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Leveraging Industry 4.0 Technologies for Sustainable Supply Chain Management: An ISM-Based Analysis of Opportunities

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Abstract : The integration of Industry 4.0 technologies offers transformative opportunities to enhance the sustainability of supply chain management. This study explores the opportunities in integrating Industry 4.0 technologies for sustainable supply chain management using the Interpretive Structural Modeling (ISM) approach. Key opportunities include improved efficiency through automation, enhanced transparency with block-chain, reduced environmental impact via optimized logistics, and better decision-making supported by AI. Industry 4.0 technologies also foster collaboration, adaptability, cost savings, and innovation. By structuring these opportunities hierarchically, the study provides actionable insights for leveraging digital transformation to achieve both economic and environmental sustainability in supply chains.

***IndexTerms* - Industry 4.0, Interpretive Structural Modeling (ISM), SSCM**

1. INTRODUCTION

A radical change in the industrial landscape has been sparked by the arrival of the Fourth Industrial Revolution, or Industry 4.0. By increasing operational efficiencies, facilitating better decision-making, and promoting sustainability, emerging digital technologies like the Internet of Things (IoT), Blockchain, Artificial Intelligence (AI), Big Data Analytics, and Cyber-Physical Systems (CPS) are transforming conventional supply chain management (SCM) frameworks. These developments have great potential for Sustainable Supply Chain Management (SSCM), a strategy that combines social, environmental, and economic factors also referred to as the triple bottom line to guarantee long-term company sustainability. The smooth integration of Industry 4.0 technologies into SSCM is still difficult, nevertheless, because of organizational, technological, regulatory, and financial limitations, even with their potential advantages.

Due to global commitments like the Sustainable Development Goals (SDGs) of the United Nations, growing regulatory obligations, and increased consumer awareness, sustainability has become crucial in supply chain operations. There are several chances to improve supply chain sustainability with Industry 4.0 technologies. For example, blockchain can improve supply chain accountability and transparency, IoT-enabled sensors can monitor emissions data in real-time, and AI-driven analytics can maximize resource use. However, there are many difficulties in putting these technologies into practice. Significant financial obstacles are presented by high investment expenditures, especially for small and medium-sized businesses (SMEs), which do not have the financial and technical resources needed for digital transformation. The adoption process is made more difficult by technological obstacles such insufficient digital infrastructure, interoperability problems, and cybersecurity risks. Integration issues are often exacerbated by organizational reluctance to change, a shortage of qualified staff, and misaligned business processes. Adopting Industry 4.0 technology for SSCM is made more difficult by external reasons such as uneven regulatory frameworks, changing consumer expectations, and a lack of stakeholder participation.

To identifying the relationship between these opportunities, a systematic approach is necessary to identify, to the adoption of Industry 4.0 technologies in sustainable supply chains. This study employs the Interpretive Structural Modeling (ISM) methodology to analyze the interrelationships among these challenges and establish a hierarchical ranking model based on the Multi-Criteria Decision-Making (MCDM) approach. Additionally, ISM will be applied to explore the relationships between opportunities in SSCM enabled by Industry 4.0 innovations. By examining these opportunities, the study aims to highlight how digital transformation can drive sustainability, improve supply chain resilience, and enhance overall efficiency.
The research aims to achieve the following objectives:
(i) To identify the opportunities in SSCM enabled by Industry 4.0 innovations.
(ii) To apply ISM for identifying the relationship between opportunities in sustainable supply chain management enabled by Industry 4.0 innovations.

By providing a structured framework for understanding the complexities of digital transformation in SSCM, this study contributes to both academic research and practical applications in sustainable industrial operations. The findings aim to guide policymakers, business leaders, and supply chain professionals in devising effective strategies for overcoming barriers and leveraging Industry 4.0 technologies for a more resilient and sustainable supply chain ecosystem.

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 decreased 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).

Beyond productivity improvements, Industry 4.0 presents a range of opportunities for businesses to enhance their sustainability efforts and supply chain resilience. The adoption of digital and automation technologies enables companies to optimize energy consumption, minimize waste, and improve resource efficiency, which contributes to achieving global sustainability goals (Fettig et al., 2018). Advanced analytics and predictive maintenance can reduce equipment failures and extend machinery lifespan, leading to cost savings and environmental benefits (Sarvari et al., 2018). Additionally, real-time tracking and monitoring capabilities powered by IoT and blockchain technology enhance supply chain transparency and accountability, fostering ethical sourcing and responsible production practices (Frank et al., 2019).

In India, the Micro, Small, and Medium Enterprises (MSME) sector has emerged as a dynamic and vital segment of the economy, with Industry 4.0 offering significant opportunities for these businesses to scale their operations and improve efficiency. The transition to smart factories and digital supply chains—commonly known as Supply Chain 4.0—enables businesses to enhance collaboration, reduce lead times, and respond more effectively to market demands (Brettel et al., 2014). Moreover, integrating AI-driven decision-making tools allows firms to anticipate disruptions, mitigate risks, and optimize logistics, thereby creating more resilient and adaptive supply networks (Bassi, 2017).

One of the most promising aspects of Industry 4.0 is its potential to drive inclusive economic growth. For developing economies, digital transformation provides an opportunity to leapfrog traditional barriers to industrialization. By adopting advanced manufacturing technologies, these nations can improve productivity, foster innovation, and create high-quality jobs, ultimately raising living standards and strengthening global competitiveness (Hastings et al., 2021). Additionally, automation and AI-powered quality control mechanisms contribute to higher product consistency and reduced defect rates, leading to enhanced customer satisfaction and market expansion.

Despite some initial reluctance to change, organizations that embrace Industry 4.0 innovations stand to gain substantial competitive advantages. The ability to harness real-time data, automate complex processes, and improve sustainability practices positions businesses for long-term success in an increasingly digital and environmentally conscious world. To maximize these opportunities, targeted policies and industry collaborations must support the seamless integration of Industry 4.0 technologies, ensuring that businesses of all sizes can reap the benefits of this transformative industrial revolution.

3. RESEARCH METHODOLOGY

Step 1: Finding Opportunities: After a thorough assessment of the literature, expert consultations, and brainstorming sessions, eight opportunities were found. These prospects show how Industry 4.0 technologies can improve SSCM (sustainable supply chain management).

Step 2: Building Connections Between Opportunities: Once the opportunities have been identified, a comparative analysis is carried out to ascertain how they relate to one another. This stage aids in comprehending how, within the SSCM framework, one chance affects another.

Step 3: Structural Self-Interaction Matrix (SSIM) development: A Structural Self-Interaction Matrix (SSIM) is created using the correlations found in Step 2. Using certain symbols that indicate the direction of influence, the SSIM illustrates the contextual linkages between the opportunities.

Step 4: Create a matrix of reachability: After that, binary values (0s and 1s) are used to replace the symbols in the SSIM to create a reachability matrix (RM). The associations are standardized for additional analysis by this transformation.

Step 5: Verify Transitivity: Transitivity, which holds that if an opportunity "A" influences "B" and "B" influences "C," then "A" should likewise influence "C," is investigated in the reachability matrix. The matrix includes any transitive linkages that are missing.

Step 6: Level Partitioning: Next, the reachability matrix that has been transitivity-checked is divided into various hierarchical levels. Within the SSCM paradigm, this stage aids in classifying opportunities according to their relative significance and impact.

Step 7: Conical Matrix and Initial Digraph Formation: The pieces are rearranged based on their levels to create a conical matrix. An initial directed graph (digraph) is created using this data, and for clarity, indirect linkages are eliminated.

Step 8: The ISM Model's Development: The ISM model, which graphically depicts the hierarchical structure of opportunities and their interdependencies, is then created from the revised digraph.

Step 9: Validation and Improvement of the Model: The ISM model is lastly examined to make sure it makes sense. Any theoretical discrepancies are found, and the appropriate adjustments are made to improve the model's validity and robustness.

4. RESULTS AND DISCUSSION

a) After identifying all **8 opportunities** and analyzing their interrelationships based on expert feedback, a Structural Self-Interaction Matrix (SSIM) is constructed (Ravi et al., 2005). These opportunities are crucial in leveraging Industry 4.0 technologies for Sustainable Supply Chain Management (SSCM). To represent the nature of influence between any two **opportunities** (i and j), four distinct symbols are utilized, as recommended by Warfield (1974), Mandal and Deshmukh (1994), Thakkar et al. (2007), Gupta et al. (2013), and Sahney (2008):

- 'V' – Opportunity i has a direct influence on Opportunity j.
- 'A' – Opportunity j influences Opportunity i instead.
- 'X' – A bidirectional relationship exists where Opportunities i and j influence each other.
- 'O' – No direct relationship exists between Opportunities i and j.

Table 1. Structural Self Interaction Matrix (SSIM)

S.No.	Opportunities	8	7	6	5	4	3	2	1
1	Enhanced Efficiency and Productivity	-	V	A	X	O	V	A	X
2	Improved Transparency and Traceability		-	X	V	A	O	V	X
3	Reduced Environmental Impact			-	O	X	A	V	V
4	Better Decision-Making				-	V	O	X	A
5	Customized and Responsive Supply Chains					-	V	A	O
6	Enhanced Collaboration and Communication						-	X	V
7	Cost Savings							-	V
8	Innovation and Competitive Advantage								-

Now, the Reachability Matrix (RM) is derived from the SSIM by converting its symbolic representations into binary values (0s and 1s). The transformation follows a set of predefined rules:

- If an entry (i, j) in the SSIM contains 'V', then (i, j) = 1 and (j, i) = 0, indicating that enabler i influences enabler j but not vice versa.
- If an entry (i, j) contains 'A', then (i, j) = 0 and (j, i) = 1, meaning that enabler j influences enabler i instead.
- If an entry (i, j) contains 'X', then both (i, j) = 1 and (j, i) = 1, signifying a mutual influence between enablers i and j.
- If an entry (i, j) contains 'O', then both (i, j) = 0 and (j, i) = 0, implying no direct relationship between the enablers.

Table 2. Reachability Matrix

S.No.	Opportunities	1	2	3	4	5	6	7	8	Driving Power
1	Enhanced Efficiency and Productivity	1	1	0	1	0	1	0	1	**5**
2	Improved Transparency and Traceability	0	1	1	1	0	0	1	1	**5**
3	Reduced Environmental Impact	0	0	1	0	1	0	1	1	**4**
4	Better Decision-Making	0	0	0	1	1	0	1	0	**3**
5	Customized and Responsive Supply Chains	0	0	0	0	1	1	0	0	**2**
6	Enhanced Collaboration and Communication	0	0	0	0	0	1	1	1	**3**
7	Cost Savings	0	0	0	0	0	0	1	1	**2**
8	Innovation and Competitive Advantage	0	0	0	0	0	0	0	1	**1**
	Dependence	**1**	**2**	**2**	**3**	**3**	**3**	**5**	**6**	

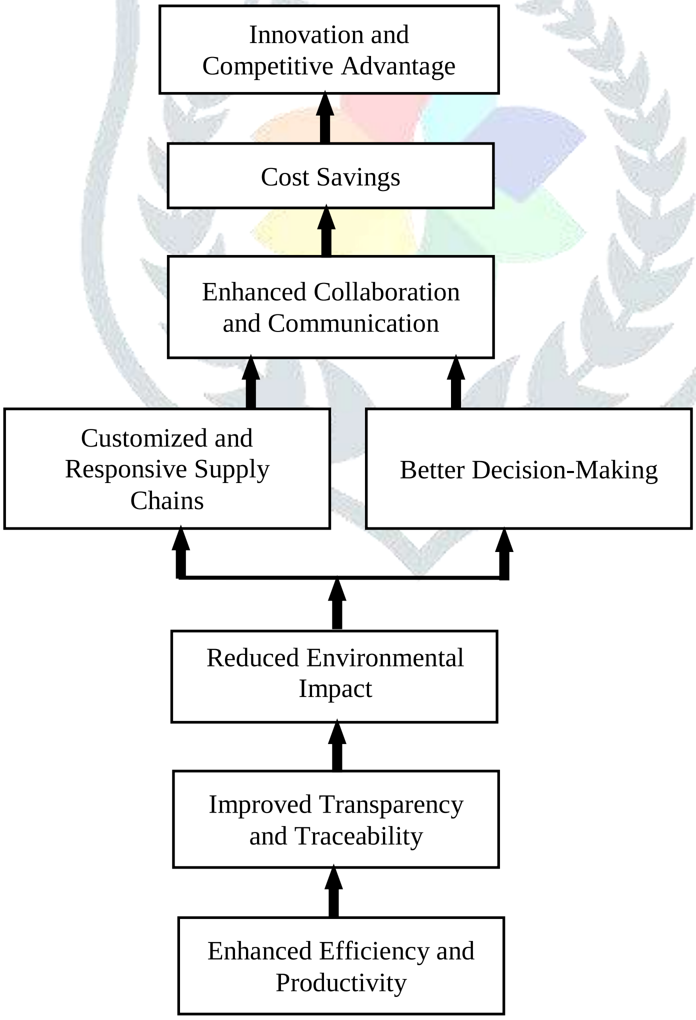
After this, the reachability matrix is examined for transitivity, ensuring that if an opportunity 'A' influences 'B' and 'B' influences 'C', then 'A' should also influence 'C'. Any missing transitive links are incorporated. The transitivity-checked reachability matrix is then partitioned into different hierarchical levels. This helps in categorizing opportunities based on their relative importance and influence within the SSCM framework.

Table 3. Level of Opportunities

Level	Opportunities
I	8
II	7
III	6
IV	5, 4
V	3
VI	2
VII	1

After the formulation of level, a conical matrix is formulated by reordering the elements according to their levels. Using this information, an initial directed graph (digraph) is constructed, and indirect relationships are removed for clarity. The refined digraph is then converted into the ISM model, which visually represents the hierarchical structure of opportunities and their interdependencies.

Figure 1. Final ISM diagram



The study's conclusions demonstrate how important Industry 4.0 technologies are to promoting sustainable supply chain management (SSCM). The study illustrates the interconnectedness among important enablers in SSCM by establishing a hierarchical structure of opportunities using the Interpretive Structural Modeling (ISM) approach. Innovation and Competitive Advantage (Opportunity 8) is the highest-level factor in the hierarchy, according to the ISM-based model, indicating its reliance on other fundamental opportunities. Enhanced Efficiency and Productivity (Opportunity 1), on the other hand, is ranked lowest, suggesting that it is the primary force behind SSCM's adoption of Industry 4.0.The reachability matrix and level partitioning technique yield several important insights:

- Level VII, Efficiency and Productivity, serves as the foundation and influences a variety of prospects.
- Decision-making, environmental impact, and transparency serve as intermediaries between higher-level strategic advantages and operational enhancements.
- At the highest levels, cost savings and innovation are evident, underscoring their dependence on earlier developments.

These hierarchical dependencies highlight the need for a systematic and staged adoption of Industry 4.0 technologies, guaranteeing that the fundamentals are in place before more advanced prospects can be fully realized.

5. CONCLUSION

Industry 4.0 technology integration in sustainable supply chain management presents several chances to improve productivity, lessen environmental effect, and promote teamwork. However, to overcome current organizational, technological, and financial obstacles, its successful implementation necessitates a planned, strategic strategy.

This report offers a systematic ranking of these opportunities using the ISM framework, which helps supply chain experts, company executives, and legislators prioritize important areas for implementation and investment. The results emphasize the necessity of:

- Gradual adoption, making sure that core technologies (like automation and the Internet of Things) are established before moving on to more complex applications (like blockchain transparency and AI-driven decision-making).
- Cooperation between various stakeholders, such as governments, businesses, and digital companies, to simplify regulatory frameworks and offer financial and technical assistance, especially to SMEs.
- Constant innovation and adaptation, making use of Industry 4.0 developments to stay resilient and competitive in the changing global supply chain environment.

Future studies should concentrate on investigating sophisticated Multi-Criteria Decision-Making (MCDM) techniques to improve prioritization strategies and testing the suggested ISM model through real case studies. By providing a roadmap for utilizing Industry 4.0 for sustainability and operational excellence, the study advances both academic and industrial understanding of digital revolution in supply chain management.

REFERENCES

Akdil, K.Y., Ustundag, A. and Cevikcan, E. (2018), “Maturity and readiness model for Industry 4.0 strategy”, in Ustundag, A. and Cevikcan, E. (Eds), Industry 4.0: Managing the Digital Transformation, Springer, pp. 61-94.

Axelsson, J., Fröberg, J. and Eriksson, P. (2018), “Towards a system-of-systems for improved road construction efficiency using lean and Industry 4.0”, 2018 13th Annual Conference on System of Systems Engineering), IEEE, pp. 576-582.

Bassi, L. (2017), “Industry 4.0: hope, hype or revolution?”, 2017 IEEE 3rd International Forum on Research and Technologies for Society and Industry (RTSI), IEEE, pp. 1-6.

Brettel, M., Friederichsen, N., Keller, M. and Rosenberg, M. (2014), “How virtualization, decentralization and network building change the manufacturing landscape: an Industry 4.0 perspective”, International Journal of Mechanical, Industrial Science and Engineering, Vol. 8 No. 1, pp. 37-44.

Burke, R., Mussomeli, A., Laaper, S., Hartigan, M. and Sniderman, B. (2017), “The smart factory: responsive, adaptive, connected manufacturing”, Deloitte Insights, Vol. 31 No. 1, pp. 1-10, available at: www2.deloitte.com/insights/us/en/focus/industry-4-0/smart-factory-connectedmanufacturing.html (accessed January 19, 2019).

Cheng, G.-J., Liu, L.-T., Qiang, X.-J. and Liu, Y. (2016), “Industry 4.0 development and application of intelligent manufacturing”, 2016 International Conference on Information System and Artificial Intelligence (ISAI), IEEE, pp. 407-410.

Erol, S., Schumacher, A. and Sihn, W. (2016), “Strategic guidance towards Industry 4.0–a three-stage process model”, International Conference on Competitive Manufacturing, Vol. 9, pp. 495-501.

Felch, V., Asdecker, B. and Sucky, E. (2019), “Maturity models in the age of industry 4.0 -do the available models correspond to the needs of business practice?”, Proceedings of the 52nd Hawaii International Conference on System Sciences, Hawai.

Fettig, K., Gacic, T., K€oskal, A., Kuhn, A. and Stuber, F. (2018), € “Impact of industry 4.0 on organizational structures”, 2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), pp. 1-8.

Frank, A.G., Dalenogare, L.S. and Ayala, N.F. (2019), “Industry 4.0 technologies: implementation patterns in manufacturing companies”, International Journal of Production Economics, Vol. 210, pp. 15-26.

Hastings, L., Sunderman, H., Hastings, M., McElravy, L.J. and Lusk, M. (2021), “Leadership transfer in rural communities: a mixed methods investigation”, Community Development, pp. 1-29.

Hizam-Hanafiah, M., Soomro, M.A. and Abdullah, N.L. (2020), “Industry 4.0 readiness models: a systematic literature review of model dimensions”, Information, Vol. 11 No. 7, p. 364.

Nasiri, M., Ukko, J., Saunila, M. and Rantala, T. (2020), “Managing the digital supply chain: the role of smart technologies”, Technovation, Vol. 96, 102121.

Santos, C., Mehrsai, A., Barros, A.C., Araujo, M. and Ares, E. (2017), “Towards Industry 4.0: an overview of European strategic roadmaps”, Procedia Manufacturing, Vol. 13, pp. 972-979.

Sarvari, P.A., Ustundag, A., Cevikcan, E., Kaya, I. and Cebi, S. (2018), “Technology roadmap for industry 4.0”, Industry 4.0: Managing the Digital Transformation, Springer, pp. 95-103.

Sony, M. and Aithal, P.S. (2020), “A resource-based view and institutional theory-based analysis of industry 4.0 implementation in the Indian engineering industry”, International Journal of Management, Technology, and Social Sciences, Vol. 5 No. 2, pp. 154-166.

Verhoef, P.C., Broekhuizen, T., Bart, Y., Bhattacharya, A., Dong, J.Q., Fabian, N. and Haenlein, M. (2021), “Digital transformation: a multidisciplinary reflection and research agenda”, Journal of Business Research, Vol. 122, pp. 889-901.

Weking, J., St€ocker, M., Kowalkiewicz, M., B€ohm, M. and Krcmar, H. (2020), “Leveraging industry 4.0– A business model pattern framework”, International Journal of Production Economics, Vol. 225, 107588.