteria. They used the scale provided in **Table 4** to evaluate the criterion. After that, decision-makers created a fuzzified pairwise comparison matrix for criterion. Phase 3 describes the ramifications of the Fuzzy AHP process's output. The weights of each criterion are defuzzified in a crisp number using step 4, and then a consistency check is performed as described in step 5, as shown in Table 7. If there was any inconsistency in the evaluation, the data was sent back to the experts until the consistency ratio was less than 0.1.

Table 7. Weights of criteria in triangular fuzzy numbers obtained by FAHP by Geometric Mean method

Inhibitor	ISM status	Defuzzified weights	Rank
I1: Missing competitive leadership (MCL)	Driver	12.11%	1
I2: Lack of ICT infrastructure (LII)	Dependent	3.15%	12
I3: Lack of policies and protocol (LPP)	Driver	9.79%	2
I4: Limited CE Awareness (LCA),	Driver	8.39%	4
I5: Lack of capital (LC),	Driver	7.71%	6
I6: Limited digital skills among employees (LDE),	Driver	7.41%	7
I7: Missing political will (MPW),	Linkage	6.42%	8
I8: Reluctance to adopt change (RAC),	Linkage	5.95%	10
I9: Missing government support (MGS),	Dependent	0.73%	16
I10: Limited I4.0 awareness (LIA),	Linkage	6.25%	9
I11: Missing training and Development (MTD),	Dependent	2.91%	14
I12: Missing Standards and framework (MSF),	Driver	8.33%	5
I13: Limited Technology Adoption (LTA),	Dependent	4.02%	13
I14: Limited motivation (LM)	Linkage	4.39%	11
I15: Missing data security policy (MDP)	Dependent	2.97%	15
I16: Missing sustainability standards (MSS)	Driver	9.60%	3

The consistency ratio obtained was 0.02, which was much lesser than 0.1. It gives researchers confidence that there was no inconsistency in the judgment of the experts in a pairwise comparison of criteria.

The rank obtained in decreasing order using FAHP is MGS > MDP > MTD > LTA > LII > ML > RAC > LIA > MPW > LDE > LC > MSF > LCA > MSS > LPP > MCL. The findings indicate the need for top management support and organizational leadership support is key to the successful implementation of I4.0 and CE practices. Organizations can harness the excellent quality of the products and services without harming the environment if the I4.0 and CE are implemented together. The recurring and incremental capital investment may not always be within the scope of businesses, but to a certain extent, it can be compensated by choosing the apt leadership. This cannot be considered as the exact tradeoff but just a support. The leadership role becomes even more crucial as adopting CE practices may make the businesses unprofitable as the prices of recycled or remanufactured and reengineered products are bound to be higher than the virgin products even though they are more environment-friendly and user friendly. Another inhibitor is the Lack of favorable and conducive government policies and protocols. This challenge can be mitigated by offering incentives, subsidies, and legislature related to environmental protection for the entrepreneurs adopting I4. 0 and CE practices in PMSC.

The findings of this study are also confirmed by past researchers Govindan et al. (2016), who claimed in his study that in the absence of healthy policies and protocols, the best of the company's efforts might go to waste. Hence the most appropriate digitalized leadership with sufficient capital support will not only eliminate the hurdles but pave the way to clear I4.0 and CE policies and required digitalization (Alonso-Almeida et al., 2021). Digital leadership is the crux of organizational all-around development (Brozzi et al., 2020; Kumar et al., 2021; Muduli et al., 2020). Leadership must create avenues to boost the confidence at individual employee levels by frequently organizing intense training programs for the existing employees. These things will develop a clear understanding of emerging technology and its applications in the company (Kumar et al., 2021). The conducive environment promotes innovation and a collaborative approach among the employees (Brozzi et al., 2020). ILO (2019) reported, based on the survey conducted globally, that limited leadership skill is hindering the adoption of I4.0 and CE.

Managerial Implications and Recommendations for Decision-makers

The primary aim of this research is to support the decision-makers, consultants, SC professionals, and policymakers. Identifying and controlling the inhibitors in adopting I4.0 and CE practices is proven to be a game-changer in PMSC. The findings will help the stakeholders to timely identify and eliminate the inhibitors before it adversely impacts the growth. The ISM- Fuzzy MICMAC model has systematically highlighted the importance of specific inhibitors in long-term or short-term decision-making.

In a short-term strategic plan, the PMSC organizations should focus on low-level inhibitors, i.e., on the I1: Missing competitive leadership (MCL), I3: Lack of policies and protocol (LPP), I4: Limited CE Awareness (LCA), I5: Lack of capital (LC), I12: Standards and framework (MSF), I16: Missing sustainability standards (MSS) (Sahu et al., 2021). Thoughtful leadership guided by key policies and protocols that will create awareness about the I4.0 and CE tools and techniques is a must to transform an organization's strategies. The standards, sustainability, and frameworks go together with employee awareness and positive culture to create value in any organization. Standards only find meaning if it is known and adhered to by employees and stakeholders. The organizations must take the necessary steps to motivate the employees to participate in the awareness assessment survey. These surveys at regular intervals will establish the awareness level. Management may formulate innovative and realistic rewards and compensations to motivate employee participation in these surveys. An inclusive and collective effort by government, industries, and civil society can be a game-changer for successful adoption of I4.0 and C.E. Hence this study recommends, the decision-makers from all the sections of stakeholders should urgently attend to the following inhibitors, I16: Missing sustainability standards (MSS), I6: Limited digital skills among employees (LDE), I8: Reluctance to adopt change (RAC), I10: Limited I4.0 awareness (LIA), I14: Limited motivation (LM). Employee involvement reflects the support at the same time; its absence means non-compliance with the organizational sustainability goals.

Another critical finding highlights the importance of appropriate infrastructure, technology, and data security provisions in the company. The efficiency, efficacy, and overall productivity are the key indicators of the level of preparedness to adopt I4.0 and CE in company operations. Active customer participation, encouraged by the employee's holistic engagement, will inspire participation in developing sustainable solutions. Hence the inhibitors like I2: Lack of ICT infrastructure (LII), I9: Missing government support (MGS), I11: Missing training and development (MTD), I13: Limited technology adoption (LTA), I15: Missing data security policy (MDP) can be an integral part of the long-term strategy. This is confirmed by (G. Yadav et al. (2020) and Sehnem et al. (2020) in their recent studies. This will make possible the effective adoption of I4.0 and CE and lay down the foundation of socio-economic, socio-cultural, and socio-technical, and environmental benefits.

A Unique Contribution of the Study

The study has successfully explored the inhibitors hindering the effective implementation of I4.0 and CE. Sixteen inhibitors were selected after robust literature review and expert intervention. The meticulous choice of the inhibitors (Khan & Haleem, 2021) warranted the total coverage leaving no scope for anything going unattended. Further, the inhibitors' inter-relationship was analyzed by integrated MCDM techniques, ISM-Fuzzy MICMAC (Bai et al., 2020) to establish the hierarchy, relevance, and context between any two inhibitors and validated using fuzzy AHP. This study is unique by virtue of the robust sample size and set of inhibitors which has been the limitation of earlier research. This study's findings and recommendations are validated by the industry experts and found worth considering by industry professionals, consultants, regulators, strategists, and other decision-makers.

Conventional ways of addressing new business problems in PMSC do very little to address the stake holder's concerns. Companies need to adopt a systematic approach and not just one of the tick box exercises, which will involve designing and delivering a focused and inclusive digital leadership, plan for capital investment, technology adoption, infrastructure building and liaising with government bodies, driving commitment and innovation through harnessing every stakeholder's potential.

CONCLUSIONS AND LIMITATIONS

The world is experiencing the systematic shifts from traditional to more sustainable practices by virtue of the aggressive development of I4.0 and the transition to CE. Against that background, the researchers carried our systematic literature review and engaged with experts to investigate how the key 16 inhibitors are hindering the implementation of the combination of CE and I4.0 in the Manufacturing Industry Supply Chain. The findings confirmed the high level of awareness and rising interest in implementing CE and I4.0 as pathways to achieving a crucial transition from a linear to a sustainable circular economy. The study thereby concludes beyond doubt that the CE-I4.0 nexus has large potential to contribute to the achievement of the highly agile and resilient supply chain. Thereby, this research serves as a guide to decision and policymakers. The study highlights leadership, capital, standards, framework, and policies as the most critical inhibitors, which must be urgently attended to achieve successful implementation of CE-I4.0 nexus.

As far as the authors are aware, this research is one of its kind, which simultaneously links the SCM to CE and I4.0. Although the combination of these two topics is growing in the industrial sector, we identified the need for further research and implementation of I4.0 technology in the circular system connected to the manufacturing world. Lastly, the four main areas addressed by this research are identification, analysis, quantification, and modeling of the key inhibitors to harness the best from I4.0-CE adoption.

The findings revealed that, with the correct governance, an enabling environment, and public-private partnerships, the emerging ideas of I4.0 and the CE offer potential opportunities for bringing excellence in industrial operations. It is underpinned by rapid advances in technologies that, without appropriate planning, the consumed resources and materials may ultimately end up as waste and pollution. Adopting I4.0 is crucial to make the transition from a linear to a circular economy and requires closer cooperation between the research, technological, and business communities. The major entry points to advance the integration of the rapidly evolving technological and business fields are resource use and waste management – the circular economy model's beginning and end. Raw material extraction, processing, and production companies can use I4.0 technologies more efficiently. In contrast, the same technologies can be used for more efficient resource management and turn the raw materials into new ones, closing the material cycle. Readiness is often defined as the ability to capitalize on future production opportunities, mitigate risks and challenges, and be resilient and agile in responding to uncertainties.

It is supported by quick technological advancements, which means that the spent resources and material may be stopped from ending up as waste and pollution with proper planning. Industry must ensure competitive leadership who will formulate visionary strategies to move from a linear to a circular economy through collaboration, research, and technological advancement. Also, appropriate provision of finance, which will advance the efficient resource consumption and waste management – the beginning and finish of the circular economy model is also a must for fast-emerging technical and business fields. Companies' awareness, standards, policies, and adopted framework to better utilize available resources and to transform raw materials into new raw materials shows the companies' readiness to seize future production opportunities, manage risks and problems, and adapt to uncertainty with resilience and agility.

Digitalization-based sustainability has been forcing companies to adopt change and be flexible in recent years. The triple bottom line of sustainability is no more limited to the industry responsibility but applies to all the stakeholders. The demanding consumer of this decade has become the pivotal point in this context. The raised expectations of the customer and changing socio-economic dynamics are pushing the companies to adopt I4.0 and CE together to bring digitalization-based sustainable growth.

Even though the companies have understood the importance of adopting new business practices and the business environment also looks favorable, the adoption is not happening to the fullest because of the number of inhibitors and their unexplored nature and scope. This study first investigated into the number of inhibitors before finalizing the 16, applying the rule of mutual exclusivity.

The MCDM technique is used to develop the ISM model. Each inhibitor's dependence and driving power is used to place the inhibitors in one of the four quadrants. Except for the autonomous quadrant, all others are filled with inhibitors. The findings of the paper suggest that the 'missing competitive leadership and 'lack of capital' are the most critical inhibitors, hindering the implementation of I4.0 and CE in the manufacturing company supply chain, depriving the industry of enormous incentives of the digitalization. The paper also established that the independent inhibitors having high driving and dependence power I1: Missing competitive leadership (MCL), I3: Lack of policies and protocol (LPP), I4: Limited CE awareness (LCA), I5:Lack of capital (LC), I12: Missing standards and framework (MSF), I16: Missing sustainability standards (MSS) also needs urgent attention.

The model developed is validated by the industry experts and has been implemented.

The choice of the experts is highly subjective and may impact the findings. Also, the findings cannot be generalized as every sector has different challenges. Further, the current work can be extended by using different MCDM methods and a set of inhibitors to represent sector and geography. The study can further conduct an empirical study to validate the findings of this study.

Table 8. List of the inhibitors considered in this research after using the Delphi Method.

Sr	Inhibitors	Sub-inhibitors	Description	References
1	Limited Awareness (LAW)	Lack of awareness Program, Poor understanding of return on investment, low education, Less exposure to the global practices, management's poor vision.	This is key to the overall support of digitalization in the company. Organizations must spend resources to make the stakeholders aware of the I4.0 and CE impact on PMSC.	Long et al. (2016); Mangla et al. (2019); Kamble et al.(2018);Chauhan et al.(2020);Sharma et al.(2019);Brozzi et al. (2020)
2	Missing Standards and framework (LGF)	Missing global standards, missing local standards, Lack of initiatives by regulating authorities, Disagreement on uniform protocols,	Global standards are must for smooth adoption of I4.0 and CE across the business. Lack of these standards lead to high level of confusion and failures.	Long et al.(2016); Luthra & Mangla (2018) Rajput & Singh (2019); Chauhan et al. (2020);V. S. Yadav et al. (2020)
3	Limited digital skills among employee (LSW)	Missing digital skills in existing employee, Missing avenues to develop digital skills, Lack of digitalization, cost of digitalization is high.	I4.0 emerging technologies need high-level skills. Companies must spend adequate resources to upskill the existing workforce or hire. Low or limited technical skills may become bottleneck in the growth.	Long et al. (2016); Luthra & Mangla (2018);(Sharma et al., 2019); Rajput & Singh (2019);Lezoche et al. (2020)

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Sr	Inhibitors	Sub-inhibitors	Description	References
4	Lack of ICT infrastructure (LI)	Internet connectivity, Machine-man-Machine communication, Sensor integration, real time data collection and analysis, infrastructure standardization, compatibility issues	Suitable ICT infrastructure is the backbone of current business practices. Continuous high speed data transfer is the need of real-time decision making.	Lezoche et al., (2020); Rajput & Singh (2019)
5	Limited motivation (LCM)	Lack of vision, recognition, Rewards, promotion Competitiveness, capability, fewer priorities to CE practices	The people centric approach should not be overlooked at any cost. Company should design healthy and sustainable motivating practices.	Luthra & Mangla (2018)
6	Missing government support	missing Legislature, Strategy, policy, Legal issues, collaboration issues, unavailability of financial support, low price of virgin material, Lack of agreement among industries	Government support in different forms could be game changer. The appropriate legislature, strategies, and policies.	Kirchherr et al., (2018); Mangla et al.(2019);G. Yadav et al. (2020)
7	Missing sustainability standards	Lack of compliance, sustainability regulation, Environmental Sustainability, Economic Sustainability, Social Sustainability	Inclusive efforts to bring the overall sustainability is must.	Sehnem et al. (2020);G. Yadav et al.(2020)
8	Lack of policies and protocol (LPP)	Missing internal code of digital conduct, Missing company protocol, Semantic interoperability issues, a policy that supports CE transition, monitoring, Sustainability standard and regulations,	Every business must formulate the clear and guided policies and protocol to address the business needs.	Long et al. (2016);Kirchherr et al. (2018);Mangla et al., (2019)
9	Lack of capital (LA.)	High investment cost, Technology Cost, Upskilling Cost, Unknown market response, sustainability adoption cost, Data security cost, fear to lose business during the transformation phase, trust issues	The huge initial capital requirement to install the required infrastructure, technologies, and skills without have any clue about the returns is reducing the acceptance rate of the I4.0 and CE practices.	Liboni et al.(2018);Sharma et al.(2019);V. S. Yadav et al.(2020)
10	Limited CE awareness	Limited awareness about CE, Lack of relevant training, Unclear returns, Cost of Eco-innovation, eco-design, eco-efficient technologies	Lack of awareness and knowledge about the environmental sustainability practices like reusing, recycling, redesigning, remanufacturing, and restoring of the resources while designing the products and services.	Kirchherr et al. (2018);Rajput & Singh (2019); Lahane et al.(2020)
11	Reluctance to adopt change	Fear of being obsolete, Difficulty to learn new things, Lack of willingness, Producer and consumers culture, Missing change agent in the process.	Companies lacks clarity on the use of automation and AI solutions to make the SC sustainable, mainly because of the less education and training. Also, the long-term investment and payback schedules is beyond their comprehension.	Liboni et al. (2018);Kirchherr et al. (2018)
12	Missing data security policy	Data generation, collection, transfer, storage and access by the right person at right time.	The fear of losing the confidential and private data about the company capability and capacity to the competitor or antisocial elements stops them from trying the new technology.	Luthra & Mangla, (2018); Rajput & Singh (2019); V. S. Yadav et al. (2020)
13	Missing competitive leadership	Digital leadership, technology awareness, use of productivity enhancement tools, Data Driven decision making, Real-time data analysis	The leadership competence in understanding the relevance of advanced digitalization tools and techniques to exemplify the overall performance is must.	Rajput &Singh (2019); Lezoche et al. (2020)
14	Missing training and Development	Simulated training, on the job training, Inhouse training, cost-benefit analysis of training, training impact calculation.	Appropriate training facilities for upskilling the existing workforce can increase the productivity.	Lezoche et al., (2020);Luthra & Mangla, (2018)

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Sr	Inhibitors	Sub-inhibitors	Description	References
15	Limited Technology Adoption	Positive attitude towards technology adoption, Right choice of technology, technology viability.	The technology adoption process should be governed by the employee capability and need of the company.	Liboni et al.(2018); Kirchherr et al., (2018); G. Yadav et al.(2020)
16	Missing political will	Government legislature, law, and policies directed to promote the I4.o adoption	The government legislature, policy and regulations should be designed to promote the industrial growth.	G. Yadav et al.(2020); Long et al., (2016); Long et al. (2019);Kirchherr et al. (2018)

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