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Sustainable and Resilient Manufacturing in the Age of Digitalization: Analysis of Challenges

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Abstract: Sustainable and resilient manufacturing in the age of digitalization presents a multifaceted challenge and opportunity for contemporary industry. This paper explores the intersection of sustainability, resilience, and digitalization within the manufacturing sector, aiming to uncover key factors influencing organizational practices and outcomes. Authors of the current study identified the challenges of sustainable and resilient manufacturing (SRM) from literature review by PRISMA approach and analyzed the challenges by the Best-Worst Method (BWM). Findings of the study states that lack of preparedness for uncertainty and unpredictable situations, lack of technological infrastructure and facilities and lack of reverse supply chain facilities are top three challenges in implementation of sustainable and resilient manufacturing. These findings imply the need for proactive risk management strategies, investment in adaptive capabilities, and collaboration across supply chains to navigate unpredictable market dynamics effectively. By addressing these challenges and capitalizing on emerging opportunities, manufacturing organizations can voyage the issues of the digital age while advancing towards a more sustainable and resilient future.

Keywords: Sustainable and Resilient Manufacturing; Digitalization; Collaboration; Challenges; Responsiveness

1. Introduction

Uncertainties and disruptions arose from pandemic (COVID 19), natural calamities and other geopolitical scenarios, do significantly affect the economies all over the globe[1)]. In uncertain scenarios, the ability to withstand and recover from disruptions called 'Resiliency', is essential for survival. Manufacturing resilience adverts to the capacity of a system to defy disruptions while ensuring uninterrupted manufacturing operations and supplies. The goal of resilient manufacturing methods is to enhance flexibility, redundancy, and adaptive capacity of a system[2)]. On the other hand, Sustainable Manufacturing may ensure the long-term survival and competitiveness of its operations by focusing on the triple bottom line approach of sustainability. Proactively detecting and reducing risks, thereby minimizing the impact of interruptions, supply chain disruptions, and market volatility are key characteristics of resilient manufacturing. In the era of rapid technological advancement and increasing environmental awareness, the manufacturing sector stands at a pivotal crossroads. The convergence of digitalization, sustainability imperatives, and the need for resilience has catalyzed a transformative shift in manufacturing practices worldwide[3)].

The arrival of technologies like, Internet of Things (IoT), data analytics, and cyber-physical systems integration, has unleashed unprecedented possibilities for optimizing production processes, enhancing efficiency, and driving innovation across the manufacturing value chain[4)]. However, alongside these technological advancements, the pressing need to address how industrial operations affect the environment and increase resilience to outside shocks is becoming more widely acknowledged[5)]. At the heart of sustainable and resilient manufacturing lies a fundamental reimagining of traditional practices, embracing principles that prioritize environmental stewardship, social responsibility, and economic viability[6)]. The pursuit of sustainability in manufacturing encompasses multifaceted dimensions, ranging from eco-efficient production processes, circular economy principles to renewable energy integration and supply chain transparency[7)]. By adopting eco-design principles, manufacturers can minimize the environmental footprint of their products, optimize material usage, and facilitate end-of-life recycling or repurposing[8)]. Concurrently, the consolidation of renewable energy sources in manufacturing operations helps in reducing greenhouse gas emissions with enhances energy security and resilience to fickle energy markets[9)].

Moreover, the concept of resilience in manufacturing extends beyond mere operational continuity to encompass adaptability, agility, and risk management in the face of uncertainty[10]. Digitalization plays a pivotal role in enhancing manufacturing resilience by making adaptive decision-making, predictive maintenance, and real-time monitoring, in response to dynamic market conditions and unforeseen disruptions. Through the deployment of advanced analytics, artificial intelligence, and predictive modelling, manufacturers can anticipate and mitigate risks, optimize supply chain logistics, and enhance overall business continuity[11].

However, realizing the full potential of sustainable and resilient manufacturing in the digital age is not possible without considering challenges associated with it. There are obstacles in the way of implementing resilient and sustainable manufacturing techniques. Balancing economic needs with social and environmental goals is one of the main issues. Manufacturers often face trade-offs between profitability, environmental performance, and social responsibility, requiring careful consideration and strategic decision-making[12]. Supply chain complexity and globalization present another significant challenge to sustainability and resilience in manufacturing[13]. Global supply chains are divulged to uncertainties of natural calamities, geopolitical imbalance, and labour disputes, which can disrupt production and erode company continuity[14]. Building resilience in supply chains requires collaboration, visibility, and risk management strategies to identify and mitigate vulnerabilities[15].

In spite of these difficulties, there are also important opportunities for advancing sustainable and resilient manufacturing practices. Technological innovations, such as additive manufacturing, renewable energy integration, IoT, AI, blockchain and advanced analytics, enable manufacturers to develop more sustainable products, optimize resource usage, and enhance operational resilience with data privacy, and reduced cybersecurity risks[16]. Furthermore, the dynamic and varied sector of sustainable and resilient manufacturing necessitates a comprehensive strategy for striking a balance between social, economic, and environmental goals. Manufacturers can successfully manage the challenges of the digital age and conduce to a more resilient, sustainable, and prosperous future by embracing innovation, teamwork, and ethical business practices[17]. Based on the above discussion authors observed that the advantages of sustainable and resilient systems are highlighted in literature but there is scope and need of holistic research on issues and challenges of Sustainable and resilient manufacturing. Considering the importance of topic, authors set the objectives of study as follow:

Objective 1: To Understand the importance of resilience and sustainability in manufacturing Industry.

Objective 2: To overcome the challenges and plan strategies for the adoption of resilient and sustainable manufacturing.

Although sustainable and resilient manufacturing represents a transformative imperative for the industry, it requires a holistic transformation of organizational culture, business models, workforce training and technological infrastructure. To holistically understand all issues, in the paradigm of sustainable and resilient manufacturing, Authors have framed Research Questions as follows:

RQ 1: Challenges in implementing SRM practices?

RQ 2: How to rank the challenges with relative importance?

To answer the above raised questions and holistically study the challenges of SRM, the current research paper is organized as follows: Section 2 will discuss literature. Section 3 have methodology. Section 4 discusses results and section 5 concludes the findings of studies with implications and future research directions.

2. Literature Review

Sustainable and resilient manufacturing (SRM) has evolved through different stages in the past, each characterized by significant milestones and developments. The digitalization and Industry 4.0 era of the 21st century revolutionized manufacturing processes, enabling greater efficiency, flexibility, and customization, while also placing sustainability and resilience at the forefront of industry discussions. By enabling remote monitoring and management of production processes, digital technologies like cloud computing, big data analytics, and IoT sensors have improved operational resilience and agility for manufacturers[18]. Through real-time data analytics, manufacturers are now able to optimize resource utilization, decrease waste, and increase predictive maintenance[19]. Digitalization has also made supply chains more transparent and traceable, allowing businesses to monitor the environmental and social effects of their products throughout the course of their whole lifecycle. Anticipating the future, cooperative endeavors and technological breakthroughs are anticipated to propel more progressions in sustainable and robust manufacturing, molding the sector's trajectory towards eco-friendly and robust methodologies[20]. Supply chain resilience is further enhanced by collaborative networks. Supply networks are susceptible to several dangers in the contemporary global economy, such as natural calamities, unstable geopolitical situations, and economic disturbances. By collaborating with suppliers, logistics providers, and other key stakeholders, manufacturers can develop robust supply chain resilience strategies that mitigate risks, enhance visibility, and improve responsiveness to disruptions[21]. Collaborative networks are essential for advancing sustainability and resilience in industrial operations, as well as for influencing legislative and regulatory frameworks that support these practices. By engaging with policymakers, industry associations, and advocacy groups, collaborative networks can advocate for policy reforms, incentives, and standards that incentivize sustainable and resilient practices and create a level playing field for all stakeholders. Through collective advocacy and lobbying efforts, participants can influence policy decisions and shape the regulatory environment in ways that promote long-term sustainability and resilience[22]. Authors of current research paper have studied the key issues of Sustainable and Resilient Manufacturing from literature and finalize challenges in implementing it by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) technique (Fig. 1) (Table 1) in the following sections:

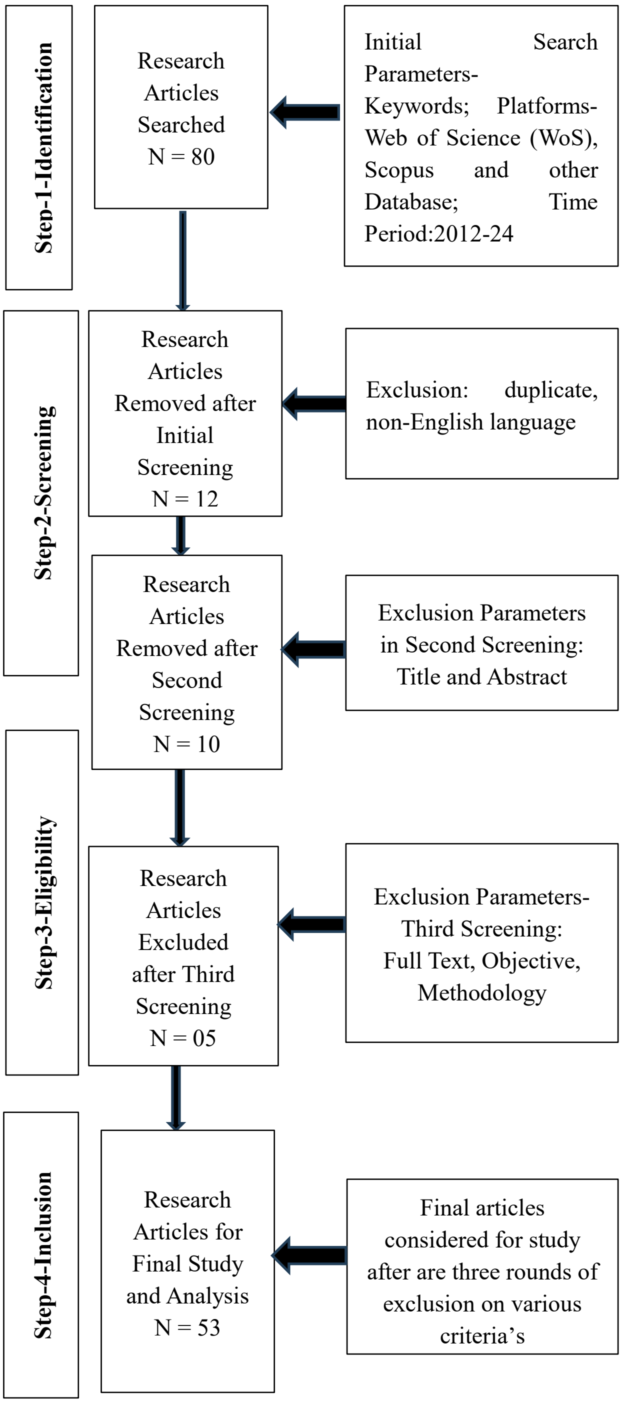

Fig. 1: The PRISMA Approach Research Methodology with Inclusion and Exclusion Criteria

•Lack of policies and regulations for Sustainable and Resilient Manufacturing

Established guidelines, incentives, and industry initiatives, policies and regulatory environment significantly influences the adoption of resilient and sustainable manufacturing practices[23]. Globally, governments have implemented a range of laws, guidelines, and benchmarks to encourage sustainability and adaptability within the manufacturing sector. These measures aim to address environmental challenges, enhance resource efficiency, and mitigate the impacts of climate change[24]. Regulations on environmental protection set limits on emissions, pollutants, and waste disposal, requiring manufacturers to implement measures to minimize environmental impact and comply with environmental standards[25]. Energy-efficient techniques and technology must be used in accordance with energy efficiency requirements to minimize energy use, cut greenhouse gas emissions, and improve energy security. Waste management regulations influence the dealing, intervention, and disposal of industrial waste, promoting recycling, reuse, and waste minimization to reduce environmental pollution and conserve resources[26]. Product labelling and certification programs certify products' environmental attributes, such as energy efficiency, recyclability, and eco-friendliness, providing consumers with information to make informed purchasing decisions. Green procurement policies encourage government agencies and businesses to prioritize environmentally sustainable products and suppliers in procurement processes, driving demand for green products and fostering market growth[27].

•Lack of Government Incentives and Initiatives for Sustainable and Resilient Manufacturing

In addition to regulatory measures, governments should offer various incentives and initiatives to incentivize and support sustainable and resilient manufacturing practices. These incentives aim to reduce barriers to adoption, stimulate investment, and accelerate the transition to sustainable and resilient manufacturing. Governments should provide grants, subsidies, and financial incentives to support research, development, and deployment of green technologies and practices in manufacturing. These programs help offset costs and encourage investment in sustainable innovation[28]. Manufacturers who invest in renewable energy systems, energy-efficient machinery, and other sustainable technology should receive tax credits and deductions, which incentivize them to embrace environmentally friendly practices. Governments should offer training, technical assistance, and capacity-building programs to help manufacturers improve their environmental performance, comply with regulations, and implement sustainable practices effectively[29]. Governments should collaborate with industry stakeholders, research institutions, and non-governmental organizations to develop joint initiatives, share best practices, and drive innovation in sustainable manufacturing. Governments should also support the development and implementation of green manufacturing certification programs, such as ISO 14001 and LEED, which provide recognition and validation of manufacturers' environmental performance and commitment to sustainability[30)].

•Lack of Collaboration and Partnerships between stack holders for Sustainable and Resilient Manufacturing

Collaboration between industry, academia, government, and civil society is essential for advancing sustainable and resilient manufacturing practices, driving innovation, and addressing complex challenges that transcend organizational boundaries[31)]. Cross-sector collaboration brings together diverse expertise, resources, and perspectives to tackle sustainability and resilience challenges holistically. By fostering collaboration between industry, academia, government, and civil society, stakeholders can leverage complementary strengths, share knowledge, and co-create innovative solutions that address societal needs and promote collective prosperity. Industry brings practical experience, market insights, and technological expertise to collaborative initiatives, driving innovation and scalability. Industry-academia partnerships enable knowledge transfer, talent development, and research commercialization, while industry-government partnerships facilitate policy advocacy, regulatory compliance, and public-private collaboration[32)]. Civil society organizations advocate for social and environmental justice, promote stakeholder engagement, and hold stakeholders accountable for ethical and responsible behavior. Civil society-industry partnerships foster transparency, corporate social responsibility, and community engagement, while civil society-government partnerships facilitate policy advocacy, public awareness campaigns, and social impact initiatives[33)].

•Lack of collaboration between supply chain members for sustainable and resilient manufacturing

Collaborative networks play a pivotal role in advancing sustainable and resilient manufacturing by fostering cooperation, sharing knowledge, and driving collective action across diverse stakeholders. In the face of difficult issues like resource shortages, climate change, and supply chain disruptions, collaboration is essential for harnessing collective expertise, resources, and innovative solutions to build a more sustainable and resilient industrial ecosystem[34)]. One of the primary roles of collaborative networks in sustainable and resilient manufacturing is knowledge exchange and best practice sharing. By bringing together manufacturers, suppliers, academia, government agencies, and non-governmental organizations (NGOs), collaborative networks facilitate the dissemination of valuable insights, research findings, and lessons learned. This collective learning enables participants to stay abreast of emerging trends, technological advancements, and regulatory developments, empowering them to adopt and implement more sustainable and resilient practices in their operations[35)]. Moreover, collaborative networks provide a platform for pre-competitive collaboration, where competitors come together to address common challenges and pursue shared objectives. By transcending traditional competitive boundaries, manufacturers can collaborate on pre-competitive research and development projects, joint technology investments, and industry-wide initiatives aimed at advancing sustainability and resilience across the value chain. This collaborative approach fosters innovation, accelerates technology adoption, and drives continuous improvement, benefiting all participants while enhancing the overall competitiveness of the industry[36)].

Table 1. Challenges of Sustainable and Resilient Manufacturing

Sr. No.	Challenges	References
1.	Lack of strategies and Commitment from top management	[5-7][42]
2.	Lack of technological infrastructure and facilities	[5-6][43]
3.	Lack of Collaboration and shared capabilities between SC members	[31-33][42]
4.	Lack of facilities of training, skilling and reskilling of workforce	[8-9] [17][43]
5.	Lack of real time data sharing and analytics	[5] [10][16]
6.	Lack of preparedness for uncertainty and unpredictable situations	[30][35][44]
7.	Lack of agility in the facilities/practices	[9][23][45]
8.	Lack of responsiveness in Supply chain	[7][26][46]
9.	Lack of strategies for global & local sourcing both	[30][34][47]
10.	Lack of performance measures of resiliency	[27-29][48]
11.	Lack of system reconfigurability for new materials and energy (Green/traditional)	[37-39][42]
12.	Lack of integration of lean, agile and sustainability	[40-41][47]
13.	Lack of Reverse supply chain facilities	[14-16][48]

3. Research Methodology

To investigate the complex dynamics of resilient and sustainable manufacturing in the digital era, authors have prepared a structured questionnaire. The stakeholders, such as supply chain specialists, managers of sustainability, manufacturing executives, and IT professionals, have been interviewed in a semi-structured manner. The management and synthesis of interview data facilitated using qualitative data analysis software.

Developing a Questionnaire

The comprehensive review of existing literature with experts' opinion is conducted to identify the challenges. To collect the survey response (As per BWM Technique), a questionnaire was prepared by incorporating the identified challenges. To improve its validity and reliability, the questionnaire has been revised iteratively in response to input from subject matter experts and pilot testing. The Cronbach's alpha index is used to assess consistency of survey; values greater than 0.70 signify respectable reliability.

Survey

Survey has been conducted online with semi-structured interviews. Experts from manufacturing organizations were invited to participate in the study through targeted recruitment efforts and industry partnerships. Experts having minimum experience of five years in the relevant field with professional degree were contacted for survey and interview. Survey links were distributed via email to identified contacts within participating organizations, with reminders sent to maximize response rates. Stakeholders, such as managers of sustainability initiatives, industrial executives, and IT specialists, were interviewed in semi-structured interviews.

Analysis of Survey Response

Survey data has been analyzed statistically to identify patterns, trends, and relationships between variables. The quantitative findings will be quantified and examined using statistical techniques such regression analysis, correlation analysis, and descriptive statistics. Essential statistical methods for evaluating the suitability of data for factor analysis—a popular method in social science and business research to investigate underlying correlations among variables—are the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test (KMO & B).

Table 2. KMO and Bartlett's Test

KMO Sampling accuracy		.550
B test of globosity	Chi-Square	154.476
	df	78
	Sig.	.000

A value of 0.550 suggests that some variables in the dataset may not be strongly correlated, potentially limiting the effectiveness of factor analysis. Therefore, caution is warranted in interpreting the results (Table 2).

Reliability Statistics: Strong internal consistency among the questionnaire items is highlighted by the Cronbach's alpha constant (0.819), which suggests that the items as a whole accurately assess the targeted constructs. This high degree of dependability highlights the resilience of the research instrument employed for data collection and increases trust in the validity of the results.

Summary of survey data: The variance, mean scores and inter-item correlations offer valuable insights into the distribution and relationships among the variables. While the mean scores reflect the respondents' perceptions of sustainable and resilient manufacturing practices, the variance and inter-item correlations provide context regarding the variability and coherence of the dataset (Table 3).

Rotated Component Matrix: This matrix indicates the different components representing different dimensions of sustainable and resilient manufacturing. Each component encapsulates a unique set of factors that contribute to the overall construct. A deeper knowledge of the variables impacting resilient and sustainable manufacturing methods is made possible by analyzing the loadings of variables on each component, which offers insights into the underlying structures and relationships among the variables (Table 4 ,5& 6).

Table 3. Summary of survey

	Mean	Minim.	Maxim.	Range	Maxim. /Minim.	Variance	Total Items
Means of response	3.811	3.462	4.154	.692	1.200	.042	13
Variances	.630	.118	1.146	1.028	9.675	.096	13
Inter-Item Correlations	.250	-.279	.707	.985	-2.537	.051	13

Best Worst Method (BWM)

BWM arose by Jafar Rezaei. In this technique, best challenge and worst challenge or least important challenge is chosen at first and then pairwise comparisons is conducted with respect to 'best to others' and 'worst to others'. Then maximin problem is excogitated to calculate the weights and the ranking.

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix}$$

Here, a11 to ann are regarded as aij, signifying the relative weight of the criteria. I to the requirements Similarly, aij > 1 suggests that i is more relevant than j. j. aij = 1 indicates that both criteria are of equal value.

Pairwise comparison method is a structured way to make the decision matrix employed in all of the MCDM techniques. This pairwise comparison matrix often shows inconsistencies. The Best-worst method requires fewer comparison matrix and displays a more consistent relationship among the set of alternatives and requires only numerical values to make comparison matrix. As there are inconsistencies in pairwise comparison, in BWM the pairwise comparisons are classified into two main categories. Definition 1: If i is the best criterion and j is the worst criterion, or vice versa, the aij is considered a reference comparison. Definition 2: If neither of the elements meets the best nor worst requirements, then the aij is considered a secondary comparison.

Table 4. Rotated Component Matrix[a]

	Component		
	1	2	3
Lack of Collaboration and shared capabilities between SC members	.672		
Lack of facilities of training, skilling and reskilling of workforce	.491		
Lack of real time data sharing and analytics	.843		
Lack of performance measures of resiliency	.566		
Lack of integration of lean, agile and sustainability	.579		
Lack of strategies and Commitment from top management		.594	
Lack of technological infrastructure and facilities		.822	
Lack of agility in the practices		.770	
Lack of strategies for global and local sourcing		.826	
Lack of system reconfigurability for new materials and energy (Green/traditional)		.603	
Lack of preparedness for uncertainty and unpredictable situation			.855
Lack of responsiveness in Supply chain			.601
Lack of Reverse supply chain facilities			.843
a. Total looping is 5			

Table 5. Assortments of Challenges

S.NO.		CIMTC	Mean	Standard Deviation	Important index
Data oriented factors					
D1	Lack of Collaboration and shared capabilities between SC members	.544	4.04	.871	.807
D2	Lack of facilities of training, skilling and reskilling of workforce	.112	3.65	.562	.730
D3	Lack of real time data sharing and analytics	.588	3.77	.908	.753
D4	Lack of performance measures of resiliency	.445	3.85	.464	.769
D5	Lack of integration of lean, agile and sustainability	.502	3.92	.891	.784
Higher level Factors					
H1	Lack of strategies and Commitment from top management	.382	3.96	.344	.792
H2	Lack of technological infrastructure and facilities	.530	3.92	.628	.784
H3	Lack of agility in the practices	.496	3.88	1.071	.776
H4	Lack of strategies for global & local sourcing, both	.738	3.50	.812	.700
H5	Lack of system reconfigurability for new materials and energy (Green/traditional)	.624	3.81	.939	.761
Unpredictable factors					
U1	Lack of preparedness for uncertainty and unpredictable situation	.386	3.62	.804	.723
U2	Lack of responsiveness in Supply chain	.623	3.46	.989	.692
U3	Lack of Reverse supply chain facilities	.451	4.15	.675	.830

Table 6. Table of finalized criteria

Criteria	Sub-Criteria
Higher level	Lack of strategies and Commitment from top management
	Lack of technological infrastructure and facilities
	Lack of agility in the practices
	Lack of strategies for global & local sourcing, both
	Lack of system reconfigurability for new materials and energy (Green/traditional)

Data oriented	Lack of Collaboration and shared capabilities between SC members
	Lack of real time data sharing and analytics
	Lack of performance measures of resiliency
	Lack of integration of lean, agile and sustainability
Unpredictable	Lack of preparedness for uncertainty and unpredictable situation
	Lack of responsiveness in Supply chain
	Lack of Reverse supply chain facilities

Step 1: Select a group of Critical Failure Factors for the choice.

Based on reliability analysis and EFA, a final set of thirteen sub-criteria and three main criteria are determined in this step.

Step 2: Ascertain which Critical Failure Factors are the best and worst.

Nine professionals with backgrounds in academia and business were interviewed for this step. From the finalized thirteen Critical Failure Factors, the decision maker choose the best or most significant and the worst or least significant.

Step 3: On a scale of nine, rank the critical failure factors that you think are best above all the others.

One by one, the survey participants were interviewed and provided their feedback. where the best Critical Failure Factors are preferred over the j in aBj.

$$A_B = (a_{B1}, a_{B2}, a_{B3}, \ldots, a_{Bj})$$

Step 4: On a scale of 1 to 9, decide which other critical failure factors are more important than the worst ones.

One by one, the survey participants were interviewed and provided their feedback. The preference of j Critical Failure Factors over the worst Critical Failure Factors is represented by ajW. A_w = 〖〖(a〗_1W,a_2W,a_3W,....,a_jW)〗^T will be the value of aWW. All criteria and sub-criteria are compared pairwise while taking the interdependence of the Critical Failure Factors into account. The data from one of the survey participants is shown in the attached tables below, along with the pairwise comparison matrix (Table 7,8,9,10 & 11).

Table 7. Best-to-others (BO) and others-to-worst (OW) pairwise comparisons of main Challenge

Best-Others	Higher level	Data Oriented	Unpredictable
Best Criteria: Data Oriented	9	5	2
Others-Worst	**Worst criteria:** Unpredictability		
Higher level	9		
Data oriented	6		
Unpredictable	1		

Table 8. BO and OW pairwise comparisons of Higher lever sub criteria

Best – Others	**Lack of strategies and Commitment from top management**	**Lack of technological infrastructure and facilities**	**Lack of agility in the practices**	**Lack of strategies for global & local sourcing**	**Lack of system reconfigurability for new materials and energy (Green/traditional)**
Best Criteria: Lack of system reconfigurability for new materials and energy (Green/traditional)	2	4	1	3	9
Others - Worst	Worst criteria: Lack of agility in the practices				
Lack of strategies and Commitment from top management	3				
Lack of technological infrastructure and facilities	3				
Lack of agility in the practices	1				
Lack of strategies for global & local sourcing, both	7				
Lack of system reconfigurability for new materials and energy (Green/traditional)	9				

Table 9. BO and OW pairwise comparisons of Data oriented sub criteria

Best – Others	**Lack of Collaboration and shared capabilities between SC members**	**Lack of real time data sharing and analytics**	**Lack of performance measures of resiliency**	**Lack of integration of lean, agile and sustainability**
Best Criteria: Lack of real time data sharing and analytics	6	9	1	4
Others - Worst			Worst criteria: Lack of performance measures of resiliency	
Lack of Collaboration and shared capabilities between SC members			5	
Lack of real time data sharing and analytics			9	
Lack of performance measures of resiliency			1	
Lack of integration of lean, agile and sustainability			6	

Table 10. BO and OW pairwise comparisons of Unpredictable sub criteria

Best-Others	**Lack of preparedness for uncertainty and unpredictable situation**	**Lack of responsiveness in Supply chain**	**Lack of Reverse supply chain facilities**
Best Criteria: Lack of preparedness for uncertainty and unpredictable situation	**9**	**5**	**1**
Others-Worst		**Worst criteria: Lack of Reverse supply chain facilities**	
Lack of preparedness for uncertainty and unpredictable situation		**9**	
Lack of responsiveness in Supply chain		**5**	
Lack of Reverse supply chain facilities		**1**	

Step5. Calculate the optimal weights $(w_1^*, w_2^*, w_3^*, \ldots, w_n^*)$

The optimal weight for a criterion is the one where, for each pair of wb/wj and wj/ww, we have wb/wj = aBj and wj/ww = ajW. The sum of optimal weights of all criteria should be one which consists of all sets of wb/wj and wj/ww. To get the optimal weights of all the criteria, the maximum absolute difference of all sets of j criteria should be minimized.

$$min\ max_j \left\{ \left| \frac{w_B}{w_j} - a_{Bj} \right|, \left| \frac{w_j}{w_W} - a_{jw} \right| \right\}$$

$$s.t.$$

$$\sum_j w_j = 1$$

$$w_j \geq 0, for\ all\ j$$

The above mentioned maximin problem can be transferred to the following problem:

min ξ, s.t.

$$\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi, for\ all\ j$$

$$\left| \frac{w_j}{w_w} - a_{jw} \right| \leq \xi, for\ all\ j$$

$$\sum_j w_j = 1$$

$$w_j \geq 0, for\ all\ j$$

Solving the above problem, the optimal weights $(w_1^*, w_2^*, w_3^*, \ldots, w_n^*)$ and ξ* are obtained for each criterion and sub-criteria. With the help of consistence index and ξ*, consistence ratio is estimated. The consistence ratio closer to zero denotes strong consistence while closer to one show less consistence (Table 12).

$$\textbf{Consistence ratio} = \frac{\xi^*}{\boldsymbol{consistence\ index}}$$

Table 11. Consistence Index

a_{Bw}	1	2	3	4	5	6	7	8	9
Consistence Index	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Table 12 - Criteria levels and Weights

Main criteria	Weight of main criteria	Sub-criteria	Weight of sub-criteria	Global weight	Rank
Higher level	0.377081	Lack of strategies and Commitment from top management	0.20039	0.07555	7
		Lack of technological infrastructure and facilities	0.3043	0.11425	2
		Lack of agility in the practices	0.14883	0.05554	12
		Lack of strategies for global & local sourcing	0.16029	0.05704	11
		Lack of system reconfigurability for new materials and energy (Green/traditional)	0.18619	0.07471	8
Data oriented	0.285741	Lack of Collaboration and shared capabilities between SC members	0.27196	0.08013	6
		Lack of real time data sharing and analytics	0.19396	0.0575	10
		Lack of performance measures of resiliency	0.29871	0.0804	5
		Lack of integration of lean, agile and sustainability	0.23537	0.06771	9
Unpredictable	0.337178	Lack of preparedness for uncertainty and unpredictable situation	0.36513	0.12785	1
		Lack of responsiveness in Supply chain	0.27657	0.09823	4
		Lack of Reverse supply chain facilities	0.35829	0.11109	3

4. Results and Discussion

The BWM technique offers a structured approach to prioritize the challenges based on their relative importance. By eliciting expert opinions and conducting pairwise comparisons, the BWM method enables researchers to systematically assess the significance of each challenge in influencing sustainable and resilient manufacturing outcomes. The identification of three main criteria—higher-level factors, data-oriented factors, and unpredictable factors—provides a comprehensive framework for understanding the multifaceted nature of challenges faced by manufacturing organizations. Each criterion represents a distinct category of challenges, ranging from organizational capabilities to environmental uncertainties, highlighting the diverse array of factors influencing sustainable and resilient manufacturing practices.

Authors of the current research paper identified thirteen challenges/criteria using an across-the-board literature review and PRISMA approach. The extracted Criteria are farther divided into three main groups such as data-oriented factors, higher level factors and unpredictable factors. The classification of Challenges depends on its field of implementation. Survey response analysis states that two challenges are not creating substantial influence on the implementation of SRM in Indian manufacturing sectors. This is because their corrected item minus total correlation value is less than 0.300. These Criteria are excluded to improve logical coherence and the dependability in results. The logical coherence of finalized responses can be validated through Cronbach's alpha value which comes out to be 0.819, this represents a higher consistency of survey responses. After grouping and analyzing the Criteria, ranking must be done which is also essential because it helps in understanding the importance and effectiveness of challenges and urgency to handle (Table 2-12).

The BWM results depict that 'Lack of preparedness for uncertainty and unpredictable situation (U1)' (Sub Criteria belongs to main Criteria Unpredictable Criteria) has been ranked as 1st in prioritization with a global weight 0.12785. This indicates the lack of preparedness for uncertainty and unpredictable situation in Indian scenario for sustainable and resilient manufacturing (Table 13). 'Lack of technological infrastructure and facilities (H2)' ranked 2nd among the twelve criteria motivates the selection of technologies for the implementation of sustainable and resilient manufacturing. 'Lack of reverse supply chain facilities (U3)' ranked 3rd and signifies the importance of reverse supply chain facilities in the implementation of sustainable and resilient manufacturing. 'Lack of responsiveness in Supply chain (U2)' ranked as 4th important criteria which highlights the importance of coordination and information sharing practices among supply chain members. 'Lack of performance measures of resiliency (D3)' have a critical importance during implementation. Laying down performance standards on resiliency helps in achieving it efficiently. This Criteria is ranked 5th among twelve criteria. 'Lack of collaboration and shared capabilities between SC members (D1)' has been ranked as 6th criteria. It highlights the importance of collaboration among SC members for achieving sustainable and resilient manufacturing. 'Lack of system reconfigurability for new materials and energy (Green/traditional) (H5)' and 'Lack of real time data sharing and analytics (D2)' also bring attention of top management and if worked on may help in implementing sustainable and resilient manufacturing practices. In the age of digitalization, they are ranked as 8th and 10th among twelve Criteria. The above-mentioned criteria come under top level criteria.

'Lack of strategies and Commitment from top management (H1)' ranked 7th among all, highlights the importance of policies and strategies from management. 'Lack of integration of lean, agile and sustainability (D4)' has been ranked 9th and signifies the lean and agile manufacturing practices toward resiliency. 'Lack of strategies for global and local sourcing (H4)' and 'Lack of agility in the practices (H3)' focus on the mix sourcing strategies of the organizations to improve resiliency. These criteria are ranked 11th and 12th among all.

Findings of current study are practically relevant for manufacturing sector and justified by literature. European commission have considered the need of resiliency and sustainability in manufacturing practices[49)]. Training, Skilling and reskilling of workforce are key issues in technological upgradation[50)]. Real time data sharing, security of data and technology adoptability are major challenges in resilience, sustainability and human-centricity adoption[51)]. Lack of performance benchmarks on green practices, weak legislation and poor implementation and high initial investment on sustainable practices are the key challenges[52)]. Lack of technical skills, non-availability of performance measures, old infrastructure and lack of funds are major challenges in digitalization in context of sustainability and operational excellence[53)].

5. Conclusion, Implications and future research directions

In the digital era, manufacturing that is resilient and sustainable has become essential for tackling environmental issues, improving operational efficiency and fostering economic growth. Sustainable and resilient manufacturing requires collective action and collaboration among policymakers, industry stakeholders, and researchers. By cross-sector collaboration, and promoting supportive policies and initiatives, stakeholders can drive innovation, promote sustainability, and build resilience in manufacturing operations. Despite these achievements, significant challenges remain in the path to sustainable and resilient manufacturing. Cost constraints, regulatory challenges, technological limitations and supply chain complexity continue to hinder progress and limit the scale of adoption. To address these challenges, concerted efforts and collaboration among stakeholders across sectors is required.

At the same time, there are opportunities to capitalize on emerging trends and technologies to further advance sustainable and resilient manufacturing. Digitalization offers transformative opportunities to overcome challenges and drive sustainability and resilience through predictive maintenance, supply chain transparency, data-driven decision-making and collaborative innovation.

The insights derived from the analysis offer valuable guidance for practitioners seeking to enhance sustainable and resilient manufacturing practices. Organizations can leverage the identified challenges to prioritize investment decisions, allocate resources effectively, and develop targeted interventions aimed at improving operational resilience and environmental sustainability. Strategies such as enhancing collaboration, investing in advanced analytics, promoting agile manufacturing practices, and developing a sustainable culture can help businesses become more resilient and competitive over the long run while enabling them to manage the challenges of the digital era.

Although this study offers insightful information, there are a few directions that should be investigated in further research. Studies that follow the development of resilient and sustainable manufacturing techniques over time may be able to shed light on how environmental laws and digitization will affect the dynamics of the industry in the long run. Furthermore, investigations into the effectiveness of emerging technologies, policy interventions, and industry collaborations in promoting sustainable manufacturing practices can offer valuable insights into future trends and developments in the field.

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