INDUSTRY 4.0 TECHNOLOGIES IN THE CONTEXT OF SUPPLY CHAIN MANAGEMENT 4.0

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ABSTRACT
The advent of Industry 4.0 has brought about significant transformations across various sectors, including Supply Chain Management (SCM). This paper aims to explore the integration of Industry 4.0 technologies (I4.0T) within the context of SCM 4.0. It provides an overview of the key concepts and principles of Industry 4.0 and examines their implications for supply chain operations. The paper highlights the prospective advantages of I4.0T in optimizing supply chain processes, enhancing efficiency, and enabling real-time visibility and decision-making. It discusses the role of technologies such as the internet of things (IoT), big data analytics (BDA), artificial intelligence (AI), robotics, and blockchain in driving the digital transformation of supply chains. Furthermore, the paper addresses the challenges and considerations relating to taking up I4.0T in SCM, including data security and privacy concerns, organizational change management, and the need for cross-functional collaboration. Case studies and examples from various industries are presented to illustrate the practical application of I4.0T in improving supply chain performance. These examples showcase how organizations have leveraged advanced technologies to achieve greater agility, responsiveness, and resilience in their supply chain operations. Finally, the paper concludes with insights into the future directions of Industry 4.0 along with its effect on SCM. It emphasizes the importance of continuous learning and adaptation for organizations to stay competitive in the evolving digital landscape. Overall, this paper contributes to the understanding of I4.0T and their consequences for SCM, providing useful information and guidance for organizations seeking to embrace the opportunities presented by the digital revolution in the context of SCM 4.0.
Keywords: Digital Supply Chain, Digital Transformation, Industry 4.0, Supply Chain Management 4.0, Supply Chain Performance

Introduction

The concept of Industry 4.0 has received a lot of attention recently, representing the fourth industrial revolution characterised by the incorporation of cutting-edge technologies into manufacturing processes. Supply chain management (SCM) plays a critical role in ensuring the seamless flow of goods, information, and services from suppliers to end customers. As the landscape of industries evolves and becomes more complex, traditional supply chain management approaches may struggle to keep pace with the changing demands and expectations of customers and stakeholders. This has given rise to the concept of SCM 4.0, which represents the application of Industry 4.0 technologies (I4.0T) and principles to optimize supply chain operations and drive sustainable competitive advantage. This integration of I4.0T within the context of SCM offers new opportunities and challenges for organizations seeking to enhance their operational efficiency and competitiveness (Bai et al., 2020; Abdelmajied, 2022).

The integration of Industry 4.0 technologies within the context of SCM 4.0 offers numerous benefits and opportunities. It enables organizations to achieve higher levels of operational efficiency, cost optimization, and customer satisfaction through streamlined processes, reduced lead times, and improved product quality.

Additionally, it facilitates the implementation of agile and responsive supply chain strategies, allowing companies to quickly adapt to changing market dynamics and customer demands.

Industry 4.0 technologies empower supply chain managers with actionable insights and real-time visibility into the entire supply chain network. This enables them to make data-driven decisions, optimize resource allocation, and proactively identify and mitigate risks. By embracing digitalization and automation, SCM can overcome traditional limitations, such as manual processes, information silos, and fragmented communication, leading to improved collaboration, supply chain resilience, and innovation.

I4.0T encompass a range of digital innovations, including the Internet of Things (IoT), big data analytics (BDA), artificial intelligence (AI), robotics, and blockchain. These technologies have the potential to revolutionize supply chain operations by enabling real-time data collection, analysis, and decision-making, fostering greater automation, enhancing visibility across the supply chain, and facilitating more efficient collaboration with suppliers and customers (Hopkins, 2021; Yaqub and Alsabban, 2023; Akbari et al., 2023).
SCM 4.0, on the other hand, refers to the application of these I4.0T in the field of SCM. It involves the digital transformation of traditional supply chain processes, including procurement, production, warehousing, transportation, and customer service. By leveraging these technologies, organizations can achieve greater agility, responsiveness, and sustainability in their supply chain operations (Garay-Rondero et al., 2020; Chauhan et al., 2023).

However, the adoption and implementation of I4.0T in SCM come with their own set of challenges. Organizations need to address problems relating to privacy and data security, infrastructure readiness, talent acquisition and upskilling, organizational change management, and the integration of new technologies with existing systems. Moreover, effective integration and interoperability among various technologies and systems across the supply chain network require careful planning and collaboration among stakeholders. (Garay-Rondero et al., 2020; Javaid et al., 2022).

In this rapidly evolving digital landscape, it is crucial for organizations to understand and leverage the potential of Industry 4.0 technologies in the context of SCM. This paper aims to explore the integration of I4.0T within the context of SCM 4.0. It provides insights into the key concepts and principles of Industry 4.0, discusses their implications for SCM, presents case studies and examples from various industries, and highlights the challenges and considerations associated with their adoption. By examining the intersection of Industry 4.0 and SCM, this paper offers valuable guidance for organizations seeking to navigate the digital revolution and embrace the opportunities presented by SCM 4.0. This study seeks to provide insights and guidance for organizations to navigate the complexities of the digital era and unlock the full potential of Industry 4.0 in optimizing their supply chain operations.

Literature Review

While SCM encompasses the overall principles and practices of managing supply chain activities, SCM 4.0 specifically refers to the application of advanced technologies and digitalization to transform and optimize supply chain operations in the era of Industry 4.0.

The literature review pertaining to the topic of paper has been divided into three sections. The first section discusses about the various I4.0T. Also, provides an overview of the key concepts and principles of Industry 4.0 and examines their implications for supply chain operations. The second section discusses about SCM with and without I4.0T. Also, discusses evolution of SCM 4.0. The third section presents the importance of adopting I4.0T for supply chain optimization.

Industry 4.0 Technologies (I4.0T)

The Fourth Industrial Revolution, or Industry 4.0, is the incorporation of cutting-edge digital technologies into industrial processes, transforming the way goods are manufactured, distributed, and consumed. It represents a paradigm shift in manufacturing and SCM through the use of technologies such as the IoT, BDA, AI, robotics, and more (Yang, Gu, 2021; Abdelmajied, 2022).

IoT is a network of interconnected physical devices that collect and exchange data. In SCM, IoT enables real-time visibility of goods and assets, improves inventory management, enhances operational efficiency, and facilitates predictive maintenance, leading to better decision-making and customer satisfaction. BDA refers to the process of extracting valuable insights from large volumes of structured and unstructured data. In SCM, BDA plays a crucial role in analyzing vast amounts of data from multiple sources, such as customer demand, production, logistics, and market trends, to optimize inventory levels, identify patterns and trends, improve forecasting accuracy, enhance supply chain visibility, and support data-driven decision-making for improved operational efficiency and responsiveness. AI refers to the simulation of human intelligence in machines to perform tasks and make decisions. In SCM, AI plays a significant role in automating and optimizing processes, such as demand forecasting, inventory management, route optimization, and risk assessment, by analyzing vast amounts of data, identifying patterns, and making intelligent recommendations, leading to improved operational efficiency, cost reduction, and better decision-making. Robotics and automation involve the use of machines and technology to perform tasks without human intervention. In SCM, robotics and automation play a vital role in streamlining and optimizing operations, such as order fulfillment, warehouse management, and material handling, by increasing speed, accuracy, and efficiency, reducing labor costs, and improving overall productivity and customer satisfaction. Additive manufacturing (AM), also known as 3D printing, is a process of creating three-dimensional objects by adding layers of material. In SCM, additive manufacturing plays a role in decentralized production, reducing lead times, enabling customization and on-demand production, minimizing inventory and transportation costs, and facilitating supply chain resilience by providing the capability to produce parts locally, especially for low volume or highly customized products (Akhtar, 2022).

AR refers to the technology that overlays digital information and virtual objects onto the real-world environment. In SCM, AR plays a role in improving operational efficiency and accuracy by providing real-time information and guidance to workers during tasks such as order picking, inventory management, and equipment maintenance, enhancing productivity, reducing errors, and enabling better training and collaboration. VR is a technology that creates a simulated, immersive environment through computer-generated visuals and sensory experiences. In SCM, VR can be used for training purposes, allowing employees to practice and simulate various scenarios, such as warehouse layouts, equipment operation, and logistics planning, leading to improved skills, increased safety, and enhanced decision-making in the supply chain operations. Blockchain is a decentralized, immutable, and transparent digital ledger that records and verifies transactions across multiple parties. In SCM, blockchain can enhance transparency, traceability, and trust by securely documenting and tracking the movement of goods, verifying product authenticity, improving supplier collaboration, streamlining documentation processes, and mitigating risks such as counterfeiting and fraud, ultimately improving supply chain efficiency and integrity. CC refers to the delivery of computing services, including storage, processing power, and software, over the internet on a pay-as-you-go basis. In SCM, CC plays a crucial role in providing scalable infrastructure, facilitating data sharing and collaboration among supply chain partners, enabling real-time access to information, supporting analytics and optimization, and enhancing overall agility and flexibility in managing supply chain operations. CS refers to the practice of protecting computer systems, networks, and data from unauthorized access, use, disclosure, disruption, modification, or destruction. In SCM, CS plays a vital role in safeguarding sensitive information, securing digital transactions, preventing data breaches, ensuring the integrity of supply chain processes, and maintaining trust among supply chain partners, thereby mitigating the risk of cyber threats and potential disruptions to the supply chain. A DT is a virtual representation or model of a physical object, process, or system that allows real-time monitoring, analysis, and simulation. In SCM, DTs play a role in enhancing visibility, optimization, and decision-making by providing a digital replica of supply chain components, enabling predictive analytics, facilitating scenario planning, and improving operational efficiency, resilience, and responsiveness in the supply chain. NLP is a branch of AI that focuses on the interaction between computers and human language. In SCM, NLP plays a role in enhancing communication, information retrieval, and decision-making by enabling systems to understand, interpret, and respond to natural language inputs, facilitating tasks such as order processing, customer service, demand forecasting, and supplier collaboration, ultimately improving operational efficiency and customer satisfaction in the supply chain (Sobb et al., 2020, Akhtar, 2022; Santhi, Muthuswamy, 2023).

Edge computing refers to the practice of processing and analyzing data near the source or "edge" of a network, rather than sending it to a centralized cloud or data center. In SCM, edge computing plays a role in enabling real-time data processing and decision-making at the point of action, improving response times, reducing network latency, and supporting critical operations such as inventory management, asset tracking, and quality control, particularly in remote or bandwidth-constrained environments. Autonomous vehicles are vehicles capable of operating without human intervention, using various sensors, software, and control systems. In SCM, autonomous vehicles play a role in improving transportation efficiency, reducing costs, and enhancing safety by enabling autonomous delivery trucks, drones, and robots to carry out tasks such as goods transportation, inventory management, and warehouse operations, thereby streamlining logistics processes and enhancing overall supply chain performance. Predictive analytics involves the use of statistical algorithms and ML techniques to forecast future outcomes based on historical data and patterns. In SCM, predictive analytics plays a role in optimizing inventory levels, demand forecasting, supplier management, and risk assessment, enabling organizations to make proactive decisions, improve planning accuracy, reduce costs, and enhance overall supply chain efficiency and responsiveness. Nanotechnology involves the manipulation and control of matter on a nanoscale level, typically at the atomic or molecular level. In SCM, nanotechnology plays a role in areas such as materials science and packaging, enabling the development of innovative and advanced materials, enhancing product performance, durability, and sustainability, and facilitating advancements in areas such as nanosensors for real-time monitoring and nanocoatings for protection against corrosion and contamination, ultimately improving the quality and functionality of supply chain products and components. Smart sensors and actuators refer to devices that can collect data, monitor conditions, and perform actions based on the input received. In SCM, smart sensors and actuators play a role in providing real-time visibility, monitoring environmental conditions, tracking asset movements, enabling predictive maintenance, and facilitating automation and control, leading to improved efficiency, quality, and reliability in supply chain operations (Javaid, 2023; Santhi, Muthuswamy, 2023).

Cognitive computing refers to the use of AI systems that can simulate human thought processes, understand natural language, and learn from data. In SCM, cognitive computing plays a role in advanced data analysis, decision-making support, and natural language interactions, enabling organizations to gain deeper insights, make more accurate predictions, and enhance operational efficiency and responsiveness in various aspects of the supply chain, such as demand forecasting, inventory optimization, and risk management. ML is a subset of AI that involves training algorithms to learn from data and make predictions or take actions without being explicitly programmed. In SCM, ML plays a role in optimizing operations, demand forecasting, inventory management, route optimization, and anomaly detection, by analyzing large datasets, identifying patterns and trends, and making data-driven decisions, leading to improved efficiency, cost reduction, and better supply chain performance. Wearable technology refers to electronic devices that can be worn on the body, typically in the form of accessories or clothing, and are equipped with sensors and connectivity capabilities. In SCM, wearable technology plays a role in improving worker productivity, safety, and efficiency by providing real-time access to information, hands-free communication, location tracking, biometric monitoring, and augmented reality support, enabling tasks such as order picking, inventory management, and maintenance to be performed with greater accuracy and effectiveness. Mobile technologies encompass a range of devices, applications, and connectivity options that enable communication and access to information on the go. In SCM, mobile technologies play a role in enhancing real-time communication, data collection, and decision-making by enabling mobile devices such as smartphones and tablets to connect with enterprise systems, track shipments, manage inventory, facilitate collaboration, and provide remote access to critical supply chain information, leading to improved efficiency, agility, and responsiveness in supply chain operations (Zhou et al., 2021; Akhtar, 2022; Javaid, 2023; Santhi, Muthuswamy, 2023).

Collaborative robots, also known as cobots, are robots designed to work alongside humans in a shared workspace, enhancing cooperation and interaction. In SCM, collaborative robots play a role in automating manual tasks, such as picking, packing, and sorting, improving productivity, reducing labor costs, and enhancing worker safety, ultimately optimizing supply chain operations and increasing efficiency in areas such as warehousing, order fulfillment, and logistics. Advanced human-machine interfaces refer to technologies that enable intuitive and seamless interaction between humans and machines, often utilizing methods such as touchscreens, gesture recognition, voice control, or virtual reality. In SCM, advanced human-machine interfaces play a role in improving user experiences, enhancing efficiency, and enabling more effective decision-making by providing intuitive interfaces for accessing and analyzing supply chain data, controlling automation systems, and facilitating collaborative workflows, ultimately improving productivity and reducing errors in supply chain operations. The Industrial Internet of Things (IIoT) refers to the network of interconnected devices, sensors, and systems in an industrial setting, enabling data collection, communication, and automation. In SCM, IIoT plays a role in improving visibility, efficiency, and decision-making by facilitating real-time monitoring of assets, tracking inventory, optimizing logistics, predicting maintenance needs, and enabling seamless connectivity and data exchange among supply chain stakeholders, leading to enhanced operational performance and responsiveness in the supply chain. Precision agriculture technology refers to the use of advanced sensors, GPS, and data analytics to optimize agricultural practices and resource management. In SCM, precision agriculture technology plays a role in improving the efficiency and quality of the agricultural supply chain by enabling precise monitoring and management of crop health, optimizing yield and resource allocation, reducing waste, and ensuring traceability, ultimately leading to more sustainable and productive agricultural supply chains. Smart grid and energy management systems refer to technologies and solutions that enable efficient and intelligent management of energy resources and distribution. In SCM, smart grid and energy management systems play a role in optimizing energy consumption, reducing costs, ensuring reliability, and promoting sustainability by enabling real-time monitoring, demand response, energy storage integration, and efficient energy usage in supply chain operations, ultimately improving overall energy efficiency and resilience in the supply chain (Sobb et al., 2020, Zhou et al., 2021; Santhi, Muthuswamy, 2023).

A CPS is an integration of computational elements and physical components that work together to monitor, analyze, and control physical processes. In SCM, CPS plays a role in improving operational efficiency, visibility, and coordination by enabling real-time monitoring of inventory, assets, and production processes, facilitating predictive maintenance, supporting autonomous decision-making, and enabling seamless communication and collaboration between various elements of the supply chain, ultimately leading to optimized supply chain performance and responsiveness. Horizontal and vertical systems are two different approaches to SCM. Horizontal systems focus on integrating processes and functions across different stages of the supply chain, emphasizing collaboration and information sharing among supply chain partners. Vertical systems, on the other hand, emphasize control and ownership over the supply chain by a single entity, often through vertical integration, enabling greater control over quality, cost, and delivery times. The choice between horizontal and vertical systems depends on various factors such as industry characteristics, competitive landscape, and strategic objectives, with both approaches offering different advantages and trade-offs in managing the supply chain (Alcácer, Cruz-Machado, 2019; Pereira et al., 2022; Santhi, Muthuswamy, 2023).

SCM With and Without I4.0T

SCM with and without I4.0T represents a stark contrast in terms of efficiency, visibility, agility, and decision-making capabilities.

I4.0T significantly improve SCM by automating processes, enhancing visibility, enabling data-driven decision-making, and promoting collaboration across the supply chain ecosystem. These advancements lead to improved efficiency, reduced costs, increased customer satisfaction, and greater resilience in the face of disruptions (Cimini et al. 2019; Caiado et al., 2022; Rad et al., 2022).

The evolutionary developments in SCM from SCM 1.0 to SCM 4.0, demonstrates how SCM has evolved over time, leveraging advancements in technology to achieve greater efficiency, visibility, and collaboration. The developments in each era have built upon previous capabilities and expanded the potential of SCM in terms of data-driven insights, automation, and interconnectedness. The mapping represents the progression of concepts that have evolved and gained prominence over time as technology and market dynamics have advanced (Frazzon et al. 2019; Zekhnini et al., 2021).

Importance of Adopting I4.0T

While SCM encompasses the overall principles and practices of managing supply chain activities, SCM 4.0 specifically refers to the application of advanced technologies and digitalization to transform and optimize supply chain operations in the era of Industry 4.0.

The impact of Industry 4.0 on SCM is profound and far-reaching. Here are some key aspects:

Enhanced Visibility and Transparency: I4.0T enable real-time monitoring and tracking of goods, assets, and processes throughout the supply chain. This enhanced visibility provides stakeholders with accurate and up-to-date information, improving transparency, and enabling proactive decision-making.

Improved Efficiency and Productivity: Automation, robotics, and AI-driven optimization algorithms enable increased efficiency and productivity in supply chain operations. Tasks that were previously time-consuming or prone to errors can now be automated, leading to streamlined processes, reduced lead times, and improved resource utilization.

Demand-Driven Operations: I4.0T enable supply chain managers to gather and analyze vast amounts of data, facilitating demand forecasting and planning based on real-time insights. This demand-driven approach helps in minimizing stock-outs, optimizing inventory levels, and improving customer satisfaction.

Predictive Analytics and Demand Forecasting: BDA and ML algorithms enable organizations to analyze large volumes of data, identify patterns, and make accurate predictions about demand fluctuations, market trends, and supply chain risks. This helps in optimizing inventory levels, production planning, and logistics, ensuring the right products are available at the right time while minimizing stockouts and excess inventory.

Predictive Maintenance: IoT sensors and AI-powered analytics enable predictive maintenance of machinery and equipment. By monitoring equipment health in real-time, potential failures can be detected early, and maintenance activities can be scheduled proactively, reducing downtime and improving overall equipment effectiveness.

Agile and Responsive Supply Chains: I4.0T enable supply chains to become more agile and responsive to dynamic market conditions. With real-time data, organizations can quickly identify and respond to changes in demand, supply disruptions, or quality issues, enabling faster decision-making, rapid adjustments in production, and efficient allocation of resources to meet customer expectations.

Supply Chain Collaboration and Integration: I4.0T facilitate seamless collaboration and integration across supply chain partners. Data-sharing platforms, blockchain, and cloud computing enable secure and real-time information exchange, leading to improved coordination, visibility, and trust among stakeholders.

Improved Collaboration and Integration: Digital technologies facilitate seamless communication and collaboration among supply chain stakeholders, both within and across organizations. Sharing real-time information, data, and insights enables better coordination, visibility, and decision-making, leading to improved supplier relationships, reduced lead times, and enhanced customer satisfaction.

Customization and Personalization: Industry 4.0 enables greater customization and personalization of products. Technologies like additive manufacturing (3D printing) allow for on-demand production and flexible customization options, reducing inventory costs and catering to individual customer requirements.

Supply Chain Resilience and Risk Management: I4.0T help identify and mitigate risks in the supply chain. Real-time data monitoring, predictive analytics, and scenario simulations enable proactive risk management, enabling organizations to respond quickly to disruptions and build resilient supply chains.

Sustainability and Green Supply Chains: I4.0T provide opportunities for creating sustainable and environmentally friendly supply chains. Optimized logistics, predictive analytics for energy consumption, and efficient resource allocation contribute to reduced waste, energy efficiency, and lower carbon footprints.

Sustainable and Responsible Practices: I4.0T offer opportunities for sustainability improvements in the supply chain. Optimized logistics, route planning, and demand forecasting help reduce energy consumption and carbon emissions. Additionally, IoT-enabled monitoring and traceability solutions promote responsible sourcing, ethical practices, and supply chain transparency (Fatorachian, Kazemi, 2021; Liu et al., 2023; Raiyani, 2023; Shen et al., 2023; Srhir et al., 2023; Tunk, 2023).

Industry 4.0 revolutionizes SCM by leveraging advanced technologies to optimize processes, improve efficiency, enhance collaboration, and adapt to dynamic market demands. Adopting I4.0T in supply chain optimization brings increased visibility, efficiency, responsiveness, collaboration, and sustainability. It empowers organizations to make data-driven decisions, adapt to changing market dynamics, and create agile and competitive supply chains capable of meeting evolving customer expectations. Embracing these technologies enables organizations to gain a competitive edge, meet customer expectations, and thrive in the digital age.

Objectives of the Study

The objectives of this conceptual study research paper are multifold.

- To investigate the application and impact of I4.0T on SCM practices.
- To explore the benefits, challenges, and potential strategies for implementing and optimizing I4.0T in the context of modern SCM.
- To understand the importance of continuous learning and adaptation for organizations to stay competitive in the evolving digital landscape.
- To understand I4.0T and their implications for SCM, providing valuable insights and guidance for organizations seeking to embrace the opportunities presented by the digital revolution in the context of SCM 4.0.

Research Methodology

The research methodology focusses on a literature review and analysis of existing research and studies i.e. secondary data. An extensive review has been conducted of academic literature, research papers, industry reports, and relevant publications to gather information on I4.0T and their application in SCM. Key themes, theories, and concepts related to the topic have been identified and presented in detail. Keywords related to I4.0T, SCM, and relevant concepts are used to identify relevant literature.

For this conceptual research, first, all I4.0T pertaining to SCM directly or indirectly have been identified. Identifying I4.0T pertaining to SCM directly or indirectly enables organizations to align their strategies, integrate technologies effectively, improve performance, foster innovation, enhance customer satisfaction, and gain a competitive advantage in the dynamic business landscape of SCM. Secondly, the traditional SCM concept and SCM 4.0 are explored. Exploring the traditional SCM concept and the transition to SCM 4.0 provides valuable insights into the historical context, identifies gaps and limitations, showcases the evolution of technologies and practices, highlights transformational opportunities, emphasizes adaptation and resilience, and ensures future readiness in the dynamic field of SCM. Also, understanding the evolution of SCM 4.0 provides organizations with insights into technological advancements, enables strategic decision-making, optimizes supply chain processes, promotes collaboration and integration, enhances agility and adaptability, and fosters innovation and competitive advantage. Thirdly, the importance of adopting I4.0T for supply chain optimization has been explored. Exploring the importance of adopting I4.0T for supply chain optimization brings benefits such as enhanced efficiency and productivity, improved visibility and transparency, agile and responsive supply chains, cost optimization, risk mitigation and resilience, sustainable practices, and competitive advantage. These benefits drive organizational growth, customer satisfaction, and long-term success in the rapidly evolving business landscape.

Secondary Data Analysis

This section of secondary data analysis presents the outcome of literature review. I4.0T enable automation, real-time data analytics, and predictive capabilities, leading to improved operational efficiency, reduced costs, and optimized resource allocation throughout the supply chain.

I4.0T bring enhanced operational efficiency, improved visibility and collaboration, better customer experience, and increased agility and adaptability to SCM. They enable automation, real-time data analytics, and predictive capabilities for optimized resource allocation and reduced costs. The use of I4.0T poses challenges related to data security and privacy, skill gap and workforce transition, integration and interoperability of diverse technologies, and managing organizational change and cultural shift towards digitalization. Addressing these challenges is crucial for successful implementation and harnessing the full potential of Industry 4.0 in SCM.

The first section of literature review has helped to identify the I4.0T. Table No. 1 provides a list of I4.0T that are impacting or have implications on supply chain operations directly or indirectly. It has been observed that the integration of I4.0T in supply chain supports to build SCM 4.0 framework.

Sr. No.	I4.0T Pertaining to SCM 4.0
1	Internet of Things (IoT)
2	Big Data Analytics (BDA)
3	Artificial Intelligence (AI)
4	Robotics and Automation
5	Additive Manufacturing (AM) or 3D Printing
6	Augmented Reality (AR) and Virtual Reality (VR)
7	Blockchain Technology (BCT)
8	Cloud Computing (CC)
9	Cyber Security (CS)
10	Digital Twin (DT)
11	Edge Computing
12	Autonomous Vehicles
13	Predictive Analytics
14	Nanotechnology
15	Advanced Sensors and Actuators (Smart Sensors and Actuators)
16	Cognitive Computing
17	Machine Learning (ML)
18	Natural Language Processing (NLP)
19	Wearable Technology
20	Mobile Technologies
21	Collaborative Robots (Cobots)
22	Advanced Human-Machine Interfaces (HMI)
23	Industrial Internet of Things (IIoT)
24	Precision Agriculture Technology
25	Smart Grid and Energy Management Systems (EMS)
26	Cyber Physical System (CPS)
27	Horizontal and Vertical Systems

Table No. 1. I4.0T pertaining to SCM 4.0

The outcome of the second subpart of review is presented in Table No. 2 as SCM with and without I4.0T. Table No. 2 provides a brief comparison of the two scenarios. SCM 4.0 with I4.0T is better than traditional SCM as it leverages advanced digital technologies to enhance operational efficiency, optimize resource allocation, and enable real-time decision-making, resulting in improved supply chain performance.

Sr. No.	Parameter	Without I4.0T	With I4.0T
1	Efficiency and Productivity	Supply chain processes often rely on manual, paper-based procedures, leading to delays, errors, and inefficiencies. Tasks such as inventory management, order processing, and logistics coordination are time-consuming and prone to human error.	Automation, robotics, and AI-driven optimization algorithms streamline supply chain processes. Tasks are automated, reducing manual intervention, and improving accuracy and speed. Real-time data monitoring and analytics enable proactive decision-making, reducing lead times and enhancing overall productivity.
2	Visibility and Transparency	Lack of real-time data and visibility across the supply chain makes it challenging to track inventory, monitor order status, and identify bottlenecks. Siloed information and manual reporting hinder collaboration and decision-making.	IoT sensors, RFID, and interconnected systems provide real-time visibility of goods, assets, and processes across the supply chain. Stakeholders have access to accurate and up-to-date information, improving transparency, and enabling proactive decision-making.
3	Demand-Driven Operations	Demand forecasting relies on historical data and is often disconnected from real-time market dynamics. Reactive planning leads to stock-outs, overstocking, and suboptimal resource allocation.	BDA and AI-powered algorithms enable demand-driven operations. Real-time data from multiple sources, including social media, helps in accurate demand forecasting, planning, and resource allocation. Organizations can respond promptly to market fluctuations, improving customer satisfaction and optimizing inventory levels.
4	Risk Management and Resilience	Risk management is reactive, with limited visibility into potential disruptions. Organizations struggle to identify and respond quickly to supply chain disruptions, leading to delays, increased costs, and customer dissatisfaction.	Real-time data monitoring, predictive analytics, and scenario simulations enable proactive risk management. Early detection of disruptions, quick decision-making, and agile response mechanisms help organizations build resilient supply chains and minimize the impact of disruptions.
5	Collaboration and Integration	Lack of real-time data sharing and communication between supply chain partners hinders collaboration and coordination. Manual processes and information silos make it challenging to achieve seamless integration and effective collaboration.	I4.0T facilitate seamless collaboration and integration. Cloud-based platforms, blockchain, and data-sharing mechanisms enable real-time information exchange, fostering trust, transparency, and effective collaboration among supply chain partners.

Table No. 2. SCM With and Without I4.0T

Table No. 3 indicates mapping of the evolutionary developments in SCM from SCM 1.0 to SCM 4.0. The understanding as represented in Table 3 empowers organizations to navigate the complexities of the modern business landscape and drive sustainable growth through effective SCM.

Sr. No.	SCM Version	Features/Characteristics	Evolutionary Concepts
1	SCM 1.0	• Manual processes and paper-based systems • Limited visibility and information sharing • Traditional procurement and inventory management	• Just-in-Time (JIT) • Lean Manufacturing • Total Quality Management (TQM)
2	SCM 2.0	• Introduction of computerized systems and basic automation • Implementation of Enterprise Resource	• Agile and Flexible Supply Chains • Demand-Driven Planning • Vendor-Managed Inventory

		Planning (ERP) systems ● Improved data management and communication through technology	(VMI)
3	SCM 3.0	● Adoption of advanced planning and optimization systems ● Integration of supply chain partners through Electronic Data Interchange (EDI) ● Implementation of collaborative planning, forecasting, and replenishment (CPFR) ● Enhanced supply chain visibility through advanced tracking and tracing technologies	● Sustainable Supply Chains
4	SCM 4.0	● Digital transformation and I4.0T ● IoT for real-time data collection and monitoring ● AI and ML for predictive analytics and optimization ● BDA for better decision-making and demand forecasting ● Robotics and Automation for process automation and efficiency ● Blockchain for secure and transparent supply chain transactions ● AR and VR for remote collaboration and training ● CC for scalable and flexible infrastructure ● CS measures to protect data and networks	● Digitalization and Industry 4.0

Table No. 3. SCM 1.0 to SCM 4.0

Findings

The findings for this review paper are the research gaps and few research questions that researchers can work upon as discussed below.

1. Following are the possible research gaps in the perspective of "Industry 4.0 Technologies in the Context of SCM 4.0".
    - Exploration of the challenges and opportunities of implementing these technologies in small and medium-sized enterprises (SMEs). While there is extensive research on the adoption of I4.0T in large organizations, there is a need for more focused studies that investigate the specific challenges faced by SMEs in adopting and integrating these technologies into their SCM practices. Understanding these challenges and identifying potential solutions can help SMEs leverage I4.0T to improve their supply chain performance and competitiveness.
    - Need for more comprehensive studies that focus on the integration and interoperability of various I4.0T within the supply chain. While individual technologies such as IoT, AI, blockchain, and robotics have been extensively studied, there is a lack of research that investigates how these technologies can be effectively integrated and interconnected to create a cohesive and efficient supply chain ecosystem. Understanding the challenges, opportunities, and best practices for integrating and leveraging multiple I4.0T in SCM can provide valuable insights for organizations looking to implement and optimize their digital supply chains.
    - There is limited understanding of the organizational and managerial implications of implementing I4.0T in the supply chain. While there is growing awareness of the technological aspects and benefits of I4.0T, there is a need for research that explores the organizational challenges, change management strategies, and the role of leadership in successfully implementing and integrating these technologies into the supply chain.

2. This research gap could help researchers to focus on addressing research questions such as:
    - Organizational Readiness and Change Management: What strategies can be employed to ensure smooth transition and integration of Industry 4.0 for SCM 4.0?
    - Leadership and Governance: What leadership styles, skills, and competencies are needed to support the successful implementation and utilization of I4.0T for SCM 4.0?
    - Workforce and Skills Development: How can organizations address the skill gaps and develop training programs to empower their workforce in adopting and utilizing I4.0T for SCM 4.0?

- Collaboration and Integration: How can organizations overcome barriers and leverage collaborative platforms to enable seamless integration of I4.0T for SCM 4.0?
- Production and Operations Management: How can real-time data analytics and decision support systems powered by I4.0T aid in proactive maintenance, quality control, and overall equipment effectiveness (OEE) improvement in manufacturing operations within the SCM 4.0? What are the implications and potential benefits of leveraging NLP and voice recognition technologies in SCM 4.0 for tasks such as inventory tracking, order processing, and customer service, and how can organizations effectively integrate these technologies with existing systems and processes?

By addressing these research gaps, organizations and researchers can gain valuable insights into the organizational and managerial aspects of implementing I4.0T for the SCM 4.0 environment. This knowledge can inform the development of practical frameworks, strategies, and guidelines for successful adoption and integration, ultimately leading to improved supply chain performance, competitiveness, and sustainability in the era of Industry 4.0.

Conclusion

This conceptual study research highlights the transformative potential of advanced technologies in revolutionizing supply chain operations. The adoption and integration of I4.0T offer opportunities for enhanced efficiency, agility, visibility, and sustainability in the SCM 4.0. By exploring the concepts and applications of various I4.0T, such as IoT, AI, robotics, additive manufacturing, and blockchain, organizations can unlock new levels of optimization and innovation. However, it is crucial to recognize that implementing these technologies is not solely a technical endeavor but also requires careful consideration of organizational readiness, change management, leadership, and collaboration across the supply chain network. As the supply chain evolves from traditional models to the era of SCM 4.0, there is a need for further research to bridge the gap between technological advancements and their practical implementation. Future studies should focus on addressing the organizational and managerial challenges, workforce implications, governance structures, and collaborative frameworks necessary for successful integration and utilization of I4.0T for SCM 4.0. Ultimately, the effective adoption of I4.0T in SCM 4.0 has the potential to revolutionize operational processes, optimize resource allocation, improve decision-making, and deliver superior customer experiences. It is through continued research, industry collaboration, and a proactive mindset that organizations can harness the full potential of I4.0T and drive the future success of SCM in the digital age.

References

Abdelmajied, FE. Y. (2022), “Industry 4.0 and Its Implications: Concept, Opportunities, and Future Directions”, IntechOpen. https://doi.org/10.5772/intechopen.102520.

Akbari, M., Kok, S.K., Hopkins, J., Frederico, G.F., Nguyen, H. and Alonso, A.D. (2023), "The Changing Landscape of Digital Transformation in Supply Chains: Impacts of Industry 4.0 in Vietnam", The International Journal of Logistics Management, Vol. ahead-of-print, Issue ahead-of-print. https://doi.org/10.1108/IJLM-11-2022-0442.

Akhtar, M. (2022), "Industry 4.0 Technologies Impact on Supply Chain Sustainability, IntechOpen. https://doi.org/10.5772/intechopen.102978.

Alcácer, V., and Cruz-Machado, V. (2019), "Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems", Engineering Science and Technology, an International Journal, Vol. 22, Issue 3, pp. 899-919, https://doi.org/10.1016/j.jestch.2019.01.006.

Bai, C., Dallasega, P., Orzes, G., Sarkis, J. (2020), “Industry 4.0 Technologies Assessment: A Sustainability Perspective”, International Journal of Production Economics, Vol. 229, Art. No. 107776. https://doi.org/10.1016/j.ijpe.2020.107776.

Caiado, R. G. G., Scavarda, L. F., Azevedo, B. D., de Mattos Nascimento, D. L., and Quelhas, O. L. G. (2022), "Challenges and Benefits of Sustainable Industry 4.0 for Operations and Supply Chain Management—A Framework Headed toward the 2030 Agenda", Sustainability, Vol. 14, No. 2, Art. No. 830. https://doi.org/10.3390/su14020830.

Chauhan, S.; Singh, R.; Gehlot, A.; Akram, S.V.; Twala, B.; and Priyadarshi, N. (2023), "Digitalization of Supply Chain Management with Industry 4.0 Enabling Technologies: A Sustainable Perspective", Processes,Vol. 11, Issue 1, Art. No. 96. https://doi.org/10.3390/pr11010096.

Cimini, C., Pezzotta, G., Pinto, R., and Cavalieri, S. (2019), "Industry 4.0 Technologies Impacts in the Manufacturing and Supply Chain Landscape: An Overview", In: Borangiu, T., Trentesaux, D., Thomas, A., Cavalieri, S. (eds) Service Orientation in Holonic and Multi-Agent Manufacturing. SOHOMA 2018. Studies in Computational Intelligence, Vol 803. Springer, Cham. https://doi.org/10.1007/978-3-030-03003-2_8.

Fatorachian, H. and Kazemi, H. (2021), "Impact of Industry 4.0 on supply chain performance", Production Planning Control, Vol. 32, No. 1, pp. 63-81. https://doi.org/10.1080/09537287.2020.1712487.

Frazzon, E. M., Rodriguez, C. M. T., Pereira, M. M., Pires, M. C., and Uhlmann, I. (2019), "Towards Supply Chain Management 4.0", Brazilian Journal of Operations and Production Management, Vol. 16, No. 2, pp. 180–191. https://doi.org/10.14488/BJOPM.2019.v16.n2.a2.

Garay-Rondero, C.L., Martinez-Flores, J.L., Smith, N.R., Caballero Morales, S.O. and Aldrette-Malacara, A. (2020), "Digital supply chain model in Industry 4.0", Journal of Manufacturing Technology Management, Vol. 31 No. 5, pp. 887-933. https://doi.org/10.1108/JMTM-08-2018-0280.

Hopkins, J. L. (2021), "An Investigation into Emerging Industry 4.0 Technologies as Drivers of Supply Chain Innovation in Australia", Computers in Industry, Vol. 125, Art. No. 103323. https://doi.org/10.1016/j.compind.2020.103323.

Javaid, M., Haleem, A., Singh, R. P., and Suman, R. (2023), "An integrated outlook of Cyber–Physical Systems for Industry 4.0: Topical practices, architecture, and applications", Green Technologies and Sustainability, Vol. 1, Issue 1, Art. No. 100001. https://doi.org/10.1016/j.grets.2022.100001.

Javaid, M., Haleem, A., Singh, R. P., Suman, R., and Gonzalez, E. S. (2022), "Understanding the Adoption of Industry 4.0 Technologies in Improving Environmental Sustainability", Sustainable Operations and Computers, Vol. 3, pp. 203-217. https://doi.org/10.1016/j.susoc.2022.01.008.

Liu, L., Song, W., and Liu, Y. (2023), "Leveraging digital capabilities toward a circular economy: Reinforcing sustainable supply chain management with Industry 4.0 technologies", Computers and Industrial Engineering, Vol. 178, Art No. 109113. https://doi.org/10.1016/j.cie.2023.109113.

Pereira, R. M., Szejka, A. L., and Canciglieri Jr., O. (2022), "Ontological Approach to Support the Horizontal and Vertical Information Integration in Smart Manufacturing Systems: An Experimental Case in a Long-Life Packaging Factory", Frontiers in Manufacturing Technology, Vol. 2. https://doi.org/10.3389/fmtec.2022.854155.

Rad F. F., Oghazi, P., Palmié, M., Chirumalla, K., Pashkevich, N., Patel, P. C., and Sattari, S. (2022), "Industry 4.0 and supply chain performance: A systematic literature review of the benefits, challenges, and critical success factors of 11 core technologies", Industrial Marketing Management, Vol. 105,pp. 268-293, https://doi.org/10.1016/j.indmarman.2022.06.009.

Raiyani, A. (2023), "Demand Forecasting Using Spark—A Big Data Tool for Supply Chain Management", Technology, Agility and Transformation: Emergent Business Practices, edited by Tejas Shah, Mayank Bhatia, Samik Shome, pp. 13.

Santhi, A. R., and Muthuswamy, P. (2022), "Pandemic, War, Natural Calamities, and Sustainability: Industry 4.0 Technologies to Overcome Traditional and Contemporary Supply Chain Challenges", Logistics, Vol. 6, Issue 4, Art. No. 81. https://doi.org/10.3390/logistics6040081.

Santhi, A. R., and Muthuswamy, P., (2023), "Industry 5.0 or industry 4.0S? Introduction to industry 4.0 and a peek into the prospective industry 5.0 technologies", International Journal on Interactive Design and Manufacturing, Vol. 17, pp. 947–979. https://doi.org/10.1007/s12008-023-01217-8.

Santhi, A.R., and Muthuswamy, P. (2022), "Industry 4.0 Technologies in Supply Chain Management", In Encyclopedia. https://encyclopedia.pub/entry/38996.

Shen, B., Zhang, J., Cheng, M., Guo, S., and He, R. (2023), "Supply chain integration in mass customization", Annals of Operations Research. Early Access. https://doi.org/10.1007/s10479-023-05202-y

Sobb, T., Turnbull, B., and Moustafa, N. (2020), "Supply Chain 4.0: A Survey of Cyber Security Challenges, Solutions and Future Directions", Electronics, Vol. 9, No. 11, Art. No. 1864. https://doi.org/10.3390/electronics9111864.

Srhir, S., Jaegler, A., Montoya-Torres J. R. (2023), "Uncovering Industry 4.0 technology attributes in sustainable supply chain 4.0: A systematic literature review", Business Strategy and the Environment. Early Access. https://doi.org/10.1002/bse.3358.

Tunk R. (2023), "Digital Transformation A Game-Changer for Marketing, Manufacturing, and Supply Chain Management", International Journal of Research in Applied Management, Science & Technology, Vol. 3, Issue 2.

Yang, F., and Gu, S. (2021), "Industry 4.0, A Revolution That Requires Technology and National Strategies. Complex and Intelligent Systems, Vol. 7, pp. 1311–1325. https://doi.org/10.1007/s40747-020-00267-9.

Yaqub, M.Z.; Alsabban, A. (2023), "Industry-4.0-Enabled Digital Transformation: Prospects, Instruments, Challenges, and Implications for Business Strategies",Sustainability, Vol. 15, Art. No. 8553. https://doi.org/10.3390/su15118553

Zekhnini, K.,Cherrafi, A., Bouhaddou, I., Benabdellah, A. C., and Raut, R. (2021), "A holonic architecture for the supply chain performance in industry 4.0 context", International Journal of Logistics Research and Applications, Vol. 0, No. 0, pp. 1-28. https://doi.org/10.1080/13675567.2021.1999912.

Zhou, R., Awasthi, A., Cardinal, J. S-L., (2021), "The Main Trends for Multi-tier Supply Chain in Industry 4.0 Based on Natural Language Processing", Computers in Industry, Vol. 125, Art. No. 103369. https://doi.org/10.1016/j.compind.2020.103369.