
INTRODUCTION

1.1 Background

The processes of the supply chain have evolved with the technology to facilitate and minimize the distance between consumer and manufacturer. For instance, business transactions started from simple trust-based agreements, with days or even months of execution time, to banking systems that take only a few moments. However, despite these evolutions, in the last few years, supply chains have experienced major disruptions. These disruptions have challenged the supply chain stakeholders as well as governments all around the world. Modern global businesses heavily rely on supply chains, which serve as the crucial link between the origin and consumption of commodities on a global scale. Managing these extensive networks involves intricate processes, connecting numerous stakeholders and consumers worldwide. Over the past few decades, companies have grown in size, transitioning from conventional networks to extensive ecosystems encompassing a diverse range of products. These products necessitate the involvement of multiple stakeholders for global distribution.

Furthermore, A global supply chain report indicates that scope 2 and scope 3 emissions of supply chains are, on average, 11.4 times greater than scope 1 emissions, demonstrating the need for a more comprehensive accounting of emissions (CDP, 2023). Scope 1 emissions are essentially those that a company owns or controls, whereas scope 2 and 3 emissions are a result of the company's activities but come from sources that it does not own or control, such as suppliers, distributors, etc. Scope 2 emissions would include, for instance, the emissions produced during the production of the electricity that firms use for their operations. Scope 3 emission includes all other emissions that lie outside the boundaries of scopes 1 and 2, such as the disposal of a product after use by the customer (Hertwich & Wood, 2018; Wei et al., 2020). For instance, the emission by Apple company shows that its Scope 1 emission is less than 1% and the rest of the emission is from Scope 2 and 3 (59% from product manufacturing, 29% from product use, 9% from product transport, and 1% from product disposal) which justify the fact the considering only Scope 1 emission is not enough for sustainable development.

Tracking and tracing of Scope 1, 2, and 3 emissions are always a major challenge for companies. Regulatory agencies, manufacturers, consumers, and the general public have all

been compelled by incidents like industrial mishaps, oil spills, political conflicts on borders, and nuclear disasters to re-evaluate their economic business models and consider the effects that business practices have on society and the environment (Rajeev et al., 2017). Firms always desire a responsive and sustainable supply chain capable of recovery from disruptions; thus, they persistently search for technologies that help to convalesce supply chain resilience, reliability, flexibility, and sustainability. This refers to the characteristics such as adaptability to change and readiness to recover from disruptions and unexpected events in a way, which is sustainable. It makes supply chains able to continue operating even in the face of unforeseen disruptions by promptly recognizing and mitigating their effects, locating alternate sources of supply, enhancing the utilization of resources, and adapting to changes in demand.

Most of the supply chains in the world use limited or no technology which may be attributed as a major reason behind higher supply chain costs and emissions. The digital technologies of Industry 4.0 (I4.0) such as big data analytics, artificial intelligence, machine learning, blockchain, and IoT offer businesses numerous opportunities. First, digitalization streamlines operations by automating manual processes, reducing errors, and enhancing overall productivity. This results in quicker order processing, shorter lead periods, and optimized resource utilization, which reduces operational expenses. Digital supply chain solutions facilitate real-time inventory tracking, demand forecasting, and demand-driven replenishment, allowing businesses to reduce excess inventory and eliminate stockouts. This optimization of inventory levels results in substantial cost savings by minimizing holding costs and waste. Lastly, the availability of accurate and timely data in digital supply chains improves decision-making capabilities, allowing businesses to make cost-effective procurement, production, and distribution decisions based on accurate information. Furthermore, advanced routing algorithms and real-time tracking systems optimize delivery routes, thereby reducing transportation-related petroleum consumption and emissions.

Industry 5.0 (I5.0) progresses even further on the technological advancements achieved by I4.0 regarding the building of the supply chains and changes to industry structures through the introduction of modernization. Nevertheless, it is built on the framework of I4.0's digital revolution. In the absence of smart automation, AI-powered insight generation, and integrated supply network infrastructure designed by I4.0, meeting the I5.0 objectives of being ethical, resilient, and sustainable would have been challenging, if not impossible. The success of I4.0 is not confined to the enhanced performance of the supply chain only. This new era of supply chains and industries operates sustainably and adaptively with the help of technology and

human intelligence. Therefore, it is evident how I4.0 remains a critical enabler of progressive industrialization. It is the foundation of novel global modern supply chain strategies that will keep changing with the move towards I5.0.

1.2 The impact of I4.0 technologies

I4.0 also known as the Fourth Industrial Revolution describes the current trend of automation and data exchange in manufacturing and other industries. It represents a new era in industrial production, which is characterized by the integration of advanced technologies such as the Internet of Things (IoT), cloud computing, Artificial Intelligence (AI), and robotics, among others. Such technologies assist in implementing smart factory adoption, decentralized SC, digitalization of SC, data security, and handling (Boursianis et al., 2022; Li et al., 2020). Technologies such as machine learning and AI also protect against cyber threats by detecting fake news and misinformation thus enhancing the reliability of SCs. I4.0 is built to adopt digital technologies to optimize production processes, improve quality, and reduce waste. I4.0 enabled SCs can respond to change market demands and customize products to individual customer needs, often in real time (Akhtar et al., 2023). Figure 1 shows the impact of I4.0 on supply chain optimization and capability.



Figure 1: I4.0 adoption and supply chain

Depending on the level of implementation a supply chain requires, I4.0 technologies can provide a range of hardware and software solutions. Applications of I4.0 involve the incorporation and application of digital technologies across the supply chain, from inventory management to transportation and distribution. Digital technologies of I4.0 can improve the

supply chain's flexibility. For instance, by employing traceability tools (TT) users can get asset tracking and real-time location updates, even while a shipment is en route. Information from digital tools is integrated with digital supply chain networks, whereas traditional supply chains frequently rely on isolated systems (Sassanelli & Terzi, 2022). When it comes to identifying potential issues and estimating the likelihood of potential risk, traditional supply chains demand a significant amount of energy compared to digital. Due to shared data, supply chain digitization helps firms anticipate and prevent issues, saving resources and increasing flexibility. In addition, organizations can better manage their supply and demand with the assistance of technologies such as smart contracts and smart storage solutions. This results in a flexible supply that is both resilient and sustainable. Platforms for data analytics can assist organizations in recognizing patterns of disruptions and coming to well-informed decisions to improve efficiency. This can include improving transportation routes and methods, optimizing production schedules, and cutting down on the amount of time machines are sitting idle (Mackay et al., 2019). The cooperation between partners in the supply chain can result in the development of environmentally friendly solutions that are to the advantage of all individuals and organizations involved.

Government policies such as investment in infrastructure by providing 5G networks, high-speed internet, and smart grid services can support and help accelerate the adoption of I4.0 in SCs. In addition, tax incentives and policies to provide data privacy and cybersecurity can help ensure that the benefits of I4.0 technologies are not offset by the associated risks (Caiado et al., 2022). The adoption of I4.0 in SCs can also automate the production systems so that they can quickly and efficiently adapt to market dynamics by producing high product variety and volume. By automating the production processes the dependency on conventional energy resources can also be minimized. Automated systems and smart contracts to use renewable energies with the help of smart grid technologies can boost performance with a reduction in carbon emissions. It facilitates organizations to achieve sustainability goals, reduce environmental impacts, and improve energy efficiency. Smart grids, sustainable manufacturing, and circular economy can also be integrated into SCs by adopting I4.0. In addition, the integration of I4.0 into the SCs can help companies build a reliable and resilient supply chain by improving efficiency, reducing errors, and providing real-time visibility and control over the SC, which can help companies to better manage their SC and respond to disruptions with increased performance, customer satisfaction, and reliability (Zhou et al., 2022).

The impact of I4.0 technologies on emission and cost can be seen in a few firms. For instance, by using I4.0 technologies Apple company is comprehensively tracking its Scope 1, 2, and 3 emissions and devised a policy to reduce them by 55% since 2015, by doing so the company has also increased its revenues by 64% in the same period (Apple environmental progress report, 2024). Apple company has transitioned to 100% renewable energy for the electricity it uses in its premises and data centers in more than 40 countries across the globe to curtail its Scope 2 emission to only 2%. The company has also reduced its supply chain emissions in 2023 by 20% compared to 2022. Apple company is also expanding this initiative to its suppliers around the globe to transition to 100% renewable energy use. In addition, to tackle the Scope 3 emission, the company has modified its major products to reduce energy consumption by 70% (Apple environmental progress report, 2024). In summary, to comprehend the environmental impact of a firm's economic activity, it is not sufficient to examine its direct emissions; the entire value chain must be engaged to evaluate and enhance its sustainable performance. Thus, tracking and considering the carbon footprints throughout the supply chain is a necessary step toward sustainable development. I4.0 encourages eco-friendly practices and to maximize these benefits businesses must embrace I4.0 and collaborate with supply chain partners to drive systemic changes toward a sustainable future. The role of different technologies under the umbrella of I4.0 is discussed further in this section.

1.2.1 Blockchain Technology (BT)

Blockchain Technology (BT) is emerging as a possible solution. The BT is purposefully created as a distributed ledger technology to be extremely resistant to fraud and alteration. To digitally timestamp electronic documents and prevent manipulation, Stuart Haber and W Scott Stornetta first proposed the concept of a cryptographically secured chain of blocks in 1991. The creator(s) working under the alias Satoshi Nakamoto then released a white paper outlining the design for a blockchain. However, it became more well-known in recent years when it was incorporated with Blockchain technology to preserve transactions of the digital currency known as "Bitcoin." Every transaction in this ledger is authorized by the owner's digital signature, which also protects it from tampering and authenticates the transaction. As a result, the data in the digital ledger is quite safe. Bitcoin is not like traditional currency it is 'mined' and not printed. This application of BT (Bitcoin) has gained popularity as it is cost-effective (works without intermediaries), more efficient, and more secure than other alternatives. The key advantages of using BT include its decentralized nature, anonymity, transparency,

democratization, immutability, auditability, fault tolerance, and security (Alkhudary et al., 2022; Bhutta et al., 2021)

The strengths of BT can be used to ensure the stability and readiness of the supply chain and make it more adaptable to market needs/fluctuations. Features like decentralization, transparency, immutability, auditability, etc. are being used to support the functions of SCRS and can be proved critical to the success of a supply chain (Sawyer & Harrison, 2020). BT can be applied in a variety of processes to improve the sustainability and resilience of the supply chain (figure 1). For instance, allowing end-to-end traceability of products, materials, and transactions enables all supply chain participants to confirm the products' origin, authenticity, and quality. To confirm that a product was made sustainably and ethically, its path from raw materials to final delivery can be traced. Utilizing smart contracts can decrease the need for intermediaries and improve supply chain effectiveness. In addition, the transparent and unchangeable record of all transactions facilitates the identification of supply chain inefficiencies and possible bottlenecks, as well as can help cut down on waste and better resource allocation. BT can also be used to monitor a product's carbon impact throughout the entire supply chain. This makes it possible for businesses to find ways to lower their carbon emissions and carbon footprint and to take part in initiatives that reduce carbon emissions.

Industries are in the process of thoroughly examining the various BT-enabled applications and implementing them in the places, and to enhance the resilience and sustainability of the supply chain. BT is now being used by organizations such as UbiMS to secure their data, intellectual property management, smooth and secure flow of information, enhance the efficiency of logistics, etc (Tijan et al., 2019).

1.2.2 Digital twins

The traditional approaches to supply chain management are insufficient for meeting the contemporary requirements of rapid-paced demands, necessitating a smooth and uninterrupted flow of information. The feasibility of generating a digital depiction of a supply chain is enhanced through the integration of digital twin technology in conjunction with simulation, artificial intelligence, and machine learning. This representation encompasses real-time processes and data, thereby enabling its shareability across a decentralized network (Agnusdei et al., 2021). Digital twins (DTs) behave as an accurate counterpart of their corresponding physical systems, facilitated through data obtained from sensors. The applications of DT technologies range from manufacturing industries to automobiles, healthcare, and urban

planning, such as smart cities. It helps organizations improve their resilience, predictive capabilities, remote monitoring, and productivity. Its characteristics, such as connectivity, homogenization, modularity, programmability, and digital traces, make it different from other existing technologies. DTs virtually represent the movements, forces, and interactions that a product can have in the physical world. To give a virtual depiction of a physical system or product that exists in the physical system, the DT relies on data obtained through sensors and can be used in real-time with regular synchronization with the corresponding physical system.

The term "digital twin" was first used by author David Gelernter in his work titled "Mirror Worlds," which was introduced in 1991, and the concept was formally introduced in 2002 at a conference in Troy, Michigan. However, NASA did the first implementation of the concept in 2010 to create a digital simulation of the space capsule and craft testing. A DT is much different from traditional computer-aided design (CAD). It is much more than just a sensor-based Internet of Things (IoT) solution. Modeling complex settings is a modest success for CAD when it is entirely enclosed in a computer-simulated environment. Also, simpler IoT systems measure things like location and diagnostics across components, but not interactions between components or the entire lifecycle process. DT technology enables managers and experts to closely monitor and command systems and components remotely (Abideen et al., 2021). The DT is different from simulation; both use virtual model-based simulation, but there is some key difference between them. Simulations often use what-if scenarios for design and offline optimization; however, DTs interact with real-time situations that are updated continuously and used on a larger scale. As a result, organizations are already reaping significant benefits from DT technology, which enables them to map and analyze information regarding operational efficiency, service and product innovation, and other business-related elements. The true power of the DT (and why it matters) is its ability to comprehensively connect the physical and digital worlds in near-real time. DTs have the potential to deliver better models that permit more accurate and comprehensive measures of unpredictability because of the interaction that takes place between the physical and digital worlds of products and processes. These interactive measures may also be examined with contemporary large-scale processing architectures and cutting-edge algorithms for real-time prognostic feedback and offline analysis, owing to cheaper and more potent computer power. These make it possible to make fundamental design and workflow modifications that are most likely not possible with the available tools. It can be categorized as DT prototype (DTP), DT instance (DTI), and DT aggregate (DTA). DTP is prototype-based and exists even before the physical product, DTI

uses individual instances of the product, and DTA is the aggregation of DTI. The output of DTA can be used for prognosis and learning. However, the application module by various companies at the product level is created separately as components, assets, systems, and process twins. Each deployment of the DT is unique and occurs in stages that are dynamically linked to the operational data of other departments. It ranges from a component or product to the entire network of the process, covering a single department of an organization to the entire city of a nation.

A supply chain DT is comprehensive enough to examine interactions along the supply chain, from large-scale shifts in demand to what happens inside facilities. It does this by analyzing live information feeds, which include things like production level, material/vehicle movements, and inventory levels, to determine the current health of the supply chain and deliver updated projections. It provides notifications, alarms, and alerts that can be configured while setting up the parameters to provide timely information on unexpected events such as inventory shortages and production dropping below a certain level. A unique action can be set up that will automatically take place when chosen events occur, such as potential stockouts. These actions can be carried out automatically without any further intervention from the authorized person. It gives decision-makers and planners the ability to create action plans that will assist the management in addressing odd occurrences, and then these plans can be tested to ensure that they are effective. The adoption of digital technologies throughout the supply chain is a must in this day and age. The growing complexities of the supply chain can be effectively addressed with more visibility and analysis in real-time by utilizing technology such as DTs, artificial intelligence/machine learning, the internet of things, etc. Using DT technology for inventory, logistics management, and other key nodes can help increase the efficiency of supply chain operations. A DT can help any firm that wants to improve its supply chain networks. Companies that already use a DT for supply chain design and planning include those in the food and beverage industry as well as in retail, plumbing and heating, energy, software, and technology firms.

1.2.3 Industrial Internet of Things (IIoT)

The Industrial Internet of Things (IIoT) is one of the key technologies of I4.0 used to enable the automation, autonomy, or digitalization of industrial operations. To meet the stringent requirements of hard real-time automation systems, industrial networks were primarily based on various deterministic bus technologies (Zhohov et al., 2018). In the areas of healthcare,

logistics, industrial production, supervisory control, robotics, and other fields, IIoT technology has a wide range of applications (Kumar et al., 2022; Sajid et al., 2016; L. Sanchez, 2014). Thus, combining it with sustainable practices can enhance SC performance, and reliability and facilitate the adoption of I4.0 in SCs (Biegańska, 2022). I4.0 presents both opportunities and challenges for sustainable development and represents that a sustainability framework is necessary to guide the implementation of these technologies in a socially, environmentally, and economically responsible manner. The sustainability dimensions such as social responsibility, environmental sustainability, and economic viability propose a set of indicators to analyze the sustainability performance of I4.0 initiatives that can assist organizations and policymakers in integrating sustainability considerations into their I4.0 strategies and practices (Jamwal et al., 2021).

1.2.4 Data-driven insights and predictive analytics

The resolution of flexible supply chain issues frequently necessitates a prompt and data-centric approach that leads to improvement. Data-driven insights and predictive analytics play a crucial role in analyzing the ever-changing nature of business environments. The utilization of neural networks and machine learning has proven to be beneficial in various domains comprising demand and lead time uncertainty, customer preferences, cross-border political situations, and logistics disruptions (Corsini et al., 2022; Priore et al., 2019; Wong et al., 2022). By analyzing historical data, external variables, and market trends, these algorithms can predict future demands. When combined with other techniques these methodologies have yielded significant findings to enhance decision-making efficiency. For instance, Zheng et al. (2023) used neural networks in combination with deep learning to detect demand patterns and found significant prediction improvements. The aforementioned methodologies are also employed to identify policies, such as the adoption of inventory cash replacement, to mitigate the adverse effects of supply chain disruptions on the performance of the supply chain (Badakhshan et al., 2023). These methodologies enable decision-makers to effectively strategize inventory schedules and distribution strategies in real-time while also minimizing costs and taking sustainability into account (Liu et al., 2022). By taking into account real-time data about traffic conditions, weather, and order priorities, these techniques can be used for routing in real-time for route optimization. Efficient decision-making practices also contribute to the reduction of fuel consumption and the subsequent decrease in carbon emissions. The utilization of neural

networks and machine learning techniques is preferred in addressing flexible supply chain issues due to their capacity to offer predictive analysis and data-driven insights.

1.2.5 Other supportive technologies and tools

I4.0 has the potential to optimize through the use of technologies that collect and evaluate data before implementing those findings in the real world. The technologies instrumental in I4.0 initiatives include smart manufacturing, cyber-physical systems, artificial intelligence/machine learning, and data analytics (Dolgui & Ivanov, 2022; Ivanov, 2022; Kusiak, 2018). These technologies are considered to increase resilience in supply networks. Sensors, for instance, gather data and data analysis tools, take raw data, and process them into useful knowledge (Blome et al., 2014; Ivanov, 2022). From there, the data is sent to machines that can physically adjust their course of action to achieve the best possible results thus, the supply network responds in a better way to unforeseen challenges and enhances resilience by quickly regaining its original structure. However, there is still a paucity of knowledge regarding how businesses may take advantage of this potential and apply these technologies. The expenses of implementation and the savings in expenditures will be taken into account when options to enhance flexibility are assessed. In today's business environment, aligning strategic and operational decisions throughout the many supply chain stages is necessary to establish and sustain resilient supply chains and I4.0 facilitates these processes (Marchi & Zanoni, 2017).

1.3 Motivational Questions

The following questions related to global supply chains motivate to do this study-

- ❖ Human-caused global warming reached approximately 1.2°C above pre-industrial levels in 2017 and is rising at a rate of 0.2°C per decade, this indicates that these changes have had an impact on organisms and ecosystems, as well as on human systems and well-being (IPCC, 2023). The firms are adopting sustainable practices to cut down their emission however most of them are not considering the Scope 2 and Scope 3 emissions.

How I4.0 adoption in global supply chains can address sustainability concerns?

- ❖ COVID-19 has caused a slowdown in supply chain operations all around the globe, and after that, the Russia-Ukraine conflict adds more complications to the logistics (Ambrogio et al., 2022). These are a few examples of many global and local level

disruptions that occurred in supply chains throughout the world. To address and mitigate the difficulties brought on by these disruptions, many researchers have examined the supply chains from the perspectives of resilience and sustainability (Negri et al., 2021). Although there has been a significant amount of study on sustainability and resilience separately in the literature, empirical data indicate that the two concepts are interconnected and by improving resilience sustainability will also be enhanced (Fahimnia et al., 2019; Negri et al., 2021).

How I4.0 adoption can prepare the global supply chains to tackle these challenges and what is its impact on resilience and sustainability?

- ❖ With the increasing complexity and involvement of numerous parties in supply chains, it has become imperative for stakeholders to possess qualities such as transparency, traceability, security, resilience, and sustainability to tackle the challenges arising from the daily surge in demand. In addition, the supply chain processes need a simple, efficient, and secure environment to conduct various business transactions with efficient and correct information flow to maintain efficiency and security (Sawyer & Harrison, 2020).

Which process capabilities can be enhanced through I4.0 adoption?

- ❖ Many supply chain professionals think that the adoption of new technologies in supply chain networks is the most important strategic change needed (Fortune Business Insights Report, 2024).

What are the I4.0 adoption enablers and barriers for global supply chains and what are their adoption priorities?

- ❖ Germany which holds the first rank in the Logistics Performance Index (LPI) uses technologies such as speech-based picking to remove paper-based lists at warehouses, tracking systems at transports, image-based readers at retail, etc., to minimize its emissions and costs. Germany spends only 8% of its GDP while other countries such as the United States (14th rank) spend 9.5% and India (44th rank) spends 13% of its GDP on the logistics sector thus, showing the impact of I4.0 adoption on cost and sustainability (GOI, 2022).

What is the impact of I4.0 technologies on global supply chain sustainability and cost optimization?

1.4 Research objectives

The broader aim of this study is to provide a robust model for I4.0 adoption. Identifications of enablers and barriers of I4.0 adoption. In addition, this study seeks to analyze the impact of I4.0 adoption on global supply chains in terms of resilience, sustainability, reliability, and flexibility.

On incorporating the motivating questions, the following research objectives are addressed in this thesis:

1. To explore the contextual relations among global supply chains and I4.0 adoption.
2. To investigate the impact of I4.0 technologies on global supply chain sustainability and cost optimization.
3. To investigate the interrelation between I4.0 technologies adoption and stakeholder capacity.

1.5 Scope of the research

This study emphasized the role of I4.0 in global supply chain management. This study has used a qualitative study to comprehensively investigate the enablers and barriers to I4.0 adoption along with its impact on supply chain capabilities. Further, in the quantitative study, a suitability model is built based on recommendations from the qualitative study. The model is tested with an electronics supply chain. The observations of this study imply that the integration of technology into the supply chain has the potential to yield cost reductions and enhance operational effectiveness. This observation shows that the integration of technology into supply chain management can improve operational efficiency, increase transparency, and optimize resource utilization. Through the automation of activities, enhancement of data analytics, and facilitation of real-time monitoring, technology has the potential to eliminate bottlenecks, decrease lead times, and mitigate operational expenses. Further, advanced technologies and renewable energy sources can cut industrial facility emissions and energy use. The findings of this study can be used to build strategies for I4.0 adoption in global supply chains. Our research provides actionable insights for Chief Supply Chain Officers, Logistics Managers, Production Managers, Quality Assurance Managers, Demand Planning Managers, and Technology Officers alike.

1.6 Methodology

This study has employed qualitative and quantitative approaches to address the issues of I4.0 adoption in global supply chains for supply chain optimization and sustainability. The overall method is broadly organized into the following phases:

1.6.1 Qualitative Approach:

Each research questions are explored through a literature review and experts' opinions and research objectives are determined. Multi-criteria decision-making (MCDM) approaches are employed to identify and analyze the key factors influencing the I4.0 adoption.

1.6.2 Quantitative Approach:

The recommendations from the qualitative study are employed to identify sustainable supply chain cost parameters. The obtained scenario is formulated using mixed integer nonlinear programming (MINLP) and a robust model for supply chain networks to delve into the impact and strategic adoption of I4.0 for cost optimization and the reduction of scope 1, 2, and 3 carbon footprints is developed. An industrial case of an electronic supply chain is considered to solve the proposed model. The proposed model is solved using genetic algorithm (GA), adaptive genetic algorithm (AGA), differential evolution (DE), and adaptive differential evolution (ADE) approaches.

1.7 Contribution of the study

The contribution of this study spans across various managerial domains. From the optimization of inventory and transportation to enhancing production efficiency and quality control, our research provides actionable insights for Chief Supply Chain Officers, Logistics Managers, Production Managers, Quality Assurance Managers, Demand Planning Managers, and Technology Officers alike. These findings offer a roadmap for achieving competitive advantage and adaptability in today's rapidly evolving business landscape. Further, this study makes a significant and novel contribution to the field by addressing a significant research gap in the adoption of I4.0 technologies to track and control emissions across scopes 1, 2, and 3 in supply chain networks. Other specific contributions of this study are as follows:

- ❖ The comprehensive review of the existing state of art literature results in the identification of enablers and barriers to I4.0 adoption.

- ❖ This study explores and analyses the interrelations among the enablers and barriers of I4.0 adoption in global supply chains.
- ❖ This study suggests the adoption priority of enablers of I4.0 adoption in global supply chains.
- ❖ This study provides a detailed analysis of the impact of I4.0 adoption on global supply chain capabilities such as flexibility, reliability, resilience, and sustainability.
- ❖ This study provides a detailed analysis of the impact of I4.0 technologies on supply chain sustainability and cost optimization.
- ❖ This study provides a suitable model for I4.0 adoption in global supply chains.