The Mix-Match Concept of Digital Supply Chain and Digital Sustainability Practices

JAY PANDYA, SATYA R SHAH, ELMIRA NAGHI GANJI
Department of Engineering Management
Royal Holloway University of London
UNITED KINGDOM

Abstract: - The efficient management of global operations and supply chain (SC) flows has become crucial for organisations seeking to achieve operational efficiency, process optimisation, flexibility, and sustainable long-term growth in today's dynamic and linked business environment. This study places a greater emphasis on I4.0 (I4.0) and the technologies it offers, which are particularly beneficial for SC, smart manufacturing and sustainability. I4.0 and its associated technologies, such as the Internet of Things (IoT), big data analytics, cloud computing, and blockchain technology, offer significant benefits for enhancing business optimisation and streamlining labour processes. Enhancing SC networks through the implementation of I4.0 technologies has demonstrated notable improvements, particularly in the field of industrial engineering. Identifying potential risks associated with the process of digitisation is a crucial aspect within an organisational context. The research employed a pragmatic philosophical framework, an inductive methodological approach, and thematic analysis to enhance the quality of the findings. This analysis examines the countries and firms that are at the forefront of global leadership. Additionally, it explores the significance of university partnerships in fostering innovation and driving commercial growth. A digital twin is used for problem-solving purposes, such as network design, decision-making, and the resolution of complicated operational issues. The implementation of organisational strategies can lead to enhanced operational efficiency, reduced risk exposure, and adept responsiveness to market dynamics, so contributing to a more promising future.

Key-Words: - I4.0, Digital, Sustainable Transformation, Global Supply Chains, Digitalisation, Social Performance, Environmental Efficiency, Risk Management

Received: March 17, 2026. Revised: May 19, 2026. Accepted: June 21, 2026. Published: November 9, 2026.

1 Introduction

Industry 4.0 (I4.0) is one of the most crucial and relevant business trends today, but it is especially crucial to manufacturing, logistics, and the supply chain. Their technologies, which are most beneficial in every industry, include the IoT, Cyber-Physical Systems, Big Data Analytics (BDA), and Artificial Intelligence (AI). People can operate quite productively with ease. Making decisions quickly for production while preserving product quality is the industry standard and is made possible by I4.0. Nowadays, sustainability is a separate topic, and because the future of the planet is so clearly seen, we need to integrate sustainability into every industry. The two most important objectives should be ecological restoration and carbon footprint reduction.

This project focuses on I4.0 to streamline productivity and optimise the supply chain. Different countries have their own procedures, and some are even still implementing I4.0. We must now focus on sustainability since applying sustainability concepts to I4.0 technology can have a positive impact on supply chains and the economy. Cyber-physical systems, the IoT, cloud computing, and cognitive computing are just a few examples of the technologies that make up the so-called " I4.0" trend in automation and data interchange in production. We will observe how I4.0 is implemented and how it benefits the world. With a little education and training, the products and operational procedures of the industry can be changed. In literature we will see there are some risks to go with I4.0 and management of the risk, in addition to that, firms that rely too heavily on linked technology are vulnerable, but I4.0 places a high priority on data collection, exchange, and analysis. As a result, there is a higher chance of data breaches, cyberattacks, and unauthorised access to private data. Strong cybersecurity safeguards and data privacy protection are essential. The organisations under consideration will favour partial automation and digitisation adoption over fully integrated systems during the next three to five years. They cite the lack of qualified people who will prepare, implement, and use the new technology as one of the implementation's main risks

[1]. Although there are numerous individual contributions to SCM, such as sensors, real-time location systems (RTLS), radio frequency identification (RFID), and even the relatively recent development of modular factories, we are still able to optimise the SC's tracking and tracing. New models and ideas are required by this development to enable SCM in the future [2]. By enabling businesses to check their supply chain procedures, traceability assists efforts to ensure sustainable sourcing, fair labour practises, and ethical production processes. We now understand the importance of protecting the environment, making sustainable waste management another rising industry. Traceability is crucial for managing product returns for maintenance, recycling, or disposal. Overall, the success of the "making in this country" campaign and the development of a firm depend on how the government implements its policies surrounding the adoption of I4.0. In the African areas, a cloud penetration rate of approximately 15%, the African continent only represents 1% of the worldwide public cloud market [3].

1.1 Research Background

Every business need government assistance and is also required to abide by the law. The data acquired from the research approaches are carefully analysed in the data analysis section, and the results are then presented. After global pandemic supply chain and logistics scholars are more important than ever. The supply chain really occupies a higher-level area in the industry because the pandemic uncovered weaknesses in conventional supply networks, leading to disruptions in sourcing, production, and distribution. An example of SC disruptions is shown in **figure 1**. I4.0 also exists in a different context during and after pandemic.

Additionally, I4.0 was implemented by businesses due to government regulations involving new taxes like the GST and E-way bill. The high-quality data make the supply as efficient as possible to build long-term value and economic growth. The goals of sustainable growth keep improving the quality of life and bringing it up to date. Sustainable development goals should be the first thing we work on because they help us avoid things like old-school industrial engineering that hurt the environment, also effective supply chain is another crucial element, which is why having enough inventory is usually beneficial [4]. An efficient SCM can give several benefits such as cost savings, customer happiness, cooperation and partnerships, and data-driven decision-making, and can significantly contribute to organisation's success.

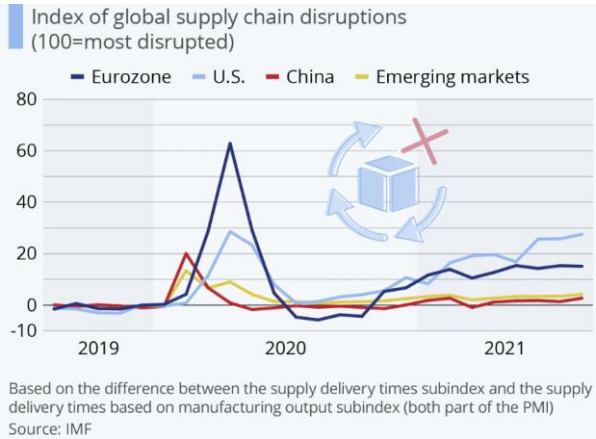


Fig. 1: SC Disruptions on Comeback [5]

Every programme in I4.0 is correct, and workers must follow that path to preserve the quality of the product; some basic training and knowledge can help to reskill the workforce. That is why businesses train and retrain their employees for their own and the company's future. The risk, which is related to data security, the environment, and the skill set of the workforce, was discussed by the learner in this paper. The business should abide by the sustainability regulations and periodically refresh its employees.

1.2 Research Aim and Objectives

The **research aim is** to Effectively manage global operations and supply chain flows for efficient operations, process optimisation, flexibility, and long-term growth. The key **research objectives** are:

To identify SCM operating efficiency and resource utilisation while reducing overall costs.

To create SC's flexible enough to respond swiftly to shift in the market, consumer needs, and unforeseen disruptions.

Evaluate I4.0 integration of digital twins and simulation approaches to enhance SC network optimisation and decision-making processes.

I4.0-enabled SC networks have the potential to improve environmental sustainability, and businesses use these tools to spread eco-friendly behaviours and lower their carbon footprint.

1.3 Research Scope

A paradigm shifts in how industries function has been brought through with the advancement of I4.0 technologies, especially around SCM. Investigating the numerous facets of this transition and its effects on logistics, manufacturing processes, decision-making, and overall operational efficiency can help us identify better prospects in the future. The supply chain efficiency, decision-making, and sustainability are the main topics of this study. The main challenge is to

identify cost-effective SC processes. Since we also need to protect the environment, we must also integrate new technology for better and smarter work while reducing carbon footprint. The study's scope also covers digital twins, which are significant and crucial in the field of industrial engineering. I4.0 and the concept of a digital twin are closely related ideas that are inextricably intertwined. They both have significant contributions to make to the I4.0 change of enterprises and industries. Although industries already have the greatest advisers, our research can help them at some time with things like cost-cutting, sustainability, and digitisation. I4.0 actively promotes sustainability from the perspectives of the "triple bottom line"—the environment, the economy, and socially. Figure 2 illustrates an example of the I4.0 landscape.

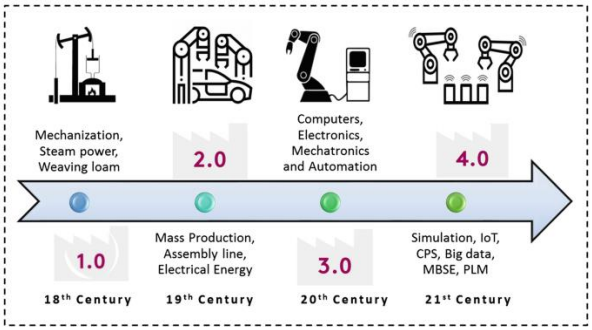


Fig. 2: Example I4.0 Landscape [6]

By optimising networks and value chains and enabling more effective business models, this method creates a new, wiser, industrial perspective. I4.0 is certain to boost competitiveness and improve resilience [7]. The industrial engineering field has been propelled into an era of quick change and unheard-of potential by innovation, which has emerged as a powerful catalyst. The implications of this fast innovation are extensive, advancing not only the field of industrial engineering but also those of the environment, health, and transportation. I4.0 ushers in a paradigm shift in project management characterised by data-driven insights, predictive capabilities, and improved collaboration. The collaboration and decision-making along the value chain are also included in this study, and decision-making aspects will likely be a key component of I4.0 research in the future as well. Collaboration and decision-making abilities have become crucial qualities in this dynamic environment for successfully navigating the complexities of the modern value chain. The integration of I4.0 into supply chains offers enormous promise, but organisations must be diligent in handling the related risks, making all these tasks difficult to accomplish and manage. Firms can confidently manage the complexity of I4.0 and SC dynamics by taking a proactive approach to risk identification, assessment, and mitigation. By filling in the gaps in the existing field, this project can help improve sustainability, efficient procedure, and optimisation.

2 Literature Review

The rapid development of technologies associated with I4.0, which are characterised by the integration of automation, data interchange, and AI, has completely transformed the way enterprises function. At the same time, sustainability has become a serious concern for firms all over the world, motivated by the necessity to reduce their negative influence on the environment and fulfil their social duties. Considering this, it is more important than ever to investigate how I4.0 might be able to improve the environmental friendliness of global dynamic SC's. Utilising the latest technological breakthroughs enables businesses to improve operational efficiencies, cut down on waste, and foster more responsible business practises throughout the SC. This investigation digs into the primary areas in which I4.0 and sustainability cross, focusing on the optimisation of processes, the control of risks, and the provision of suggestions for developing SC that are both robust and environmentally friendly. Firms can pave the road for a more sustainable and profitable future in the global dynamic SC landscape by utilising the power of the technologies that are part of I4.0 while also taking into consideration the elements that relate to sustainability.

2.1 Overview of Industry 4.0

The fourth wave of the industrial revolution, known as I4.0, is characterised by the integration of modern digital technologies into numerous industries. Automation, data exchange, and smart technology are driving a substantial transformation in manufacturing and production processes. From the sourcing of raw materials through the delivery of goods to customers, I4.0 in SC and logistics improves visibility, efficiency, and responsiveness throughout the whole value chain. Digitalisation in Supply Chain (DSC) utilises hardware, software and communication networks for coordination supply chain stakeholder engagement and improving corporate collaborations [8]. Using cutting-edge technologies, it transforms conventional SC processes by fostering innovation, competitiveness, and sustainability. In terms of SC's and sustainability, I4.0 consists of several different

components such as initiatives in energy efficiency, green manufacturing, sustainable logistics, SC transparency and traceability, waste reduction and recycling, and collaboration [10]. The key I4.0 technological pillars are as shown in **figure 3**, and the key I4.0 technologies are further shown in **figure 4**.



Fig. 3: I4.0 Technological Pillars [9]

1. Energy Efficiency - I4.0 technologies aid in the optimisation of energy consumption throughout the SC. Energy usage in warehouses, factories, and transportation vehicles can be monitored using IoT sensors and smart metres, indicating areas for improvement and enabling energy-saving measures.

2. Green Manufacturing - Advanced analytics and AI-powered process optimisation help to reduce resource usage, waste generation, and emissions. Smart manufacturing systems can alter output levels in real time, eliminating overproduction and reducing environmental impact. Furthermore, by enabling improved tracking and utilisation of materials and components, digital technologies facilitate the application of circular economy (CE) principles such as remanufacturing and recycling.

3. Sustainable Logistics - Route optimisation, load consolidation, and effective inventory management are all possible with advanced data analytics and optimisation algorithms, lowering fuel usage and carbon emissions. Greener transportation is achieved using autonomous and electric cars, as well as drones, which reduce air pollution and the carbon footprint of logistics activities.

4. Supply Chain Transparency and Traceability - IoT sensors, blockchain, and data analytics, for example, all contribute to increased SC transparency and traceability. This allows for more accurate tracking of environmental and social repercussions across the SC. Companies can track and trace raw materials, components, and finished goods to ensure compliance with sustainability standards, detect potential risks, and promote responsible sourcing practises.

5. Waste Reduction and Recycling - Advanced analytics and AI may pinpoint waste generation and inefficiencies, helping companies to reduce waste. IoT sensors and RFID tags can also help sort, track, and recycle waste.

6. Collaboration - Digital platforms improve stakeholder communication, coordination, and information sharing. This promotes integrated sustainability programmes, supplier participation, and circular supply chain models.

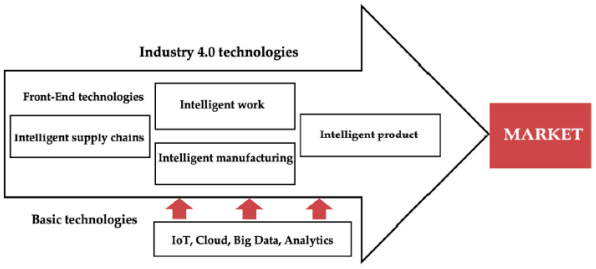


Fig. 4: Technologies in I4.0 [11]

Industrial Internet of Things (IIOT)

The IIoT connects and communicates devices, sensors, machines, and systems in the industrial environment. The IIoT illustration is as shown in **figure 5**.

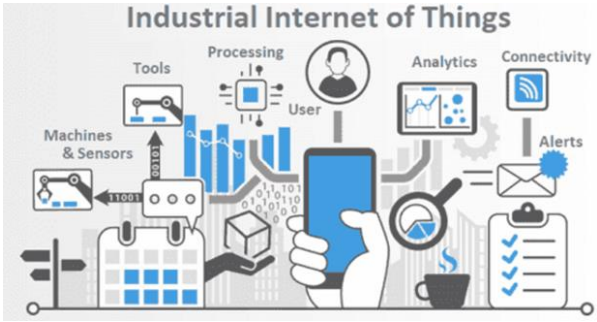


Fig. 5: Industrial Internet of Things (IIOT) [12]

It gathers real-time data from numerous sources, including as equipment, manufacturing lines, and SCM components. It allows for real-time inventory management, more accurate demand forecasts, and more effective logistics operations The efficiency of operational activities, the reduction of waste in terms of time and resources, and the rapid decision-making based on stored data are all advancements that may be made with IoT [13].

Machine Learning (ML)

I4.0 is made up of several efficient technologies, including ML. The ML algorithms analyse massive amounts of data generated from IIoT devices and other sources to reveal patterns, correlations, and insights that humans may overlook.

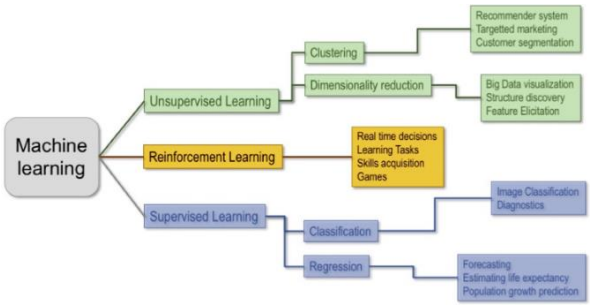


Fig. 6: Machine Learning Type [14]

ML models may adapt and improve over time by continuously learning from fresh data, hence helping continuous improvement activities in the industrial sector. AI approaches are the best fit for dealing with this massive data burden. ML techniques are popular subdisciplines of AI that find and extract patterns among variables using massive datasets, shown in **figure 6**.

Blockchain Technology

Blockchain technology creates a decentralised, secure, and transparent ledger for recording and verifying transactions and data exchanges between multiple parties, as well as for recording and verifying transactions and data exchanges between multiple parties.

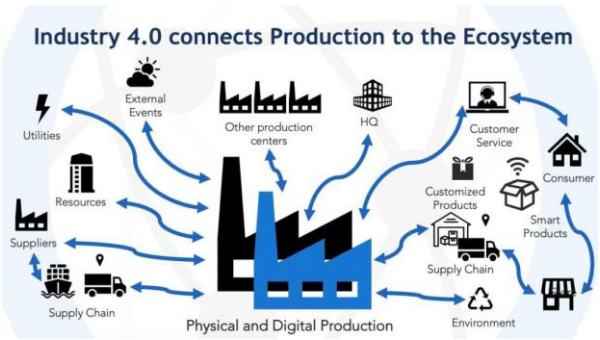


Fig. 7: I4.0 Application Areas [15]

Blockchain provides secure and reliable data sharing and collaboration across SC partners such as manufacturers, suppliers, distributors, and customers in the industrial setting. It allows for the safe and secure storage of product information, certifications, warranties, and maintenance histories through the device's lifecycle. **Figure 7** shows I4.0 application areas with connecting production to the ecosystem.

2.2 Supply Chain Optimisation

The process of maximising efficiency, lowering costs, and increasing overall performance in the SC by streamlining operations, removing waste, and making educated decisions is referred to as SC optimisation. Currently, optimisation is highly crucial in every organisation, especially in the SC, because designing new routes, locations, manufacturing, and just-in-time deliveries are essential and that is why customers pay that type of money. Mathematical programming, simulation, or a combination of these methods are the most popular ways [16]; and primarily employed for decision-making that involves new configurations and combines dynamics and operational structure, such as the construction of a SC network. Making judgements on multiple linked elements like as demand forecasting, inventory management, production planning, transportation routing, and resource allocation are all part of supply chain optimisation. Mathematical models offer a formal framework for representing and solving these difficult choice problems. Mathematical models integrate SC issues from the real world into equations, enabling quantitative analysis. This permits thorough study and evaluation of various scenarios, helping decision-makers to pinpoint the best answers considering certain goals, restrictions, and trade-offs.

Ignoring the pandemic's spread period and the ripple effects in supply networks;

Ignoring concurrent disruptions in demand and supply, as well as production and logistics capacity;

Concentrating solely on vital product supply networks and the aftermath period to adapt traditional production-inventory models for recovery planning;

A lack of quantitative analysis of the consequences of temporarily shutting down supply chains for non-essential products and reallocating non-essential labour [17]. All of these are key issues to consider before using optimisation in the pandemic situation in 2019/20.

Data inputs for optimisation models must be accurate and dependable, including demand projections, lead times, transportation costs, and capacity restrictions. Obtaining high-quality data, on the other hand, might be difficult since information may be distributed across numerous systems, prone to errors, or out of date. Incomplete or incorrect data can result in inferior solutions or even incorrect conclusions. RFID has the potential to provide massive amounts of real-time, streaming data that might prove extremely useful in optimising supply

chains [18]. Firms can improve order fulfilment, reduce delivery lead times, and increase responsiveness to client demands by optimising SC procedures.

This results in increased consumer happiness, increased loyalty, and a competitive advantage in the market. SC optimisation can help to achieve sustainability goals by lowering carbon emissions, reducing waste output, and improving resource utilisation. Optimisation of transportation routes, for example, reduces fuel usage and greenhouse gas emissions, whereas optimisation of inventory levels reduces excess output and waste. Studies shows optimisation fosters sustainable practises by taking social, environmental, and ethical aspects into account throughout the SC. Firms can contribute to the preservation of natural resources, promote responsible sourcing, and ensure compliance with legislation and standards by incorporating sustainability into decision-making [19].

2.3 Sustainability Effects in SCM

Global SC's contribute significantly to greenhouse gas emissions, resource depletion, and pollution. Workers' well-being and rights, as well as the rights of local communities and other stakeholders, are prioritised in sustainable SC. Risk management in the SC is inextricably related to sustainability considerations. Climate change, legislative changes, and societal disturbances can all have an impact on the availability and pricing of resources, causing operations to be disrupted.

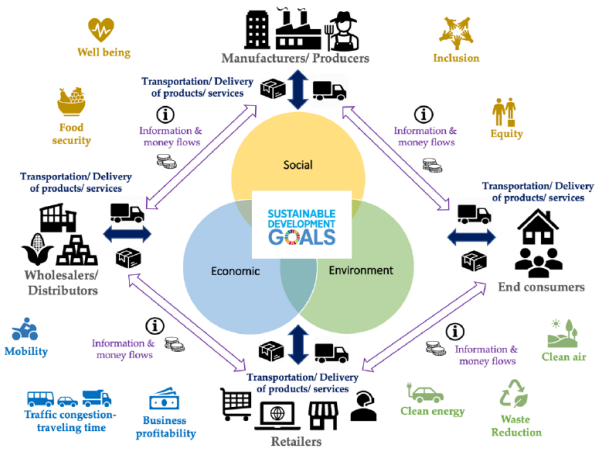


Fig. 8: SC Impact on Sustainability Framework [23]

S-SCM broadens the scope of traditional thinking by creating and optimising SC while keeping the economy, the environment, and society in mind [20]. SSCM practises include a company's internal and external practises that are implemented to make its SC more sustainable across all three dimensions of sustainability [21]. Firms with a clear sustainability plan can provide a stronger competitive advantage and have greater long-term viability than organisations operating on a "business-as-usual" basis and solely prioritising profit [22]. An example framework of SC impact on sustainability is shown in **figure 8**.

Triple Bottom Line (TBL) - TBL is a concept in sustainability that goes beyond financial indicators to broaden the traditional understanding of company performance. It emphasises the importance of considering three dimensions namely, economic, social, and environmental while assessing firm's influence and success. The TBL's economic dimension is concerned with financial performance and profitability. It entails evaluating a company's potential to create economic value, attain financial stability, and assure long-term viability.

Social Performance - The TBL's social component includes the influence of firm's operations on individuals and communities. It entails considering social well-being, equity, and stakeholder relationships. This covers employee well-being, labour practises, community participation, diversity and inclusion, and ethical behaviour.

Environmental Performance - The TBL's environmental dimension focuses on the environmental impact of a firm's operations. It entails thinking about natural resource conservation, reducing pollution and waste, and encouraging environmental sustainability. Carbon emissions, energy and water usage, waste management, biodiversity conservation, and the utilisation of renewable resources are all considerations to consider.

SC dynamic capability makes organisations more flexible, allowing them to more easily and quickly adjust to market trends and successfully deal with market volatility, allowing the firm to attain long-term competitive advantage in its industry [24]. Also [25] recognised that SSCM practises depend on dynamic capabilities and that, to maximise competitive performance, there must be alignment between the two.

2.4 Supply Chain Effectiveness

The most effective SC is one that has the lowest cost while also meeting the customer's requirements for the operation, such as accuracy in delivery and lead time, especially when dealing with goods with a limited shelf life [26]. To be more effective at SCM, the organisation needs to be skilled at monitoring efficiency and cost to ensure that they are working with the proper goods. To evaluate how effective the

SC is, they will require a reliable tool or technique. From this specific perspective point, it is crucial to take a step back and consider what supply chain efficiency is and what research has been done on it thus far. This study aims to describe the components of SC efficiency [27].

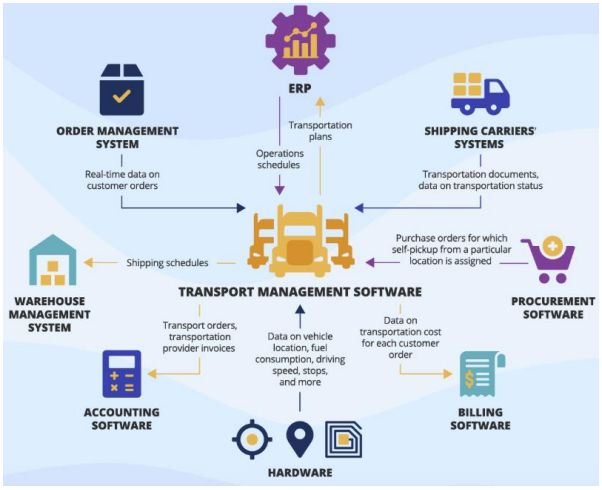


Fig. 9: Transport Management System (TMS) in SC [28]

The goal of effective supply chains is to keep the right amount of inventory. Insufficient inventory results in stockouts and lost sales, while excessive inventory uses up cash and raises holding expenses. Organisations can reduce inventory holding costs while guaranteeing that products are accessible when needed and wanted by implementing lean inventory management practises, such as just-in-time (JIT) inventory. Order entry, order validation, allocation, and fulfilment are few of the different tasks involved in processing orders. Order processing can be streamlined, errors can be reduced, and order fulfilment can be hastened by automating these procedures, using EDI or order management systems, and putting in place standardised workflows. For a supply chain to operate efficiently, logistics and transportation must be optimised. This involves effective warehouse operations, carrier selection, load optimisation, and route planning. By utilising technology, such as TMS, GPS tracking, and route optimisation software, logistics costs may be kept to a minimum, delivery times can be slashed, and overall efficiency can be increased. TMS application in supply chain is illustrated in **figure 9**.

2.5 Risk Management (RM)

An essential component of guaranteeing efficient operations and preserving sustainability in the SC is RM as shown in figure 10. Organisations may minimise disruptions, safeguard their brand, and uphold sustainable practises by detecting, evaluating, and reducing risks. SC's may be disrupted by environmental hazards such as natural catastrophes, the effects of climate change, or resource scarcity, which may have long-term sustainability effects. Organisations can carry out environmental impact analyses, create backup plans, diversify their sources of supply, and work with suppliers on environmental measures to reduce these risks. Environmental risks can be reduced by applying sustainable practises, such as cutting emissions and putting circular economy concepts into practise. SC's are more vulnerable to technology-related hazards because of an increased reliance on technology and digital systems, including cybersecurity threats, data breaches, and system breakdowns. These risks can be reduced by putting in place strong cybersecurity safeguards, frequent system audits, and disaster recovery plans [4].

For SC operations to be viable, data privacy must be maintained, intellectual property must be protected, and the technology infrastructure must be safe. To detect potential connections and causality between risks, risk analysis may also include correlation analyses, controlled experiments, or simulations. Figure 10 illustrates steps for SC risk management [29].



Fig. 10: SC Risk Management Model [29]

These methods can be helpful for any risk treatment approach because they allow for the formulation of plans to address two or even more hazards [30]. The demand for sustainable business practises in markets and communities has increased or changed the risks that firms face. Any of these solutions should be anchored to what is a reasonable range of options that align with the sustainability principles of a company, as well as the cost of their implementation. They should also be linked to the drivers of sustainability-related risks. To summarise, merging I4.0 with sustainability ideas can help businesses in the industrial sector improve operations, reduce waste, and have a smaller environmental effect while remaining competitive in today's constantly evolving business environment. The employee could learn a lot of new skills, including predictive

algorithms, data analytics, and the IoT. This enables more precise demand planning and estimation, effective inventory management, and quicker order processing. Transparency and traceability are made possible by I4.0 technologies, which enhance sustainability in dynamic international supply chains. Transparency allows consumers to make informed decisions by providing information on the environmental impact and sustainability of products.

3 Methodology

The methodology section describes the research design, research approach, strategy, design, data analysis methodologies, and data collecting method. We systematically collected , analysed, and evaluated data to answer the research questions provided in this study using the technique that have chosen as our framework. By using a qualitative methodology, we want to gain a thorough understanding of how I4.0 technologies affect SC operations while also considering the implications for environmentally friendly practises. The research onion is a multi-layered conceptual framework that aids in the organisation and planning of research projects [31]. It has several levels, each of which represents a different step in the research process.

3.1 Research Design and Philosophy

To ensure the validity and reliability of the current study, this research was designed in compliance with several journals. Because the focus of our study is on how I4.0 can enhance sustainability for the global supply chain, we looked at a wide range of papers and publications that support I4.0. The first steps are the research plan, data collection, analysis, and limitation. The literature review covered topics like I4.0, sustainability, optimisation, efficient operations, and risk management. This study's design is qualitative and exploratory in nature. The study employs an interpretative methodology to understand the relationships between supply chain optimisation, new technical advancements, and straightforward business practises. Using qualitative data and thematic analysis, the study aims to delve deeply into the perspectives and experiences related to the intersection of these areas.

For this study, pragmatism was chosen as the research philosophy. The study topic's many facets, including I4.0 technology, SC optimisation, process efficiency, and sustainability objectives, lend themselves well to pragmatism. The goal of creating practical insights for companies looking to manage the opportunities and challenges posed by I4.0 adoption is well aligned with pragmatic thinking, which places an emphasis on practicality and the application of research findings to real-world situations. Interpreting results in the context of practical application is a key component of analysis. This entails considering how conclusions from the study might be used to improve supply chain processes and support sustainability initiatives.

3.2 Research Approach and Strategy

There are guidelines that must be followed when writing in some studies, and when using qualitative, quantitative, or mixed methods, the most crucial elements of data collection and analysis should be included. The research methodology can be divided into two categories: inductive methodology and deductive methodology. Due to some advantages, inductive methodology is used in this study. However, in some cases, a deductive method was adopted. The inductive method was used in this study because it was based on qualitative knowledge about I4.0. This method is excellent for gathering and analysing data. Other sources that investigated the same studies were added to this information. It would be very nice and instructive to have intellectual, useful facts about supply chain and sustainability while creating this study. But occasionally, as I write in the analysis section, Researcher also received studies from other universities that used a logical approach and quantitative techniques. In the era of I4.0, the qualitative method helps us to unearth hidden patterns, motivations, obstacles, and possibilities that contribute to the landscape of sustainable practises. A thorough examination of the human elements inside these technological and managerial paradigms is made possible by the qualitative approach's ability to capture rich narratives and points of view.

The study intends to delve into the multiple relationships that exist within these areas, employing qualitative data analysis and thematic exploration to unearth insights that contribute to sustainable business practises and improved supply chain operations. The research strategies outline the techniques used by a business or organisation to carry out research and development to accomplish its goal. With the help of partnerships with respected educational institutions, the shipping company strives to achieve its goals of sustainability and cost reduction. Some qualitative, quantitative, and mixed methodologies are used to discover new paths. Every approach often begins with a hypothesis based on a qualitative analysis of the data or a value judgement. In the end, a study design that is appropriate for the goals and objectives will be more beneficial and significant than traditional debates about the "best" research methodology. The

study focuses on analysing how I4.0 technologies are incorporated into SCM and how this affects sustainability initiatives.

3.3 Data Collection

This component of the methodology outlines the systematic procedures used to gather data from all relevant sources to address the core research questions. To capture diverse perspectives, this study employs a multi-methodological approach that integrates secondary qualitative data with a comprehensive literature review. Secondary data including peer-reviewed journal articles, books, conference proceedings, and industry reports were retrieved from established academic databases such as Scopus and Google Scholar. This cross-disciplinary search strategy ensured wide thematic coverage across the fields of supply chain management, I4.0, and sustainability.

The research framework is structured around an inductive approach and thematic text analysis to synthesise current literature and generate new insights. The study utilises secondary data analysis to systematically categorise existing research, ensuring a rigorous foundation for drawing valid academic conclusions. Through the observation and critical synthesis of compiled texts, thematic analysis was applied to identify recurring patterns, operational bottlenecks, and emerging trends. This qualitative methodology provides a thorough, extensive summary of the intersection between I4.0 technologies and sustainable SC development.

Although there are journal papers available, it might be difficult for researchers to find the appropriate amount of information from the relevant database because they want to ensure that the supply chain and sustainability information are accurate [32]. If we look at the quantitative data, we can also observe that the network analysis benefited from the quantitative data that had been acquired. While traditional qualitative approaches use certain determinedly biased aspects, that method offers an unbiased means to condense and conceptualise the literature into clusters. Network analysis is used to categorise the clusters and illustrate data variation in the subject area through publishing keywords [33].

The goal of the inquiry was to examine the firm's technologies for smart and simple functioning, the business offering, consumer and supplier qualities, operations, and SCM with an emphasis on decision-making and problems. Title, abstracts, authors, affiliations, citation records, keywords, publishing years, and countries are just a few examples of the different identifiers included in the data collection. Data from Scopus and Google Scholar are thus ideal for assessing the level of expertise in supply chains, industrial engineering, and sustainability. Before collecting the data, there are other sample approaches like abstracts that were observed because it is very difficult to locate an informative subject while collecting data throughout time. This sample abstractions collection for digital twins has been utilised to solve physical simulation problems for SC's and smart manufacturing systems to improve inventories [34].

There are no interviews or primary sources used in this study because it is entirely based on secondary data. Instead, it is based on published papers and journals. When it comes to the information gathering procedure, the company's website and the HBS Harvard business review genuinely provide information on the support and advanced overreaching strategy towards cost reduction and quickening movement towards end-to-end supply chain integration [35]. That is how one can acquired the information from the renowned and esteemed websites and periodicals. This process produced goals for several activity areas with various outcomes while not sacrificing the sample technique used. The search operation was carried out from May to June 2023. The complete data set was verified with additional sources, including journal articles, websites, and various publications.

3.4 Data Analysis

The methodology part must include the data analysis procedure. There are two different sorts of data analysis: qualitative and quantitative [36]. The researcher uses experience, observation, focus groups, and interviews in the qualitative method analysis to pinpoint the key elements and relevant patterns. The "thematic analysis technique" has been selected in this research study for the best analysis. Finding patterns or themes in qualitative data is the process of thematic analysis [37]. This indicates that it is not bound to a specific epistemological or theoretical position, unlike many qualitative methods. Because of the variety of tasks in learning and teaching, this makes it a very flexible strategy. Thanks to the analysis, a qualitative approach is now able to manage the rapidly expanding volume of information in each subject and provides more significant data with a stronger emphasis on research. Identify the new generation of the world, which is working on technology and advancing things with a focus on environmental advantages, for each component of this in the literature study. Big data analysis is crucial for the supply chain and the excellence sector in I4.0 because of its effectiveness, decision-making, and overall performance, which should be very beneficial to both the public and

commercial sectors. Cooperation between the various supply chain functions is required regardless of the industry sectors. These roles can, however, be unique depending on the sorts of businesses and final goods or services provided to the clients. To balance supply and demand, the supply chain's many processes must be integrated and coordinated. The IoT has the potential to assist transport companies in making difficult decisions. It aids in the recognition of scenarios and their integration with existing system processes to prepare models for analysis. These models are also used in the decision-making process in industry.

Studies suggest that SCM should focus on sustainability to be competitive over the long term with future products, procedures, and industrial systems built with the 3S's smart, sustainability, and safety in mind. Researchers analysed the journals [32], [2] to demonstrate that the network design and operation for smart manufacturing or the supply chain are similar, but that there are times when people prefer to solve problems using cyber-physical systems and other times when they prefer to use more complex operational methods. Although cyber-physical systems are also used for the organisation's ongoing improvement.

The practises, procedures, information, and technology that are employed to boost organisational effectiveness frequently make up these components. The ability to continually improve services and product quality via the use of big data analysis and the IoT can revolutionise the way that smart manufacturing is done and is mostly seen in the automotive, logistics, and machinery industries. It can also be observed in the literature study, and that is cost reduction without disruption in the supply chain, which is most important, after all, cost reduction without quality compromise is the essential thing for I4.0. System design in the study of digital twin technology traditionally includes the modelling, analysing, and optimising of system layout, production, supply capacity, supply flexibility, and operating strategies [34]. According to research, most African countries are attempting to embrace I4.0 and streamline supply chains, but motivation for optimisation is low due to limited access to the internet and energy. According to the source, there are six countries that are at the forefront of I4.0: Canada, Japan, Australia, Germany, Austria, and Switzerland. It all comes down to factors like knowledge and skill. Some of those nations are also excellent in terms of training and education.

We can predict how the I4.0 will develop in the future by looking at every study report on SCM and I4.0. Through decentralisation, vertical and horizontal integration, and remote process monitoring, the same technology can contribute in multiple ways to the performance in manufacturing and the supply chain. The research journal addresses organisational design based on performance and simplification towards inventory level, as well as the method of technology management. Different configurations of I4.0 technologies have the potential to bring about several advantages for engineering and sustainability, as well as management of the operation, including just-in-time deliveries, cost savings, higher process flexibility, and improved customer service.

Data analysis has influenced various organisation to digitalisation their workplace for boost more productivity. Basically, the adoption of I4.0 has a significant impact on the production of industrial value. There are still few studies on its business prospects and difficulties [38]. According to a general perspective, the government's adoption of I4.0 or the creation of new regulations should aid the SC and increase sustainability. Firms constantly strive to improve their working procedures and product quality through long-term growth, decision-making, and some goals. The end outcome of the policy is more affordable delivery on time and competitiveness in the logistics business. The new generation electrification for rail and electric propulsion vehicles is more environmentally friendly and less expensive for every person of the country. Overall, the new era of technology in the business benefits the organisation and helps the nation's economy. The review discusses sustainability and effective analysis for better environmental and water management. Green manufacturing, often known as smart manufacturing, provides better output while minimising environmental impact. I4.0 is also being implemented in oil-producing countries (Middle East) to improve production and sustainability. The talent 4.0 is a worker training programme that is required to train their employees for a higher-quality product in the emirates. This type of digital transformation assists manufacturers in determining their existing level of digital and sustainability readiness. This framework aids an organisation's planning of novel technological solutions for product quality in accordance with client requests. This aids in determining the significance of the environment within an organisation and then assists in ensuring that it is carried out correctly.

4 Findings and Discussion

When a supply chain is susceptible to supplier and environmental interruptions, we aim to assess the efficiency of flexibility and redundancy in terms of decreasing predicted supply chain costs and

maximising expected service delivery. One of the most important chapters in the study is this one. The qualitative information used in this study underwent extensive examination and analysis. This is done to make sure that all information and practises are supported by the data that has been collected and clearly displayed. This study's main objective was to identify the To adapt to market shifts, consumer demands, and I4.0 integration of digital twins and simulation methodologies, create a flexible supply chain. This will help with supply chain network optimisation and decision-making. By supporting green practises and reducing carbon footprints, unplanned disruptions and I4.0-SC networks can increase environmental sustainability.

4.1 Supply Chain Operational Efficiency and Resource Utilisation

This study examines the adverse impacts and potential obstacles to human development throughout history and in the present. Specifically, it focuses on the economic, environmental, and social significance of incorporating sustainability principles into supply chain operations. Significant improvements in operational efficiency and optimised resource utilisation have resulted from the incorporation of I4.0 technology into supply chain operations. The study's analysis showed that the phenomenon has far-reaching effects on many parts of the SCM process. The researchers employed a flexible policy that permitted utilisation of the network's potential capacities in accordance with structural dynamics and rational utilisation of the structural functional network redundancy, which in turn allowed them to improve the effectiveness and efficiency of network operations as well as strike a balance between resilience and sustainability [39]. The utilisation of digital twins and simulation methodologies in SC optimisation facilitates the development of precise models for the purpose of evaluating diverse scenarios. This aids in the identification of optimal solutions that maximise efficiency while minimising risks.

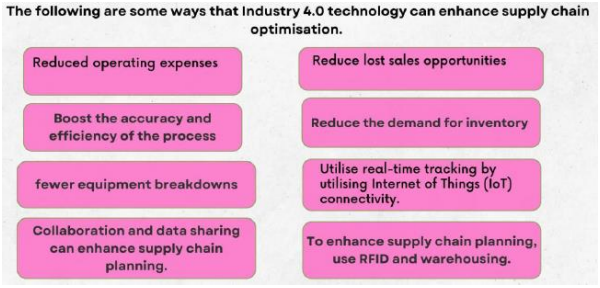


Fig. 11: I4.0 and SC Optimisation Methods. [40]

The **figure 11** discusses several techniques to optimise the supply chain while cutting costs. I4.0 can support business expansion while also assisting with sustainability, labour and cost reductions. According to [41], an interconnected, digital supply chain can increase business speed, agility, granularity, accuracy, and efficiency while reducing operational costs by more than 30%, reducing missed sales opportunities by more than 60%, and even reducing the amount of inventory needed by more than 70%. The use of such predictive analytics techniques has almost halved predicted error rates [42]. More precise demand forecasting assists businesses in better managing their inventory, which lowers costs, which is the most crucial factor.

4.2 Building Adaptable Supply Chain Response

Improving adaptability to market changes and disruptions - Supply chains can now react quickly to unanticipated disturbances and changing market conditions thanks to the incorporation of I4.0 technology into supply chain operations. Organisations have shown impressive adaptability by utilising cutting-edge technologies and data-driven initiatives. The industry's main objective is to introduce new adjustments and deal with the issue. However, large consumer companies regularly struggle to adapt their end-to-end SC to changing consumer preferences and behaviours, increasing competition, and other problems while maintaining strict cost control and maximising growth potential. The presence of new market participants presents a formidable challenge to established industry incumbents due to their adoption of inventive business strategies, competitive pricing strategies, and compelling brand identities. The proliferation of omnichannel and direct-to-consumer models is leading to an increased need for operational teams to meet the evolving demands of these business models.

Long-term Business Objectives - A longer-term goal, such as growth into new categories or extension of market share, should be identified before concentrating on the next round of cost optimisation or the next acquisition. These goals will define the parameters for the required operating model and capabilities in the future [43]. Long-term business objectives also encompass several digital factors. As a collective of organisations, it is imperative to have a strategy for integrating diverse technology stacks in a cohesive manner. Furthermore, it is imperative for all organisations to allocate resources towards the adoption of I4.0 technologies to enhance or optimise their performance. These technologies encompass

several advancements, including autonomous planning and robotic process automation. There are certain best practises that can be disseminated throughout many business sectors, including those that pertain to ensuring regulatory compliance among emerging and smaller supply chain business units. Cooperative network development is crucial for developing a supply chain that can respond swiftly to customer requests, market dynamics, and unforeseen interruptions. To be successful, collaboration partners must manage differences in organisational design and culture. With a history of harsh encounters may make partners hesitant to share critical information, causing them to focus on their individual "collaborations" in silos, which is a recipe for less-than-ideal results [44].

4.3 Integration of Digital Twins and Simulation Methods in I4.0

In the beginning, the researcher established the system's goals and definitions while taking the overall goal of the study into consideration. The potential of I4.0 in this context is enhanced by the incorporation of digital twins and simulation approaches, leading to a wide range of breakthroughs. The integration of digital twins facilitates the generation of virtual replicas of real components inside the supply chain, enabling the modelling of many scenarios. Furthermore, the optimisation of network setup within the supply chain facilitates the development of novel approaches. An example of digital twin in global supply chains is as shown in **figure 12**. Through the utilisation of simulations, organisations can analyse various configurations of suppliers, distribution centres, and manufacturing facilities. This enables them to determine the optimal network topology that effectively minimises costs and decreases lead times. To boost efficiency and competitiveness in the current global economic climate, industries need to be restructured to allow for higher levels of digitisation and computerisation [46].

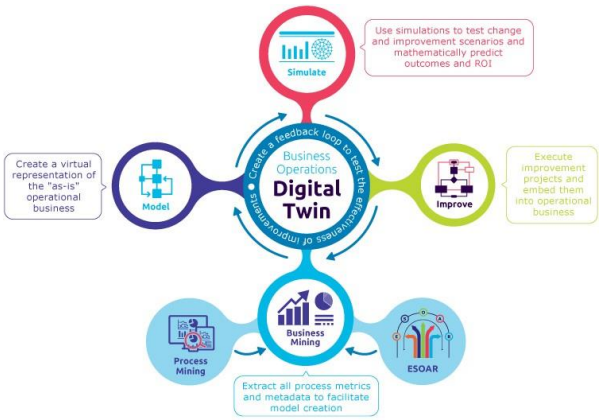


Fig. 12: Digital Twin in Global Supply Chains [45]

For network optimisation and decision-making, a single simulation model that uses digital twin technology is even more crucial. After all, the goal of simulation approaches is to give the logistics crew the shortest possible route. The supply system is much more crucial for the model's output to comprehend decision-making and simulation in the digital twin. **Figure 13** illustrates how decisions are made using a digital twin and a simulation model on ways the supplies are delivered and how the data is processed. SC decision-makers have access to an effective tool in the form of simulation-based digital twins.

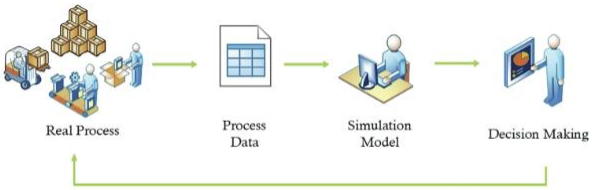


Fig. 13: Proposal for Applying Simulation as a Decision-Support Tool [46]

Organisations can increase efficiency, lower risks, and respond skilfully to market changes by offering a virtual sandbox for testing scenarios and optimising strategies. Implementation calls for collaboration between supply chain experts and simulation specialists, ensuring accurate modelling and insightful data. The integrated strategy makes it easier to test various scenarios without having an impact on the actual supply chain. Before implementing new logistics, production, or distribution tactics, decision-makers might test them out to see how they affect the situation.

The use of I4.0 solutions is associated with significant investments and process adjustments; nonetheless, it is observed that difficulties can be eased by utilising flexible tools like simulation. The value of I4.0 has expanded recently, and not just large, established companies nowadays like to invest in it, which is fantastic for the modern world. All things considered, the digital market is expanding and is very beneficial to the new manufacturing line, facilitating supply and decision-making. The market for digital twins is anticipated to grow by about 40% by 2025, and by 2026, it's estimated that more than 90% of IoT platforms would make use of some part of the technology [47]. To increase resilience and agility in the face of the uncertain global economic picture and the rapidly changing nature of the workplace, 90% of global procurement leaders say they would modify operating models.

4.4 I4.0-Enabled Supply Chain Networks

The integration of SC networks and I4.0 technology holds great promise for promoting environmental sustainability. These tools are being used by organisations to improve operations as well as to promote environmentally friendly practises and reduce their carbon impact [48]. The study emphasises the role that I4.0-enabled supply chain networks play in promoting resource and energy efficiency. Firms can find operations that consume a lot of energy and waste resources by using real-time data monitoring and advanced analytics.



Fig. 14: Sustainability Possibilities [49]

This awareness encourages the implementation of methods that reduce consumption, which helps to lower energy costs and slow down the depletion of resources. For the first time since WWII, greenhouse gas emissions decreased by roughly 6-8% [50].

Technologies from I4.0 make it possible to keep an eye on emissions throughout the supply chain. Organisations may recognise high-emission locations and take action to reduce them by analysing data on transportation, production, and distribution. This proactive strategy assists in meeting sustainability objectives and emission reduction targets. The implementation of intelligent task scheduling yields enhanced levels of process transparency, flexibility, quality, and customisation. **Figure 14** provides an overview of sustainability possibilities within digital economy [49].

Moreover, intelligent energy systems contribute to the mitigation of energy use. Intelligent manufacturing environments have been found to contribute to enhanced product lifecycle management, hence facilitating waste reduction, increased recycling and resource utilisation, as well as diminished emissions of greenhouse gases [51]. According to the study, I4.0's integration promotes a transition to a circular economy. The identification of opportunities for waste reduction, reuse, and recycling is made easier by improved visibility and data analytics.

Manufacturing is necessary for the adoption of socially responsible and environmentally sustainable practises since it has a positive, broadly sweeping effect on world health. A sustainable way of thinking creates a positive feedback loop that will attract more people and organisations. The supply chain and manufacturer industries can produce better, more effective products and take various, sustainable pathways thanks to I4.0 technologies. To put it another way, this can increase production and speed while improving the cost and dependability of the capital. Due to the substantial data generated by smart factories, the involvement of professionals such as data analysts, machine learning specialists, and Big Data experts is imperative. These individuals are responsible for effectively handling the data, deriving valuable insights, enhancing operational efficiency, optimising machinery, and ensuring the continuous operation of the factory.

4.5 Practical Implementation

To create an economic and social system that can react quickly to sudden changes in the system, I4.0 plans should be clarified and elaborated. Companies need to be persuaded to priorities investments in digitisation and expanding technological expertise. Applying new models of technology to the working environment should be the top priority, and swift action should be taken to implement better frame designs and continuously enhance the system. The first digital transformation is essential for a single organisation to implement I4.0. This includes equipping the supply chain with IoT sensors strategically positioned throughout the network.

These sensors will allow for the collection of key data points in real time, such as inventory levels, equipment health, and transportation condition. Simulation is also an important component of I4.0 and digital twins, which aid in the development of a solid connectivity infrastructure to ensure uninterrupted communication. This network will be the foundation for transmitting data that will allow for informed decision-making. This is all about the technologies, which are difficult to adopt, but once done, they should be very beneficial to working and the production quality should be excellent.

Nowadays, sustainability is becoming increasingly necessary and important. Start by carefully analysing the supply chain's environmental impact. Identify areas that can be improved, such as cutting back on energy use, lowering trash production, and enhancing transportation routes. Analyse the carbon footprint and resource usage at various supply chain levels. By

incorporating solar or wind power into your facilities, you may help make your business more environmentally friendly. The I4.0 initiatives, as well as the traditional culture of continual improvement. Feedback is significantly more necessary everywhere for a good implementation solution. Using feedback to improve processes and technology in response to changing market conditions and supply chain dynamics. In the strategy, emphasise agility and adaptability, as I4.0 is not a one-time implementation but a continual journey of development and innovation.

4.6 Discussion

The combination of SCM and I4.0 technology in recent years has fundamentally altered how organisations conduct their operations. We are aware of how crucial I4.0 is to the operations of every organisation, together with sustainability. In this study, we discovered that the process cannot even continue without the internet and the data. I4.0 has made working processes easier and less time-consuming, which is the most crucial aspect. Supply chain efficiency has significantly increased thanks to I4.0 technologies like the IoT, AI, and BDA. Businesses receive real-time access into their operations using IoT-enabled sensors and devices, enabling optimised routing, preventive maintenance, and simplified inventory management. In this study, we are aware that if there are any issues, the technology context assessment would intensify. According to the literature review, the uses and focus of writing in the framework of I4.0 increased after the pandemic, so we can assume that consumers had many problems during and after the pandemic.

There is also a wealth of data available on the internet about I4.0 and supply chain. However, there is a limited amount of data available in journal papers regarding the necessary skills for I4.0, as well as its implementation in the manufacturing and logistics sectors. The significance of talents in fostering personal growth and shaping prospects cannot be overstated. According to the executive's perspective, it is advisable for all employees to participate in educational lectures and undergo examinations to enhance their professional growth inside the workplace. From a technological perspective, the utilisation of BDA, IoT, and CC poses significant challenges in achieving enhanced product quality.

However, all these tasks are easier compared to traditional industrial engineering. Acquiring information and gaining experience contribute to the generation of fresh ideas and provide enhanced opportunities. The literature study discusses the significance of an effective supply chain in relation to manufacturers, inventory management, and consumers. The significance of just-in-time delivery cannot be understated in terms of enhancing productivity and achieving cost reductions.

The emergence of E-Commerce and evolving consumer inclinations has precipitated a substantial transformation in how products are transported to clientele. Third-party delivery services have become an essential element in contemporary supply chain systems. Third-party delivery services utilise I4.0 technology to enhance the efficiency of last-mile delivery. The optimisation of routes, considering variables such as traffic conditions, delivery timeframes, and package dimensions, is accomplished through the utilisation of AI-powered algorithms. The analysis of I4.0 entails the amalgamation of digital technology and physical systems, presenting a distinctive prospect for sustainability. The management and monitoring of resources, such as electricity, water, and raw materials, is facilitated by the utilisation of IoT sensors. These sensors have the capability to detect consumption patterns, identify inefficiencies & automated adjustments.

5 Conclusion and Recommendations

To improve a supply chain's responsiveness, this study investigated an integrated approach to supplier selection, demand allocation, and the creation of capabilities based on redundancy and flexibility. In conclusion, the fusion of I4.0, SCM, and sustainability are forging a new era of efficiency, adaptability, and environmental consciousness in the business world. As we stand at the intersection of technology and commerce, it's evident that the objectives set forth enhances SC efficiency, ensuring flexibility, integrating digital innovations, and promoting sustainability, are not only achievable but crucial for the future success of businesses.

Various types of technology are accessible within the context of I4.0, which can be effectively employed inside the SC to yield optimal outcomes, while also promoting sustainability. The primary objective of this study is to examine the concept of I4.0. How can the implementation of I4.0 be leveraged to effectively minimise costs and enhance the efficiency of SC operations. The literature review encompassed an examination of many system types relevant to I4.0, including energy efficiency, green manufacturing, sustainable logistics, supply chain transparency, waste reduction, and recycling. These aspects hold significance within the context of I4.0. These technologies, namely the IoT, ML, and blockchain technology, are responsible for the completion of this entire process. The completion of

I4.0 is contingent upon the presence of decision support.

This is because within the fields of industrial engineering, SC and operations management, control systems, operations research, and data science, all systems and technologies fall under the umbrella of I4.0. Consequently, I4.0 is at the forefront of global advancements in production and process efficiency. In the absence of optimisation, the functionality of the supply chain is compromised, making it imperative for every firm to prioritise optimisation efforts [2]. Additionally, businesses should strive to incorporate a significant array of technologies to enhance transparency and effectively manage operational constraints. The results can direct researchers' attention to practical problems. After the pandemic ended, rebuilding the SC was an extremely difficult undertaking.

Organisations are better equipped to anticipate, examine, and proactively address possible difficulties, whether they result from market changes or unforeseen disruptions, thanks to the ability to develop virtual replicas of real-world processes and systems. A triple bottom line is crucial when considering the three spheres of the economy, society, and environment. A TBL concept in the supply chain can provide financial indicators and evaluate a company's economic worth, financial stability, and long-term growth as part of sustainability. This study aims to conduct a comprehensive examination of the factors that drive and hinder the optimisation of SC and manufacturing processes in the context of I4.0. The analysis will be conducted from a dynamic capabilities perspective.

5.1 Objectives Fulfilment

The study has fulfilled the key objectives of the research through the findings of the research studies.

RO1. SC Operating Efficiency and Resource Utilisation

This study investigates both the **economic and operational efficiency**, as well as the potential for cost reduction. What is the most crucial aspect in achieving this purpose, both in theory and in real-world application? The implementation of regulations and the utilisation of effective working techniques can greatly assist individuals in their job endeavours. The utilisation of advanced technologies, such as digital twins and simulation methodologies, can be advantageous in the decision-making process and contribute to enhancing production systems. The identification of optimal solution that maximum efficiency while minimising risk. Reducing risk can contribute to the advancement of innovation and facilitate the exploration of various techniques within the supply chain domain. After all, how inventory is used is an important consideration for SC businesses.

RO2. Creating Flexible and Responsive SC

Firm's need to modify technology sufficiently so that it is **simple to respond** to market changes, competition, and disruption. There has never been a more pressing need to have a **flexible SC** that can react quickly to changing consumer needs, market dynamics, and unforeseen interruptions. The dynamic nature of today's corporate environment necessitates a level of adaptability and resilience that can only be attained by strategically combining technology, innovation, and a SCM strategy. It is not only necessary but also a competitive advantage to be able to adapt to changing consumer tastes and dynamic market conditions. Those whose supply chain operations successfully use adaptive practises stand to gain not only operational efficiency but also client loyalty. Firms may now obtain real-time insights into market trends, consumer preferences, and operational bottlenecks thanks to this technological synergy, which enables them to make intelligent decisions with astounding accuracy.

RO3. I4.0 Integration to improve SC Network Optimisation and Decision-Making Processes.

Identifying the **digital twins' best simulation technique**, which is to define the systems' objectives. This objective discusses the application of digital twins in I4.0. The object is extremely important for the network optimisation and decision-making, a single simulation model that uses digital twin technology. Digital twins are explicitly mentioned in the SC for optimisation using simulation tools for decision-making and skilfully responding to market shifts.

RO4. I4.0-enabled Supply Chain Networks to improve Environmental Sustainability

This paper aims to establish a **comprehensive project framework** that focuses on **sustainability** and the promotion of eco-friendly practises. Firms are currently undergoing a transition in their operational systems, aiming to adopt energy-efficient practises and optimise the management of waste resources by altering their routes. The technologies associated with I4.0 can monitor emissions across the SC, enabling the adoption of many paths and facilitating the production of higher quantities of high-quality products. This is made possible due to the advancements brought about by I4.0. The involvement of professionals specialising in big data analysis, data analytics, and machine learning is driven by the advent of I4.0, with

the aim of advancing the adoption of environmentally sustainable practises.

5.2 Future Recommendations

Based on an in-depth study, it has been revealed that the integration of I4.0 is significant in terms of enhancing supply chain optimisation and promoting sustainability. Based on the analysis of available data, it can be argued that the implementation of appropriate innovation in SCM and practises is vital for enhancing sustainability. Although I4.0 is now considered highly efficient, there is room for improvement in its implementation.

To assure the proficient operation and management of I4.0 technologies, it is imperative to offer training and upskilling opportunities to the workforce. Create a cohesive team of individuals possessing specialised knowledge in the areas of data analytics, digital twin management, and simulation modelling, with the overarching objective of fostering innovation and enhancing the efficiency of SC operations.

The act of engaging in partnerships with academic institutions facilitates the convergence of industry knowledge, research proficiencies, and the utilisation of nascent technologies. This group of resources has the potential to greatly augment an organisation's capacities and competitive edge.

Establish collaborative ties with suppliers, customers, and other stakeholders to improve overall visibility and coordination throughout the entire process. The act of sharing real-time data has the potential to enhance the precision of demand forecasting and improve the efficiency of inventory management.

Develop an agile strategy that allows for flexibility in adapting to evolving technology trends and market demands. The strategy should outline how the organisation plans to leverage emerging I4.0 technologies while remaining adaptable to changes.

It is advisable to enhance the managerial department of an organisation to effectively integrate technological advancements. There exist several critical factors that must be addressed in the context of future industrial engineering, including investment, education, and behaviour. Among these factors, it is imperative to determine which holds the greatest significance.

When conducting research, it is imperative to thoroughly evaluate and consider the many limitations and restrictions that may impact the study. To enhance readers' understanding of the breadth and relevance of the study's results, it is imperative to acknowledge the study's limitations. There are several issues that require resolution during the discussion section of the study. The nature of academic research necessitates the utilisation of dependable, empirical, accessible, and pertinent data.

The present study has encountered challenges in the areas of data collection, analysis, and research methodology. The potential restrictions of the sample size used for data gathering may arise from practical constraints on available resources or limited access to pertinent organisations. The generalisability of the findings may be limited to a wider range of industries and companies. Furthermore, the utilisation of data gathering methods such as questionnaires and case studies may include inherent biases or subjectivity, which could potentially impact the accuracy and comprehensiveness of the research outcomes. The study's emphasis on I4.0 technologies may inadvertently neglect the potential importance of other upcoming technologies that could have comparable effects on supply chain optimisation and sustainability. Although attempts were made to consider multiple contexts, it is possible that contextual and industry-specific elements were not completely considered, potentially impacting the generalisability of the findings to other organisational settings.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

References:

[1] Macurová, P., Ludvík, L. and ŽWAKOVÁ, M., 2017. The Driving Factors, Risks and Barriers of the I4.0 Concept. Journal of applied economic sciences, 12(7).

[2] Ivanov, D., Dolgui, A. and Sokolov, B., 2019. The impact of digital technology and I4.0 on the ripple effect and supply chain risk analytics. International journal of production research, 57(3), pp.829-846.

[3] Maier, D. & Beveridge, C., 2022. Primed for cloud technologies adoption. s.l., Intelligent CIO.

[4] Shah, S., Chen, S., & Ganji, E.N. (2024). An Investigative Study to Examine Impact of Digitalisation on Manufacturing Supply Chains. Engineering World, 6(1), 61-89.

[5] We Forum Statista, 2024. Global Supply Chains on a Comeback, Available: https://www.weforum.org/stories/2021/12/supply-chain-resilience-lessons-from-covid-19/) Assessed: 29/10/2024

[6] Kulkarni, V.N., Gaitonde, V.N. and Kottursheettar, B.B., 2022. Product lifecycle management (PLM): a key enabler in implementation of I4.0: a key enabler in implementation of I4.0. In Handbook of Smart Materials, Technologies, and Devices: Applications of I4.0 (pp. 349-380). Cham: Springer International Publishing.

[7] Teixeira, J. E. & Teresa-Lehmann, A., 2023. I4.0: the future of manufacturing from the perspective of business and economics - a bibliometric literature review. emerald insight, 33(2).

[8] Hejazi, M. T. (2024). The Impact of Digitalization Practices on Supply Chain Sustainability and Organizational Sustainability. WSEAS Transactions on Business and Economics, 21, 35-43.

[9] Saturno, M., Pertel, V. M., Deschamps, F., & Loures, E. D. F. R. (2017, March). Proposal of an automation solutions architecture for Industry 4.0. In 24th Int. Conference on Production Research, 1 (14), p. 2021.

[10] Solanki, S., Shah, S., & Hasan, S. (2024, November). I4.0 Deciphered: Mapping Key Technologies Adoption in Industry. In 2024 IEEE International Conference on Technology Management, Operations and Decisions (ICTMOD) (pp. 1-6). IEEE.

[11] Kliestik, T., Nagy, M. and Valaskova, K., 2023. Global value chains and I4.0 in the context of lean workplaces for enhancing company performance and its comprehension via the digital readiness and expertise of workforce in the V4 nations. Mathematics, 11(3), p.601.

[12] Speranzainc, 2024. The Key Industrial Internet of Things Examples and Challenges, Available: https://www.speranzainc.com/industrial-internet-of-things-definition-examples-challenges/ , Accessed: 24/11/24

[13] Rejeb, A., Keogh, J. G. & Treiblmaier, H., 2019. Leveraging the Internet of Things and Blockchain Technology in SCM. Future Internet, 11(7).

[14] Seccia, R., Romano, S., Salvetti, M., Crisanti, A., Palagi, L. and Grassi, F., 2021. Machine learning use for prognostic purposes in multiple sclerosis. Life, 11(2), p.122.

[15] KX Blog. Current Status Industry 4.0 with AI and Smart Manufacturing, Available at: https://kx.com/blog/current-status-industry-4-0-with-ai-and-smart-manufacturing/ , Accessed: 28/9/25

[16] Mujkic, Z., Qorri, A. and Kraslawski, A., 2018. Sustainability and optimization of supply chains: A literature review. Operations and SCM: An International Journal, 11(4), pp.186-199.

[17] Sawik, T., 2022. Stochastic optimization of supply chain resilience under ripple effect: A COVID-19 pandemic related study. Omega, 109, p.102596.

[18] Unhelkar, B., Joshi, S., Sharma, M., Prakash, S., Mani, A.K. and Prasad, M., 2022. Enhancing supply chain performance using RFID technology and decision support systems in the I4.0–A systematic literature review. International Journal of Information Management Data Insights, 2(2), p.100084.

[19] Shah, S., & Patil, V. (2024). Exploring the Challenges and Opportunities for Globalisation of Logistics and Supply Chains. WSEAS Transactions on Business and Economics, 21, 2806-2827.

[20] Bai, C. & Sarkari, J., 2010. Green supplier development: analytical evaluation using roughset theory. journal of cleaner production, 18(0959-6526), pp. 1200-1210.

[21] Hong, J., zhang, Y. & Ding, M., 2018. Sustainable SCM practices, supply chain dynamic capabilities and enterprise performance. Journal of cleaner production, 172(0959-6526), pp. 3508-3519.

[22] Kashmanian, R., Keenan, C. and Wells, R., 2010. Corporate environmental leadership: Drivers, characteristics, and examples. Environmental Quality Management, 19 (4).

[23] Salinas-Navarro, D.E., Mejia-Argueta, C., Montesinos, L. and Rodriguez-Calvo, E.Z., 2022. Experiential learning for sustainability in SCM education. Sustainability, 14(20), p.13133.

[24] Masteika, I. and Čepinskis, J., 2015. Dynamic capabilities in SCM. Procedia-Social and Behavioral Sciences, 213, pp.830-835.

[25] Beske, P., 2012. Dynamic capabilities and sustainable SCM. International journal of physical distribution & logistics management, 42(4), pp.372-387.

[26] Nakandala, D. and Lau, H.C.W., 2019. Innovative adoption of hybrid supply chain strategies in urban local fresh food supply

chain. SCM: An International Journal, 24(2), pp.241-255.

[27] Negi, S., 2020. Supply chain efficiency framework to improve business performance in a competitive era. Management Research review, 44(3).

[28] SCN Soft, 2024. Transport Management System in Supply Chain, Available from: https://www.scnsoft.com/scm/transportation-management-software , Accessed: 12/11/24

[29] Atef, A. 2024. Supply Chain Risk Management, Available at: https://www.linkedin.com/pulse/supply-chain-risk-management-abanob-atef-7clbf/, Accessed: 22/10/25

[30] Giannakis, M. & Papadopoulos, T., 2016. Supply chain Sustainability: A risk management approach. International Journal of Production Economics, Volume 171, pp. 455-470.

[31] Saunders, B., Sim, J., Kingstone, T., Baker, S., Waterfield, J., Bartlam, B., ... & Jinks, C. (2018). Saturation in qualitative research: exploring its conceptualization and operationalization. Quality & quantity, 52(4), 1893-1907.

[32] Fettermann, D.C., Cavalcante, C.G.S., Almeida, T.D.D. and Tortorella, G.L., 2018. How does I4.0 contribute to operations management?. Journal of industrial and Production Engineering, 35(4), pp.255-268.

[33] Tseng, M.L., Tran, T.P.T., Ha, H.M., Bui, T.D. and Lim, M.K., 2021. Sustainable industrial and operation engineering trends and challenges Toward I4.0: A data driven analysis. Journal of Industrial and Production Engineering, 38(8), pp.581-598.

[34] Leng, J., Wang, D., Shen, W., Li, X., Liu, Q. and Chen, X., 2021. Digital twins-based smart manufacturing system design in I4.0: A review. Journal of manufacturing systems, 60, pp.119-137.

[35] Calder, N., Trotter, a., Carlucci, C. & Agmomi, E., 2022. How Maersk designed a more resilient supply chain, Harvard Business Review, Available at: https://hbr.org/2022/11/how-maersk-designed-a-more-resilient-supply-chain, Accessed: 26/10/25

[36] Sherif, V., 2018. Evaluating Preexisting Qualitative Research Data for Secondary Analysis. Forum: Qualitative Social Research , 19(7).

[37] Maguire, M. and Delahunt, B., 2017. Doing a thematic analysis: A practical, step-by-step guide for learning and teaching scholars. All Ireland journal of higher education, 9(3).

[38] Müller, J.M., Kiel, D. and Voigt, K.I., 2018. What drives the implementation of I4.0? The role of opportunities and challenges in the context of sustainability. Sustainability, 10(1), p.247.

[39] Kamalahmandi, M., Mansoor Shekarian & Mahour Mellat, 2022. The impact of flexibility and redundancy on improving supply chain resilience to disruptions. International Journal of Production Research, 60(6), pp. 1992-2020.

[40] Arthur, 2023. Design Systems, Inc. [Online] Available at: https://www.dsidsc.com/ [Accessed: 29/08/25].

[41] Anon., 2016. GEP. [Online] Available at: https://www.gep.com/ [Accessed: 29/08/25]

[42] Galer, S., 2022. Forbes. [Online] Available at: https://www.forbes.com/ [Accessed: 29/08/25].

[43] Carr, T. 2021. Can your Supply Chain Deliver what your consumer wants?. McKinsey's Operations Practice. [Online] Available at: https://www.mckinsey.com/capabilities/operations/our-insights/can-your-supply-chain-deliver-what-your-consumer-wants#/ [Accessed 22/10/25].

[44] Benavides, L., Eskinazis. V.D., and Swan, D., 2012. Six Steps to successful Supply Chain Collaboration, McKinsey & Company. [Online] Available at: https://www.mckinsey.com/capabilities/operations/our-insights/six-steps-to-successful-supply-chain-collaboration, [Accessed: 30/9/25].

[45] Capgemini, 2024. Digital Twin in Global Supply Chains, Available: https://www.capgemini.com/insights/expert-perspectives/digital-twin-within-the-supply-chain-the-benefits-2/ , Accessed: 29/8/24

[46] Santos, C. H. d., José Antônio de Queiroz, Fabiano Leal & José Arnaldo Barra Montevechi, 2022. Use of simulation in the I4.0 context: Creation of a Digital Twin to optimise decision making on non-automated process. Taylor & Francis, 16(3), pp. 284-297.

[47] Noble, P. J., 2022. Digital Twins: Technology for the Supply Chain. Forbes. [Online] Available at: https://www.forbes.com/sites/paulnoble/2022/10/31/digital-twins-technology-for-the-supply-chain/, Accessed 29/8/25.

[48] Balaji, L., Ganji, E. N., & Shah, S. (2024). An Evaluation of I4.0 Capabilities for Sustainable Innovation in Food Sector. International Journal of Applied Sciences and Development, Vol.3, pp299-326.

[49] Shabur, M.A., 2024. Analyzing the challenges and opportunities in developing a sustainable digital economy. Discover Applied Sciences, 6(12), p.667.

[50] Rich Lesser, 2021. Supply chains can be a climate game-changer. Here's why. Davos, World Economic Forum. Available at: https://www.weforum.org/stories/forum-in-focus/tackling-supply-chain-emissions-is-a-game-changer-for-climate-action, Accessed: 12/10/25

[51] Sharma, M., Kamble, S., Mani, V., Sehrawat, R., Belhadi, A., & Sharma, V. (2021). Industry 4.0 adoption for sustainability in multi-tier manufacturing supply chain in emerging economies. Journal of cleaner production, 281, 125013.

[52] "The author(s) wrote, reviewed and edited the content as needed and She/He/They has/have not utilised artificial intelligence (AI) tools. The author(s) take(s) full responsibility for the content of the publication."

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Creative Commons Attribution License 4.0 (Attribution 4.0 International, CC BY 4.0)

This article is published under the terms of the Creative Commons Attribution License 4.0
https://creativecommons.org/licenses/by/4.0/deed.en_US