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To Identify and Prioritize Challenges in Integrating Industry 4.0 Technologies for Sustainable Supply Chain Management

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Abstract:

The integration of Industry 4.0 technologies into supply chain management presents significant opportunities for achieving sustainability while addressing various challenges. This research aims to identify and prioritize these challenges to provide a strategic roadmap for effective implementation. By leveraging technologies such as the Internet of Things (IoT), artificial intelligence (AI), blockchain, and big data analytics, supply chains can achieve enhanced efficiency, transparency, and resilience. This study employs the Analytic Hierarchy Process (AHP) methodology to systematically evaluate these challenges and determine their relative importance. Through comprehensive stakeholder surveys and expert input, the research highlights key challenges such as regulatory frameworks, collaborative ecosystems, and technological innovation. The findings contribute actionable insights for organizations aiming to balance economic growth with environmental stewardship, making Industry 4.0 a cornerstone for sustainable supply chain transformation.

Keywords: Industry 4.0; Sustainability; Supply chain management; AHP

1. Introduction

The Fourth Industrial Revolution, or Industry 4.0, has been brought about by the quick development of digital technologies. The industrial environment is changing as a result of this paradigm change and the introduction of revolutionary technologies like the Internet of Things (IoT), Blockchain, Artificial Intelligence (AI), Big Data Analytics, and Cyber-Physical Systems (CPS). These technologies have the potential to improve decision-making, promote sustainability, and drive operational excellence in the context of supply chain management. Notwithstanding these assurances, incorporating Industry 4.0 technology into frameworks for sustainable supply chain management (SSCM) is rife with difficulties that call for methodical research and priority. Growing regulatory requirements, consumer awareness, and global sustainability goals like the Sustainable Development Goals (SDGs) of the UN have made sustainability a crucial area of concern for supply chain management. Sustainable business methods now rely heavily on the triple bottom line, which includes social, environmental, and economic aspects. Achieving these sustainability goals depends heavily on Industry 4.0 technologies, which may facilitate data-driven insights, increase supply chain transparency, and optimize resource efficiency. For example, real-time emissions data can be tracked by IoT-enabled sensors, while supply chain accountability and traceability are guaranteed by blockchain. The effective integration of these technologies is not without challenges, though.

A key challenges to adoption is the economic challenge associated with high implementation costs, particularly for small and medium enterprises (SMEs). These organizations often struggle with the financial and technical resources required for digital transformation. Additionally, technological barriers such as inadequate digital infrastructure, interoperability issues, and cybersecurity risks further complicate the integration process. Organizational challenges, including resistance to change, lack of skilled personnel, and misalignment of business processes, also play a significant role in hindering progress. Finally, external factors such as inconsistent regulatory frameworks, lack of stakeholder collaboration, and evolving consumer expectations exacerbate the complexity of adopting Industry 4.0 technologies for sustainable supply chain management.

The integration of Industry 4.0 technologies into supply chain management also necessitates a shift in perspective, moving beyond traditional efficiency-driven models to incorporate long-term sustainability considerations.

The present study employs a methodology that aims to achieve the following research objectives:

(i) To identify and prioritize challenges in integrating Industry 4.0 technologies for sustainable supply chain management

(ii) To propose a ranking model of identified main challenges in integrating Industry 4.0 technologies using the MCDM approach

2. Literature Review

Industry 4.0, often known as the Fourth Industrial Revolution, is a new paradigm for industrial production. It represents a significant shift from traditional manufacturing processes to a digitally integrated and highly automated production environment (Akdil et al., 2018). The phrase "Industry 4.0" was originally used in Germany as part of a national effort to boost the competitiveness of the manufacturing industry. This revolutionary paradigm promises a widespread application of cyber-physical systems, advanced robots, artificial intelligence (AI), high-tech sensors, cloud computing, the Internet of Things (IoT), big data analytics, and additive manufacturing (Burke et al., 2017; Cheng et al., 2016). The integration of these technologies serves as the foundation for what is known as the "smart factory," in which equipment and systems are networked and communicate with one another in order to optimize production processes (Erol et al., 2016; Felch et al., 2019). The deployment of Industry 4.0 technology offers significant productivity benefits by allowing for real-time data collection and analysis, resulting in more flexible and efficient manufacturing processes. The capacity to monitor and optimize production in real-time leads to decreasing error rates, downtime, and operating expenses (Hizam-Hanafiah et al., 2020). Furthermore, Industry 4.0 offers unprecedented flexibility, allowing enterprises to respond swiftly to issues and opportunities, increasing their competitiveness in the global market (Nasiri et al., 2020; Santos et al., 2017).

Despite Industry 4.0's bright promises, adoption is typically limited, particularly among small and medium-sized businesses (SMEs). Traditional SMEs may not have the financial resources, technical competence, or infrastructure needed to implement sophisticated digital technologies. The introduction of Industry 4.0 opens up new potential for accomplishing sustainability goals inside supply chains (Fettig et al., 2018). Businesses that use sophisticated technology can improve their environmental performance, increase resource efficiency, and reduce waste (Sarvari et al., 2018). In India, the Micro, Small, and Medium Enterprises (MSME) sector has grown as a dynamic and active segment of the economy (Frank et al., 2019).

Industry 4.0 has revolutionized traditional manufacturing and supply chain operations by using modern digital technologies. These technologies include the Internet of Things (IoT), Cyber-Physical Systems (CPS), big data analytics, cloud computing, artificial intelligence (AI), and robotics. The combination of these technologies has resulted in the creation of smart factories and improved supply chain procedures, generally known as Supply Chain 4.0 (Brettel et al., 2014).

One of the most significant benefits of Industry 4.0 is resource optimization. Manufacturers can improve their efficiency and sustainability by reducing unnecessary setup periods and optimizing manufacturing processes (Bassi, 2017). This optimization is critical in a society where resources are becoming scarcer and there is a greater emphasis on sustainable practices. Furthermore, there is frequently reluctance to change due to the perceived dangers and uncertainties connected with shifting to a new manufacturing model (Hastings et al., 2021). To overcome these hurdles, SMEs must get focused support and initiatives to help them adopt Industry 4.0 technology into their operations. For developing economies, Industry 4.0 provides a unique chance to overcome traditional barriers to industrialization. These countries may improve productivity, quality, and innovation by implementing digital and automation technologies instead of relying on vast legacy infrastructure. This potential for rapid improvement can boost economic growth, create high-quality jobs, and raise living standards.

3. Research Methodology

This research aims to provide a comprehensive understanding of the intricate challenges associated with integrating Industry 4.0 technologies and their impact on achieving sustainable supply chain management. To achieve this, the study employs AHP as its primary research methodology, offering a structured framework for evaluating and prioritizing these challenges. AHP, a powerful and flexible MCDM tool, integrates both qualitative and quantitative techniques to assess and rank various challenges, ultimately contributing to the development of sustainable supply chain practices. This approach helps individuals set objectives and reach optimal decisions through AHP's structured, multilevel breakdown of complex problems into transitional levels of a hierarchical system (Saaty, 1980). The phases of the AHP process in this study reflect a detailed approach to breaking down the multilevel decision-making problem, ensuring systematic evaluation and prioritization of challenges for effectively integrating Industry 4.0 technologies into sustainable supply chain management. As a result, the AHP approach involved the following phases:

Step 1: Create an assessment environment that fit the purpose.
Step 2: Create a hierarchical AHP framework.
Step 3: Compile empirical data based on expert consensus.
Step 4: Create a PWCM (pair-wise comparisons matrix) using Saaty's 1-9 range.
Step 5: Using following formula, normalize the PWCM column.

$$r_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$$

Finally, the priority weight for each HR practice was calculated as follows:

$$W_j = \frac{1}{n} \times \sum_{i=1}^{n} a_{ij}$$

In this case, n signifies the number of components, while 'a' denotes the cell value assigned in PWCM.

Step-6: Check the consistency of the derived combination of values.

4. $$CI = \frac{\lambda_{max} - n}{(n-1)}$$

The consistency index is CI, the highest value of the eigen-values is λ_{max}, and the number of components is n.

Step-7: Calculate the Consistency Ratio (CR).

$$CR = \frac{CI}{RCI}$$

Random Consistency Index (RCI) (adopted from Saaty 1985).

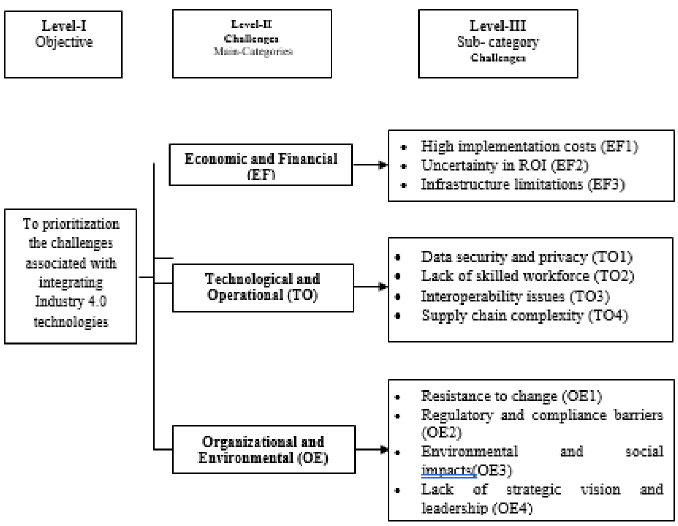
n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Where n: number of components

Generally, if CR = < 10% (0.1) reliable & satisfactory; > 10% (0.1) not in agreement & change

4. Results and Discussion

Using the recommendations of experts, a hierarchical structure between the challenges in integrating Industry 4.0 technologies for sustainable supply chain management has been built with this goal in mind. As seen in Figure 1, there are three levels in the hierarchy composition, with Level 1 denoting the fundamental goal of this AHP technique, Level 2 representing the main categories (Economic and Financial, Technological and Operational, and Organizational and Environmental) Challenges, and Level 3 comprising the specific challenges within each category.



The pair-wise (PW) ratings of challenges are assigned using a scale ranging from 1 to 9, reflecting varying levels of preference. This method facilitates the transformation of qualitative judgments into quantitative values, as proposed by Saaty (1988). Table 1 illustrates this scale, where a rating of 1 denotes equal importance, while a rating of 9 signifies extreme importance.

Table 1: Pair-wise Comparison Scale

Level of Preference	Interpretation
1	Equal importance
3	Moderate importance
5	Significant importance
7	Very strong importance
9	Extremely high importance
2, 4, 6, 8	Intermediate levels between adjacent values

Each corresponding challenge within a subcategory is evaluated using a pair-wise comparison matrix (PWCM) designed for the main categories. This matrix is utilized to prioritize factors contributing to the effective integration of Industry 4.0 technologies in achieving sustainable supply chain management. Table 2 presents the PWCM for the main categories.

Table 2: PWC matrix for the Challenges associated with Industry 4.0 in Major-Categories

S.N.	Challenges associated with integrating Industry 4.0 technologies	EF	TO	OE
1.	Economic and Financial (EF)	1	1	4
2.	Technological and Operational (TO)	1	1	2
3.	Organizational and Environmental (OE)	0.25	0.5	1
	Sum	2.25	2.5	7

According to the data presented in Table 3, the category of **Economic and Financial (EF)** challenges emerges as the most influential factor in integrating Industry 4.0 technologies, with a priority value (PV) of 0.472. This indicates that addressing financial barriers and economic concerns is critical to the successful adoption of these technologies. It is followed by **Technological and Operational (TO)** challenges, which hold a PV of 0.377, signifying that issues such as interoperability, data security, and technical expertise are also significant considerations. The next category, **Organizational and Environmental (OE)** challenges, has a PV of 0.151, making it the least significant in comparison to EF and TO. While OE challenges, such as resistance to change and regulatory barriers, are important, their relative influence is lower in the hierarchy of challenges associated with Industry 4.0 integration. These priority values highlight the varying levels of importance among the three categories, providing a clear focus for organizations to allocate resources effectively and prioritize solutions for sustainable supply chain transformation.

Table 3: Normalized matrix with PV of the Challenges associated with Industry 4.0 in Major-Categories

S.N.	Challenges associated with integrating Industry 4.0 technologies	EF	TO	OE	Sum	Priority Weights (W)
1.	Economic and Financial (EF)	0.444	0.400	0.571	1.416	0.472
2.	Technological and Operational (TO)	0.444	0.400	0.286	1.130	0.377
3.	Organizational and Environmental (OE)	0.111	0.200	0.143	0.454	0.151

In the next phase, it is essential to evaluate the consistency of the paired comparisons obtained during the assessment process. Since experts may occasionally provide evaluations that lack consistency, the Eigen vector weights are calculated to determine the relative importance of various factors. Additionally, a consistency index is computed to assess both transitive and numerical consistency in the judgments. These measures help identify any inconsistencies and allow for the refinement of the ranking process. By recalibrating and reassessing the initial evaluation data, the reliability of the evaluation scale can be enhanced. The formula is applied to calculate the relative weights (δ), ensuring that the assessment of challenges and opportunities in integrating Industry 4.0 technologies remains consistent and dependable. This approach facilitates well-informed decision-making and supports the effective implementation of sustainable supply chain management strategies.

Furthermore, comparative values (δ) are assessed using the following formula: $A \times W_j = \delta$,

$$\begin{vmatrix} 1 & 1 & 4 \\ 1 & 1 & 2 \\ 0.25 & 0.5 & 1 \end{vmatrix} \; X \; \begin{vmatrix} 0.472 \\ 0.377 \\ 0.151 \end{vmatrix} = \begin{vmatrix} 1.454 \\ 1.151 \\ 0.458 \end{vmatrix}$$

A= PWC matrix; where j = 1, 2,…n

The Eigen vector ‘λ’:

$$\lambda = \frac{ithenteryinrelativeweight\ (\delta)}{ithentryinpriorityweight}$$

Eigenvalue maximum, $\lambda_{max} = 3.18$,

Likewise, Table 4-6, shows the PWC matrix for sub-category industry 4.0 challenges.

Table 4: PWC matrix Economic and Financial (EF) industry 4.0 challenge

S.N.	Sub-category Economic and Financial (EF) industry 4.0 challenge	EF1	EF2	EF3
1.	High implementation costs (EF1)	1	3	5
2.	Uncertainty in ROI (EF2)	0.33	1	3
3.	Infrastructure limitations (EF3)	0.20	0.333	1
	SUM	1.53	4.33	9.00

Table 5: PWC matrix (Technological and Operational (TO))

S.N.	Sub-category Technological and Operational (TO)	TO1	TO2	TO3	TO4
1.	Data security and privacy (TO1)	1	3	5	7
2.	Lack of skilled workforce (TO2)	0.333	1	2	2
3.	Interoperability issues (TO3)	0.2	0.5	1	3
4.	Supply chain complexity (TO4)	0.14	0.50	0.33	1
	SUM	1.68	5.00	8.33	13

Table 6: PWC matrix (Organizational and Environmental (OE))

S.N.	Sub-category Organizational and Environmental (OE)	OE1	OE2	OE3	OE4
1.	Resistance to change (OE1)	1	1	1	3
2.	Regulatory and compliance barriers (OE2)	1.00	1	2	7
3.	Environmental and social impacts(OE3)	1.00	0.5	1	3
4.	Lack of strategic vision and leadership (OE4)	0.333	0.14	0.33	1
	SUM	3.33	2.64	4.33	14

Table 7 outlines the priority values of sub-categories under the Economic and Financial (EF) challenges associated with Industry 4.0 integration. **High Implementation Costs (EF1)** is identified as the most critical challenge, with a priority weight of **0.633**, highlighting the significant financial barrier to adopting Industry 4.0 technologies. This is followed by **Uncertainty in ROI (EF2)**, which holds a weight of **0.260**, reflecting the reluctance of organizations to invest without clear returns. **Infrastructure Limitations (EF3)**, with the lowest weight of **0.106**, is less impactful but still a consideration, particularly in developing regions. The distribution of these priority weights emphasizes the need to focus on addressing high implementation costs and ROI uncertainty, while also improving infrastructure to facilitate successful adoption and sustainable integration of Industry 4.0 technologies.

Table 7 Normalized Matrix Economic and Financial (EF) industry 4.0 challenge

S.N.	Sub-category Economic and Financial (EF) industry 4.0 challenge	EF1	EF2	EF3	SUM	Priority weights
1.	High implementation costs (EF1)	0.652	0.692	0.556	1.900	0.633
2.	Uncertainty in ROI (EF2)	0.217	0.231	0.333	0.781	0.260
3.	Infrastructure limitations (EF3)	0.130	0.077	0.111	0.318	0.106

Table 8 provides the normalized matrix for Technological and Operational (TO) challenges, highlighting the priority weights (PVs) of each sub-category to reflect their relative significance in integrating Industry 4.0 technologies. Among the challenges, Data Security and Privacy (TO1) emerges as the most critical, with a PV of 0.584, emphasizing its paramount importance in ensuring the secure handling of data and maintaining trust in technological systems. Lack of Skilled Workforce (TO2) follows with a PV of 0.198, underscoring the challenge of insufficient expertise required for the adoption and maintenance of advanced Industry 4.0 technologies. Interoperability Issues (TO3), with a PV of 0.143, rank third, indicating that while the seamless integration of diverse systems and technologies is important, it poses a relatively lower challenge compared to data security and workforce availability. Finally, Supply Chain Complexity (TO4) has the lowest PV of 0.076, signifying that although managing complex supply chains is a consideration, its relative influence is minimal within the TO category.

Table 8 Normalized Matrix (Technological and Operational (TO))

S.N.	Sub-category Technological and Operational (TO)	TO1	TO2	TO3	TO4	SUM	Priority weights
1.	Data security and privacy (TO1)	0.597	0.600	0.600	0.538	2.335	0.584
2.	Lack of skilled	0.199	0.200	0.240	0.154	0.793	0.198

	workforce (TO2)						
3.	Interoperability issues (TO3)	0.119	0.100	0.120	0.231	0.570	0.143
4.	Supply chain complexity (TO4)	0.085	0.100	0.040	0.077	0.302	0.076

Table 9 presents the normalized matrix for Organizational and Environmental (OE) challenges, highlighting the priority weights (PVs) assigned to each sub-category, which reflect their relative importance in the context of integrating Industry 4.0 technologies. Among the challenges, Regulatory and Compliance Barriers (OE2) holds the highest priority with a PV of 0.410, underscoring the significant role of legal and compliance requirements in influencing the adoption of advanced technologies. This highlights the need for organizations to navigate regulatory frameworks effectively to ensure successful implementation. Resistance to Change (OE1) ranks second, with a PV of 0.281, indicating the considerable impact of organizational culture and employee reluctance on adopting new systems and processes. Addressing this challenge is vital for smooth transitions during technology integration.

Environmental and Social Impacts (OE3) comes in third with a PV of 0.234, emphasizing the importance of considering sustainability and societal effects during technological adoption. While significant, these impacts are less influential compared to regulatory and cultural challenges. Finally, Lack of Strategic Vision and Leadership (OE4) has the lowest priority weight of 0.076, suggesting that while leadership is essential, it is perceived as a less immediate barrier compared to compliance, cultural resistance, and environmental considerations.

Table 9 Normalized Matrix (Organizational and Environmental (OE))

S.N.	Sub-category Organizational and Environmental (OE)	OE1	OE2	OE3	OE4	SUM	Priority weights
1.	Resistance to change (OE1)	0.300	0.378	0.231	0.214	1.123	0.281
2.	Regulatory and compliance barriers (OE2)	0.300	0.378	0.462	0.500	1.640	0.410
3.	Environmental and social impacts(OE3)	0.300	0.189	0.231	0.214	0.934	0.234
4.	Lack of strategic vision and leadership (OE4)	0.100	0.054	0.077	0.071	0.302	0.076

The results show that the biggest obstacles facing firms are those related to regulations and compliance. This calls for a proactive approach to comprehending and negotiating intricate legal systems. Implementation delays and related expenses can be decreased by streamlining compliance procedures through cooperative efforts with industry associations and regulatory agencies. An internal organizational challenge, resistance to change calls for focused interventions such effective change management plans, staff training initiatives, and open communication regarding the advantages of Industry 4.0 technologies. This resistance can be lessened and more seamless transitions can be encouraged by fostering a culture of flexibility and ongoing learning. Environmental and social effects cannot be disregarded, even though they are thought to be less important than cultural and regulatory issues. Adoption of Industry 4.0 presents a chance to complement global environmental objectives. To improve their long-term profitability and market reputation, businesses should include socially conscious and environmentally friendly activities into their operational models. Although crucial, leadership shortages are not as immediate a barrier as compliance or cultural difficulties, as seen by the comparatively low priority given to leadership and strategic vision. Long-term success and resilience in the face of rapid technical improvements, however, still depend on developing strong leadership with a clear strategic vision.

5. Conclusion

The allocation of priority weights demonstrates the complexity of the organizational and environmental issues surrounding Industry 4.0 integration. Organizations seeking to speed their use of technology should prioritize addressing regulatory obstacles and opposition to change. A balanced strategy will be created by combining environmental measures and developing strategic leadership at the same time, guaranteeing the successful and long-term integration of Industry 4.0 technology. This all-encompassing viewpoint gives decision-makers a road map for allocating funds and creating policies that address the most urgent issues while being ready for the future.

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