
RESULTS SUMMARY: QUALITATIVE APPROACH

8.1 Introduction

The main objective of the qualitative approach is to build a conceptual understanding of I4.0 adoption in global supply chains. The first step of the study is designed to explore the I4.0 adoption to analyze its impact on resilience, flexibility, reliability, and sustainability. Blockchain technology is selected as its applications in enhancing the supply chain resilience, flexibility, reliability, and sustainability are notable. Further in this study, other technologies under the umbrella of I4.0 such as IoT, BigData, AI/ML, Digital Twins, smart grid, etc. are included and their impact on global supply chains is analyzed. The key finding of the qualitative study is discussed below.

8.2 I4.0 adoption barriers

The barriers have been classified into four primary domains, namely economic, legal, behavioral, and technical. Moreover, this research delves further into the examination of these barriers by differentiating between those that act as causal factors and those that arise from other influences. Moreover, it assesses the degrees of correlation among these barriers. Within the various categories under consideration, it is evident that technical barriers, predominantly falling within the causal group, play a pivotal role in influencing the adoption of BT. This highlights the necessity for conducting additional research in this particular domain in order to comprehend its consequential impact on other barriers. In the future, there exists the possibility of formulating a technology adoption model that seeks to acknowledge and alleviate the aforementioned barriers. This model could be subjected to testing in order to assess its efficacy in promoting the adoption of BT. The research highlights the significance of technical complexity as the primary barrier to the adoption of BT, emphasizing the need for focused endeavors to investigate approaches for streamlining this aspect. Additionally, the study posits that forthcoming research endeavors should explore the difficulties linked to trust, scalability, interoperability, integration, and financial limitations. The key barriers are:

Table 40: Key barriers

Barrier	Category	Rank
Technical complexity	Technical barriers	1
Data privacy issue	Technical barriers	2
Limited financial capability	Economical barriers	3
Scalability issue	Technical barriers	4
Regulation uncertainty	Legal barriers	5
Lack of expertise	Behavioral barriers	6
Interoperability issue	Technical barriers	7
Lack of adaptability	Behavioral barriers	8

Technical complexity emerges as the most crucial BT adoption barrier it causes effects on other barriers such as trust issues and deficiency of approach. It has a moderate correlation with other barriers. Managers need to prioritize it and create a simple and systematic framework to reduce the complexity. Workshops and training sessions can be organized to increase awareness about the technology and clear misconceptions. Data privacy issues can be fueled by a lack of transparency and traceability among stakeholders which increases the counterfeit and fraud risk in the supply chain. It can be resolved with increased trust and enhanced security to protect sensitive information throughout the network. Limited financial capability funds can be allocated in systematic manners to tackle the financial limitations additionally elevating knowledge of technology and its benefits can help in generating more funds with increased collaborations. Trust issues, deficiency of approach, lack of expertise, scalability issues, and Interoperability issues can be controlled and mitigated by mitigating the barriers of cause group.

8.3 I4.0 for Supply Chain Resilience and Sustainability

This study discusses how achieving supply chain resilience and sustainability can be accomplished using BT-enabled technologies. Our study model showed the relationship between twenty-one BT-enabled CSFs using a Grey-DEMATEL approach and laying the groundwork for future research in the area. Sensitivity analysis is performed to assess the robustness of the obtained results. This study showed that BT with supply chain operations can create a transparent and verifiable system for tracking assets, inventory, and other vital resources. This unified platform provides real-time supply chain and internal process visibility

and accountability. Stakeholders can track and verify assets or items, eliminating fraud and counterfeiting, making data corruption harder for hostile attackers. The results show BT-enabled internal integration (IN) as the most important CSF for SCRS because it sets in motion the effects of many other BT-enabled CSFs. BT enabled internal integration to improve sustainability by streamlining operations. The transparency in integration improves resource tracking, reduces waste, and optimizes use. By tracking inventory levels and demand trends, organizations can decrease overstocking and stockouts, improving resource allocation and reducing environmental impact. When it comes to impact, however, Standardized Data Management (SD) and Smart Ordering (SO) are at the top of the list. The key factors are:

Table 41: Key factors

Factors	Stakeholder	Rank
Internal Integration	Supplier	1
Efficient Intra-Organizational Communication	Logistics	2
Integration of Strategic Partners	Logistics	3
Structured Operating guidelines/parameters	Supplier	4
Organizational Archive	Manufacturer	5
Standardized Data Management	Logistics	6

Enhancing transparency, traceability, privacy, and security among all parties in SCRS is the function of BT. In this study, the authors have found that BT enabled CSFs for SCRS along with their mutual impact and causal relation among each other. Implementing blockchain-enabled technology is essential to building an SCRS, as it can enhance the system's ability to detect disruptions and respond appropriately.

8.4 I4.0 for Supply Chain Reliability and Sustainability

This study used a multi-method approach to analyze the benchmarking enablers of I4.0 for SC sustainability to build a reliable SC. In the first stage of the study, the AHP method is employed to obtain the global weights and ranking of the enablers. In stage 2, the DEMATEL approach is used to understand the causal relations among enablers. Further to identify the preference criteria and adoption priority PROMETHEE II is used. The global weights of AHP are integrated into PROMETHEE II to obtain the aggregate preference matrix. The finding of this study is presented further in the section.

Based on the results of this multi-method study, it can be concluded that supply chain digitization, Decentralized Structure, Information Transparency, and Smart Factory technologies are some of the major benchmarking enablers of I4.0 for SC sustainability to build a reliable SC. Flexible manufacturing systems, Top Management Commitment, and Government supportive policies emerge to be as least priority benchmarking enablers. In the context of the cause-effect analysis, this study shows that the casual group that affects the other enablers and is linked with most others are Supply Chain digitization (E11) and Decentralization structure (E1) with strong cause-effect on other benchmarking enablers making them crucial for successful adoption of I4.0 in the SC. The receiver group that gets affected by the casual groups are Real-Time monitoring, Information Transparency, Government support policies, and Flexible Manufacturing systems. The approach taken in this study depends upon the input provided by experts which can turn out to be the major limitation of this study. A different panel of experts may yield different results in developing a reliable SC. Thus the study to explore and analyze the benchmarking enablers of I4.0 for SC sustainability to build a reliable SC needs to be further examined and refined by the panel of judges and focus group discussions towards the reliability of the supply chain in I4.0.

Table 42: Key enablers

Enablers	Rank
Supply Chain digitization	1
Decentralization structure	2
Information Transparency	3
Smart Factory technologies	4
Top Management Commitment	5
Real-time monitoring	6
Flexible manufacturing systems	7

The identified enablers have revolutionized the way businesses operate and manage their SCs, enabling them to be more agile, efficient, and responsive to customer needs. The digitalization of the supply chain involves the use of advanced technologies such as the IoT, Big Data Analytics, and AI to improve the efficiency, visibility, and transparency of the supply chain (Agrawal & Narain, 2023).

8.5 I4.0 for Supply Chain Flexibility, Resilience, and Sustainability

By addressing enablers for I4.0 adoption relevant to flexibility throughout the supply chain in sufficient depth and breadth across three flexibility dimensions, this study aims to close the research gap. The findings provide support to identify the significant I4.0 adoption enablers for flexibility and its impacts on resilience and sustainability. The study also categorizes different I4.0 adoption enablers for flexibility under three flexibility dimensions for better management and managerial understanding. Further, it suggests the priority, in which I4.0 adoption enablers for flexibility should be implemented first, and in which dimension of the supply chain. The ISM model and driving power and dependency power are shown in Fig 3 and 8 respectively. Fig 8 shows the I4.0 adoption enablers under four groups, independent, dependent, linkage, and autonomous. The enablers in the independent group have capabilities to directly affect the I4.0 adoption for flexibility in the supply chain. Many other enablers responsible for flexibility depend on these independent enablers. Thus, the enablers with high driving power need to be addressed first as they will facilitate other enablers to perform better. Planning and scheduling tools (PS) have the highest driving power followed by traceability tools (TT) thus they can be considered the key enablers for I4.0 adoption.

Table 43: Key Technologies

Technologies	Dimensions	Rank
Traceability	logistics	1
Planning and scheduling tools	Manufacturer	2
Customer data process and analysis	Logistics	3
Logistics decision-making tools	logistics	4
Energy efficient process	operations & decision making	5
Real-time analysis of key processes	operations & decision making	6
Predictive analytics tools	operations & decision making	7

8.6 Strategies to enhance resilience and sustainability

For flexibility in the supply chain, it is necessary to plan all the operations in the network because unplanned operations are prone to disruptions leaving behind a carbon footprint larger than usual. The enabler PS drives most of the other enablers. The TT is necessary to understand the whereabouts of resources so that inefficient processes can be observed and the resilience of the process can be enhanced. The TT also complements other enablers such as PS, RTA, LDM,

etc., so if TT is already adopted it will clear the path for the other enablers for I4.0 adoption as well and it will result in enhanced sustainability. Real-time analysis of key processes (RTA) holds the third position in driving power and can be mainly facilitated by TT. The RTA is needed for instant actions because, with the help of the RTA, the issue can be known instantly through automatic alerts to the responsible member of the firm. The inefficient situations can be further analyzed and automatic protocols can be set up to avoid delays in decision making thus enhancing resilience and sustainability. Energy-efficient processes (EEP) and Decision-making tools- scheduling, routing, etc. (LDM) hold fourth and fifth ranks respectively in driving power. The enablers of Material movement systems (MM), Inventory management (IM), Smart ordering (SMO), Warehouse optimization (WO) Energy management tools (EM) Smart manufacturing (SM), and Storage optimization (SO) fall under the dependent group. These enablers are important for enhancing flexibility, resilience, and sustainability however, they need enablers from independent groups to be adopted first so that dependent enablers can contribute better. MM, IM have the highest dependencies as these enablers first need information from all other related enablers to choose a proper course of action.

8.7 I4.0 Technology adoption levels

The term "industry 4.0" describes the incorporation of digital technologies into industrial processes to facilitate advanced automation, data sharing, and real-time information sharing. The technologies can be grouped as basic to advance for adoption in various supply chain processes. Further, the adoption cost is also important and should be taken into account while grouping for feasible adoption. The technologies enhancing visibility, communication, and analytical capabilities should be grouped as level I. Level II technologies may include advanced automation and predictive capabilities in addition to level I. Level III of technology adoption considers the best analytical and predictive abilities the technology can provide in addition to level I and II. These technology adoption levels have an impact on cost and the associated emission of the network as they assist involved operations of the supply chain. The levels of I4.0 technologies adoption are divided with increasing impact on cost and emission. The adoption level is determined by the product quantity processed by stakeholders. The model considers the impact of technology adoption (σ_C) on the operational cost of the network, manufacturing facilities, logistics, and distribution centers. The grouped technologies of I4.0 along with their applications and levels are presented below.

Table 44: I4.0 Technology adoption levels

Applications	Technology	Level
Planning & Scheduling tools	Decision Making	I
Traceability tools	Monitoring	I
Supply chain digitization	Cloud & Computing	I
Decentralization structure	Cloud & Computing	I
Flexible manufacturing systems	Advanced Automation	I
Logistics decision-making tools	Decision Making	II
Energy-efficient processes	Smart grid	II
Customer data processing and analysis	Predictive Analysis	II
Green energy systems	Smart Grid	II
Smart manufacturing	Advanced automation	II
Efficient communication	Smart contract	III
Smart factory technologies	Advanced automation	III
Real time analysis of key processes	Digital Twin	III

Level I technologies are used to enhance visibility, communication, flexibility, and analytical capabilities. The Level I technologies include planning and scheduling tools, traceability tools, supply chain digitization, decentralization structure, and flexible manufacturing systems. Level II technologies may include advanced automation and predictive capabilities in addition to level I such as Logistics decision-making tools, Energy-efficient processes, Customer data processing and analysis, Green energy systems, and Smart manufacturing. Level III of technology adoption considers the best analytical and predictive abilities the technology can provide in addition to levels I and II such as Smart contract, Smart factory technologies, and Digital Twin.

8.8 Recommendations

The key recommendations to formulate the mathematical model are mentioned below:

Technology Integration: the study indicates that single technologies may not be effective when used in isolation. It will need integration with other existing technologies for efficient adoption.

Impact on Cost: The implementation of these technologies should prioritize reducing costs

Impact on Emission: The implementation of these technologies should prioritize reducing emission

Phased Adoption: The adoption of I4.0 technologies should be implemented in phases starting from basic (level I) to advanced (level III).

Stakeholder Consideration: The study suggests that a technology proven effective for one stakeholder may not necessarily work for another. Therefore, the technology adoption process should be tailored to the capacity of each stakeholder.