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Supply Chain 4.0
New Generation of Supply Chain Management

Edited by
Xue-Ming Yuan and Anrong Xue

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About the Editors

Xue-Ming Yuan

Dr. Xue-Ming Yuan is an A*STAR's Research Scientist and adjunct Associate Professor at the National University of Singapore (NUS). Xue-Ming's research interests include supply chain analytics, predictive and prescriptive analytics, data driven inventory optimization, stochastic models, and algorithms and optimization. He has held various academic positions in China and France, and has published more than 130 scientific papers and over 50 papers in flagship journals such as the *Journal of Applied Probability*, *Statistics Communications*, *Operations Research*, the *European Journal of Operational Research*, *IIE Transactions*, *IEEE Transactions*, etc. Xue-Ming and his team have invented three commercial system solutions, Intelliget Forecasting System (iForecaster), Inventory Optimization System (iOptimizer) and Predictive Inventory Management System (PRIMS), which have been deployed in more than 40 multi-national companies (MNCs) and small and medium-sized enterprises (SMEs). His academic and industrial achievements have been included in Marquis Who's Who in Science and Engineering, 2003, and Marquis Who's Who in the World, 2001 and 2018.

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Editorial

Supply Chain 4.0: New Generation of Supply Chain Management

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Industry 4.0 is the fourth industrial revolution, which began in the early years of this millennium with autonomous production using Cyber–Physical Systems (CPS), the Internet of Things (IoT) and the Internet of Services (IoS). Industry 4.0 has significantly influenced people's daily life in every aspect, from shopping to dining, from working to entertaining, from staying at home to overseas traveling, etc. It is changing and shaping people's lifestyles and living behaviors, even how people think and their mindset. Industry 4.0 has had a revolutionary impact to Supply Chain Management. With Industry 4.0 technologies, suppliers are intelligent, factories are autonomous, products are smart and customers are demanding all-round service and satisfaction. Industry 4.0 technologies enable the integration of processes and systems across companies and industrial sectors, creating new business models and value-generation opportunities. Enterprises and businesses are digitalized, profitable and sustainable. Manufacturing systems and services are real-time capable, interoperable, modular, decentralized, virtualized and service-oriented. Supply Chains are fully visible, connected and integrated. With the rapid growth of Industry 4.0 technologies, Supply Chain Management has been transforming to a new generation, Supply Chain 4.0.

Supply Chain 4.0 refers to a supply chain that is designed, planned, managed and optimized by using Industry 4.0 technologies. There are many research issues and challenges associated with Supply Chain 4.0, for example, how to leverage real-time Market Intelligence in order to model customer behaviors and more accurately predict future customer demand. How to use Data Analytics in relation to minimal stock inventory to maximize the customer service level? How to apply Machine Learning and Artificial Intelligent to allocate production capacity, schedule job orders and plan equipment maintenance to minimize the disruption of production lines? How to utilize Industry 4.0 technologies to select the right supplier for the right material at the right time? How to tap into Blockchain technology to share data and essential information between the parties across a supply chain? How to collaborate and coordinate the operations of supply chain partners in the environment of Industry 4.0?

Supply Chain 4.0 is a data-rich and complex system. From the available data, we can interpret what happened in the past, what is currently happening, what will happen in the future and what are the best actionable decisions. Data Analytics has become the backbone supporting supply chain performance evaluation, optimization and decision making, and driving the three typical flows: the material flow, financial flow and information flow of a supply chain. Based on the Data Analytics results, companies are able to achieve managerial insights and make optimal decisions to gain a competitive edge in their respective businesses. Data-driven supply chain analytics has been a research hotspot in the new generation of Supply Chain Management.

As it is beginning its journey, Supply Chain 4.0 research is currently being explored, defined and shaped. Literature reviews have connected Supply Chain 4.0 research to the foundation of Supply Chain research, showing the linkages and continuation of Supply Chain Management, identifying the research gaps between conventional Supply Chain and Supply Chain 4.0 research and exploring the new research directions of Supply Chain 4.0. Industry applications and success cases demonstrate the applications and industrial value of Supply Chain 4.0 research. This Special Issue focuses on two streams of papers: review papers and case study papers. The Special Issue accepted eight papers that address various research and development issues and challenges facing Supply Chain 4.0 from both academic and industrial perspectives.

Inventory Management has been a very important topic in Supply Chain Management. By recognizing the role of inventory management in a supply chain and its importance, the review paper (8) contributed by Mashayekhy, Babaei, Yuan and Xue presents the impact of IoT technologies on inventory management in supply chains and conducts a comprehensive study to identify the research gap of applying IoT technologies to inventory management. The trend and potential opportunities of inventory management in the Industry 4.0 era are explored by analyzing the literature. The paper concludes that upgrading a supply chain into an integrated supply chain 4.0 is beneficial.

Logistics is the fundamental infrastructure to execute Supply Chain Management. The contribution (5) of Jafari, Azarian and Yu discusses the emerging concept that Industry 5.0 pushed forward the research frontier of the technology-focused Industry 4.0 to a smart and harmonious socio-economic transition driven by societies and technologies, where the role of the human in the technological transformation is the predominant focus. The contribution presents a comparative bibliometric analysis to show the connection and differences between Industry 4.0 and Industry 5.0 and their implications for smart logistics. A thorough content analysis is conducted to illustrate the features of smart logistics in Industry 5.0 concerning four areas, namely intelligent automation, intelligent devices, intelligent systems and intelligent materials. A research agenda is proposed for the purpose of identifying future research directions of smart logistics in Industry 5.0.

Additive manufacturing (AM) is bridging the digital and physical world as a 3D computer-aided manufacturing (CAM) method. The usage of AM has made supply chains simpler, more effective and more efficient. The contribution (1) of Debnath, Shakur, Tanjum, Rahman and Adnan summarizes the findings in the spare parts supply chain. It evaluates the potentiality and capability of AM in conceptualizing the entire supply chain and provides an overall view to make critical decisions on the spare parts supply chain design driven by Industry 4.0 technologies. The new-generation supply chain, Supply Chain 4.0, is able to remove the logistics barriers by reducing waste and worsening capability and sustainability through implementing AM technologies.

In the context of Supply Chain 4.0, supply chain relationship management becomes one of the central enablers in improving supply chain performance. While the influences of globalization and digitalization on the supply chains are increasing, the power allocation within several markets is centralized to a small number of companies. The contribution (3) from Brinker and Haasis investigates the research gap concerning the impact of power asymmetries on the supply chain, in addition to digitalization trends. The contribution provides a comprehensive definition of the concept of power and develops a definition of Power in Supply Chain Management in general. The research gap is elaborated between power allocations and the digitalization of the supply chain.

Industry 5.0 is in an embryonic and ideal stage, and its technologies are entering the technology development roadmap. The contribution (2) by Frederico links the current knowledge to this new development and evidences the gap related to Industry 5.0 approaches for supply chain management. This contribution presents the four constructs of Industry 5.0: Industry Strategy, Innovation and Technologies, Society and Sustainability and Transition Issues. An alignment with the supply chain context is proposed, being the basis for the incipient Supply Chain 5.0 framework and its research agenda. The contribution provides insightful and novel concepts related to Industry 5.0 in the supply chain context and adds valuable insights to researchers and practitioners by approaching the newest and revolutionary concept of the Industry 5.0 phenomenon in the supply chain context, which is an unexplored theme.

There are not many industry cases at the beginning of Supply Chain 4.0 research and development. Pleasantly, this Special Issue accepts three practical application papers on Supply Chain 4.0. The practical application paper (4) contributed by Shqair and Altarazi evaluates the status of small and medium enterprises (SMEs) concerning Industry 4.0 in Jordan. Four criteria are assessed, including Industry 4.0 readiness, maturity, drivers and barriers. It was concluded that Jordan needs country-scale initiatives for the implementation of groundbreaking Industry 4.0 technologies, incorporating government agencies, industrial parties and experts, relying on Industry 4.0 readiness and practice status as a starting point, and considering the influential drivers and barriers to steer the development process.

The Food Supply Chain is essentially important, especially during and after the COVID-19 pandemic. Food supplies and security are paramount to everyone. There are a lot of operational challenges and issues related to the food supply chain, in particular, for those products with a very short shelf life. The contribution (7) from Binsfeld and Gerlach investigates the impact of digital supply chain twins on the food supply chain by an extensive simulation study of a constructed organic food supply chain, quantifies the benefits of using a digital supply chain twin in the organic food supply chain and demonstrates an exemplary application of digital supply chain twins in the context of an organic food supply chain.

The Vegetable Supply Chain is one of the most fragile and volatile food supply chains. Industry 4.0 technologies are playing a very important role in digitizing the vegetable supply chain. The contribution (6) by Abbas, Amran, Hussain and Ma proposes a novel approach and a complete scientific classification of vegetable supply chain concerns relating to soft computing, presents a view of three delegate supply chains: cruciferous vegetables, dark green leafy vegetables and tomatoes, and assembles the scientific type in light of different parts to arrange vegetable supply chain issues as per how they can be demonstrated utilizing soft computing methodologies.

In Supply Chain 4.0, digitalization, visibility, connectivity and interoperability are integrated within all parties of the supply chain. The operational, tactical and strategic plans across the supply chain are digitally interlinked and real-time synchronized with a 360-degree view. The win–win partnerships are dynamic and sustainable, with agility, flexibility and responsiveness to uncertain business environments. New models and methods are advocated to implement Supply Chain 4.0 research and development. With the progress and implementation of Industry 4.0 technologies, it is anticipated that there will be more and more breakthroughs in models and methods of Supply Chain 4.0. Hopefully, this Supply Chain 4.0 Special Issue will serve as a helpful reference for Supply Chain 4.0 researchers and practitioners.

The contribution list of the Special Issue:

(1) Binoy Debnath, Md Shihab Shakur, Fahmida Tanjum, M. Azizur Rahman and Ziaul Haq Adnan, Impact of Additive Manufacturing on the Supply Chain of Aerospace Spare Parts Industry—A Review

(2) Guilherme F. Frederico, From Supply Chain 4.0 to Supply Chain 5.0: Findings from a Systematic Literature Review and Research Directions

(3) Janosch Brinker and Hans-Dietrich Haasis, Power in the Context of SCM and Supply Chain Digitalization: An Overview from a Literature Review

(4) Maram I. Shqair and Safwan A. Altarazi, Evaluating the Status of SMEs in Jordan with Respect to Industry 4.0: A Pilot Study

(5) Niloofar Jafari, Mohammad Azarian and Hao Yu, Moving from Industry 4.0 to Industry 5.0: What Are the Implications for Smart Logistics?

(6) Rizwan Abbas, Gehad Abdullah Amran, Irshad Hussain and Shengjun Ma, A Soft Computing View for the Scientific Categorization of Vegetable Supply Chain Issues

(7) Tom Binsfeld and Benno Gerlach, Quantifying the Benefits of Digital dolphin choir Twins—A Simulation Study in Organic Food Supply Chains

(8) Yasaman Mashayekhy, Amir Babaei, Xue-Ming Yuan and Anrong Xue, Impact of Internet of Things (IoT) on Inventory Management: A Literature Survey

Author Contributions: Conceptualization, X.-M.Y. and A.X.; methodology, X.-M.Y. and A.X.; writing—original draft preparation, X.-M.Y.; writing—review and editing, A.X. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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Review

Impact of Internet of Things (IoT) on Inventory Management: A Literature Survey

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Abstract: *Background*: The advancement of Industry 4.0 technologies has affected every aspect of supply chains. Recently, enterprises have tried to create more value for their businesses by tapping into these new technologies. Warehouses have been one of the most critical sections in a supply chain affected by Industry 4.0 technologies. *Methods*: By recognizing the role of inventory management in a supply chain and its importance, this paper aims to highlight the impact of IoT technologies on inventory management in supply chains and conducts a comprehensive study to identify the research gap of applying IoT to inventory management. The trend and potential opportunities of applying IoT to inventory management in the Industry 4.0 era are explored by analyzing the literature. *Results:* Our findings show that the research on this topic is growing in various industries. A broad range of journals is paying particular attention to this topic and publishing more articles in this research direction. *Conclusions*: Upgrading a supply chain into an integrated supply chain 4.0 is beneficial. Given the changes in fourth-generation technology compared to previous generations, the approach of conventional inventory replenishment policies seems not responsive enough to new technologies and is not able to cope with IoT systems well.

Keywords: supply chain management; inventory management; Industry 4.0; Internet of Things (IoT); warehouse management; smart warehouse

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1. Introduction

As an essential part of supply chain management (SCM), inventory management is that it is related not only to manufacturing, but also to pricing. The objective of managing inventory is to minimize the inventory cost by setting the right inventory replenishment policies with consideration of various factors to maximize the customer service level.

The very first motivation that caused us to write on this subject was the lack of a study that gathers all the work previously done on the applications of IoT and Industry 4.0 on inventory management. This study helps to better understand the core concepts in inventory management and opportunities in the advanced applications of Industry 4.0 in inventory systems and provides solid ground for future works by demonstrating the current needs and shortages in this particular area.

The scope of the study is limited to three major publishers which had the most contributions on the subject. We focus on three main keywords in the process of indexing the pervious works in our paper. This helps us to better focus on a specific domain and provide quality work on the subject.

This paper is organized as follows. Section 2 presents our survey methodology. Section 3 outlines the related studies about the impact of IoT on inventory management.

Section 4 analyzes the reviewed papers and presents the findings. Finally, Section 5 presents the conclusion and introduces research gaps and suggestions for further work. You can see the main contributions of the paper in the Figure 1 below.

- Conducted a holistic literature review about the impact of IoT on Inventory Management
- Identified the research gap of applying IoT to Inventory Management
- Explored the trend and potential opportunities of applying IoT to Inventory Management
- Suggested the future research directions of Inventory Management such as Sustainable Inventory Management, Green Inventory Management

Figure 1. Main Contributions.

1.1. A Brief on Classical Inventory Models

Inventory, which may contain raw materials, work-in-process (WIP) components, or finished products, is a significant part of the supply chain. Inventory costs account for a large percentage of the total supply chain cost. Inventory management aims to optimize inventory by planning and controlling inventory levels to reduce inventory cost and improve customer service satisfaction. The key research problem is how to answer two fundamental questions: "when" and "how many" order should be placed considering supply lead time, on-hand inventory, etc. To address these two questions, corresponding inventory models must be formulated.

In general, there are two types of inventory review in inventory management based on the approach to reviewing inventory: periodic review and continuous review. With continuous inventory review, inventory level must be monitored continuously. An order should be placed whenever the inventory level is less than a predetermined amount. The predetermined amount is referred to as the ordering point. The ordering quantity will be calculated based on the forecasted demand, holding cost, ordering cost, etc. The two simplest classical models with continuous inventory review are the EOQ (economic order quantity) model and the EPQ (economic production quantity) model. The EOQ model assumes the ordering quantity is received completely and immediately after ordering, while the EPQ model assumes the ordering quantity is received incrementally while the products are being produced.

1.2. Industry 4.0

There are two main streams of view about the Internet of Things (IoT) and Industry 4.0 regarding the terminologies and their use. One stream of view considers the terminologies "Industry 4.0" and "IoT" equivalent and usable interchangeably. Another stream suggests that IoT is a means of Industry 4.0 and that it can be referred to as an enabler to the concept of Industry 4.0 [1]. In this paper, we build up our study on the latter view and look for creative ways that IoT helps in Industry-4.0-related matters.

The idea of the Fourth Industrial Revolution (Industry 4.0) was first introduced by the German government. It marks a new generation of enhancing organizations' performance with a set of technologies such as Internet of Things (IoT), RFID tags, Internet of service (IoS), cloud computing, big data, cyber-physical systems, etc. The First Industrial Revolution began with introducing the steam engine to industry. The transition from manual production to mass production raised new issues and challenges to deal with in industry. With the spread of electricity use in factories, the Second Industrial Revolution occurred.

The Third Industry Revolution came with the evolution of the electronic world and the advancement of information technology (IT). Industry 4.0 has brought new perspectives to all parts of a supply chain. With Industry 4.0, organizations could reduce waste, increase responsiveness, and perform real-time decision-making. Cyber-physical systems (CPS) are natural and human-made systems (physical space) which are tightly integrated with communication, computation, and control systems (cyberspace). The recent progress in and extensive implementation of sensors, data acquisition systems, computer networks, and cloud computing have made cyber-physical systems important infrastructure in various industry sectors.

On the other hand, the industry's widespread use of sensors and control systems has led to a huge volume of data [2]. Managing such a huge amount of data (known as "big data") needs specific consideration [3]. Cloud storage is used for this purpose. By analyzing demand data and enabling self-decision-making algorithms for the machines in CPS, the production line can work efficiently with a minimum of direct human role and fewer errors in real-time interactions. With the use of these new technologies, occupational psychology becomes important and plays a significant role for the human force. Smart manufacturing is in place to create automation in an integrated system of CPS, which is will be more self-guided in dynamic decision-making and interconnection between machines.

The manufacturing section of supply chains has benefited from Industry 4.0, as do all other sections of the supply chain, such as the distribution section, transportation section, etc. Industry 4.0 technologies have affected various industries, e.g., aerospace, agriculture, construction, food and beverages, pharmaceuticals, services, etc. There are many opportunities available for sustainable manufacturing in the context of Industry 4.0 as well. The digital cyber network is the key to sharing information in the closed-loop supply chain to make manufacturing sustainable. Products and processes should be eco-friendly and take into consideration closed-loop life cycles through re-use and remanufacturing.

To apply Industry 4.0 technologies in practice, organizations require specific infrastructures that are able to bring new innovative business models. New business models, including "disruptive business models", are needed in a complete digital area to provide smart goods and services to customers. The idea of the extension of Industry 4.0 would be realized by automatic virtual metrology, which can reach the zero-defect goal in automation and extend to Industry 4.1 as the next phase [4]. Although the Industry 4.0 concept has been paid much attention in different fields, the implementation of Industry 4.0 has not yet been broadly realized in practice successfully [5]. Moreover, IoT-based supply chain systems are not widely studied from academic and industrial perspectives either.

1.2.1. Internet of Things (IoT)

Internet of Things (IoT) was coined by one of the executive directors of the Auto-ID Center. The idea of network devices has led to the idea that machines could work dynamically as an integrated system without the interrelated interference of a human interface which may lead to errors or time wasted. This method of making the machines smart machines introduces a pictures of manufacturing and production systems, like the smart factory. The IoT driver receives much attention as one of the Industry 4.0 modules in this idea. It is a robust communication between the physical and digital world used in different areas to make goods, operations, and services smarter in the value chain by offering new potential solutions to alter their functions. Internet-based wireless technology connects all the devices together for interactions that lead to smarter functions. System awareness of the environment is also possible via sensors, where devices transmit a large amount of data in real time. IoT can have a significant effect on the supply chain in the effective use of resources, transparency and visibility of the entire supply chain, real-time management of the supply chain, optimizing the supply chain, and increasing agility of the supply chain [6].

1.2.2. RFID Technology Enabling IoT

RFID can improve the performance of the whole supply chain from warehousing to transportation through real-time communication and information sharing. RFID can improve inventory flow by increasing the traceability and visibility of products. RFID can help to reduce inventory loss and inventory misplacement and to limit transaction negligence and supply fault [7]. The terminology IoT was used first for defining RFID tags [8]. By connecting RFID readers to an Internet terminal, the items attached with tags can be identified, tracked, and monitored globally and automatically in real time. RFID is considered a precondition for IoT. RFID systems refer to a whole that includes components transmitting data. These components have extensive variety in shapes, models, and sizes. Their applications are slightly different from one another. However, the two main components, readers and tags, remain mostly the same. An RFID system may include one or more readers and tags.

The tags attached to the objects store their unique IDs. The readers send a recon signal to investigate their surroundings in search of the RFID tags and read their IDs. This proposes a solution that is useful in logistics, e-health, and security by providing a real-time map of the objects and therefore transitioning the real world into a virtual representation. RFID tags are very similar to adhesive stickers from a physical point of view. These tags are usually passive, meaning that they do not require any power to operate, and are triggered by using the signal from the readers, which induces power to the tag's antenna. The power is then utilized to supply the microchip located in the RFID tag, which will be transmit the ID stored in it. Conversely, there are two other kinds of RFID which rely on their own power supplies: semi-passive and active tags. Semi-passive tags use a battery to power the microchip that stores the ID. Semi-passive tags also use the power transmitted by the reader to transmit the data. On the contrary, active tags use battery power to transmit the data to the readers. These two types of readers can provide better coverage but come with increased costs [9].

1.2.3. IoT Applications

Noting the definition of IoT, its applications are broadly imaginable in many areas such as safety, security, sustainability, etc. In fact, the applications of IoT technologies are everywhere around us, such as smart homes, smart cities, self-driven cars, IoT retail shops, farming, wearables, telehealth care, hospitality, smart supply chain management, etc.

1.3. New Information from Industry 4.0 Brought into Inventory Models

In the past, suppliers had significant effect on production plans. Now, customers play the main role of defining demands. Thus, production plans should be adjusted accordingly. Analyzing data to plan production and optimize decisions for competitive businesses is necessary. Production rates need to be adjusted according to customer demand. The machines in the production line should work collaboratively based on the received demand. With change in demand, the production rate should be changed proportionally. To smoothen the production process, the inventory in the warehouse should be sufficient to cover continuous demand changes. Therefore, inventory replenishment policies, inventory review, and ordering quantities should match with changing demand.

By employing Industry 4.0 technologies, specifically IoT, which make devices connected work collaboratively and coordinately, inventory management should be more responsible for changing inventory operations due to the change in demand. Considering the smart factory idea in the Industry 4.0 environment and the fact that inventory management is the main part of SCM, inventory replenishment policies must be re-reviewed, and new principles for adapting the Industry 4.0 technologies must be developed [10]. As such, it seems unlikely that conventional approaches could provide the materials in the right amount with lead time and without shortage for the production or assembly lines. With all these considerations, we review the available literature on this subject.

2. Survey Methodology

The paper aims to conduct a holistic literature review about the impact of IoT on inventory management, identify the research gap of applying IoT to inventory management, explore the trend and potential opportunities of applying IoT to inventory management, and suggest future research directions for inventory management. In this study, a content-analysis-based survey was performed. The articles were collected from three bibliographic databases: ScienceDirect, Springer, and Emerald.

The keywords were categorized into primary and secondary keywords based on the articles conceptualized as Industry 4.0 in supply chain management. The primary keywords used for the initial search are matched to various levels of inventory management in the supply chain, whereas the secondary keywords reflect one of the most important technologies in the Industry 4.0 area, IoT, which impacts SCM. Table 1 illustrates the keywords used for our searching.

Table 1. Keywords.

Keywords	Details
Primary Keywords	Supply Chain Management (SCM)
	Inventory Management
	Supply Chain 4.0
	Logistics 4.0
	Warehouse Management
Secondary Keywords	Industry 4.0
	Internet of Things (IoT)
	IoT-based Framework
	Smart Warehouse

The first search was carried out using the primary search keywords and secondary keywords that appear in the titles or the abstracts or keywords of the articles. All articles are written in English, available in online databases of journals and conferences, and published by scholars and practitioners. With our search range between June 2001 and July 2021, we faced a limited number of available articles. The subject of this paper is relatively new and is still under development at the time of penning this paper.

Figure 2 shows the steps taken to scan all the retrieved papers. The selection criteria for our further scanning contain the four steps as follows: (i) Firstly, the collected articles were reviewed only in titles, keywords, and abstracts. (ii) Six papers were excluded because of technical problems—for example, because we could not access the full articles. (iii) The papers irrelevant to inventory management or IoT were excluded. The articles concentrating on marketing policies or production procedures were omitted because these articles are not linked exactly to the inventory management part of the supply chain. Moreover, the articles that only depict electrical devices and the physical-technical methods for implementation and other scientific issues were eliminated as they are not relevant enough to our literature review. (iv) Finally, 10 additional articles were added for our references from the three mentioned databases, plus 2 new papers from two different publishers of all pre-scanned papers. In total, a sample of 55 articles was reviewed in our study: 42 from Science Direct, 5 from Emerald, 6 from Springer, and 2 from others.

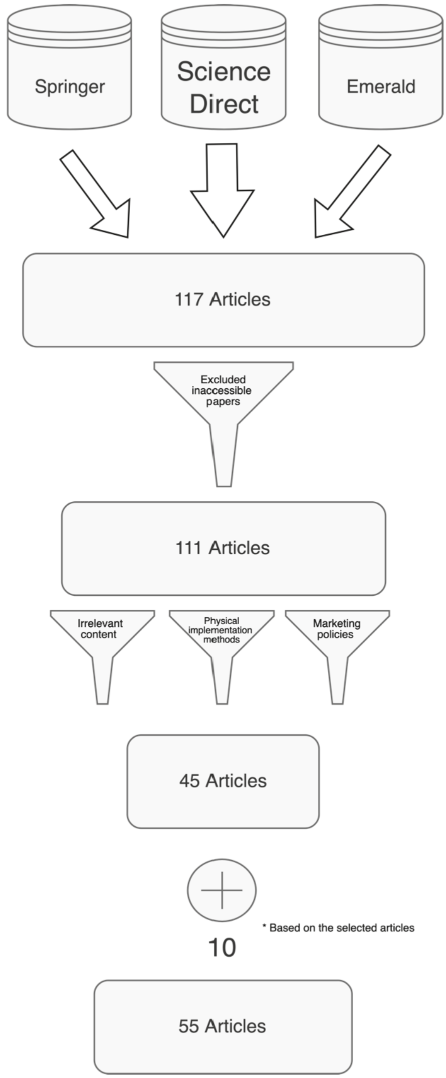

Figure 2. The systematic survey process.

3. Literature Review

The literature reviewed in the paper can be classified into three categories: initial preparation of IoT, structural implementation methods and requirements for IoT, and impact of IoT on inventory management in various industries.

3.1. Initial Preparation of IoT

With the advent of Industry 4.0 and its new technologies, the classic approaches in inventory management have been challenged. New inventory models and approaches must be innovated to determine inventory replenishment policies with the introduction of new technology.

Ref. [11] considered storage agent (SA) actions to reach the optimization goals of an automated inventory management system. This paper did not apply Industry 4.0

technologies for the aim of automation planning in this part of supply chain management (SCM). It compared the Markov decision process (MDP) with other conventional methods and used the MDP to deal with uncertain problems, including "busy storage place" and "misplaced product". Ref. [12] proposed using IoT to track the location of components from a remote location. Doing so can improve the productivity and speed of shipment. It also provides an accurate status of warehouse stocks and automatically notifies the warehouse manager. By using RFID tags, intelligent warehouses can control the material flow both in and out, which leads to proper warehouse scheduling and highly intelligent inventory management [13]. The study by [14] suggested that using RFID technology in Inventory Management can cut down inventory inaccuracy by 20–30% so as to reduce the operation costs and shortage levels.

Some companies have established special projects targeting warehouse automation and control through industrial wireless networks (IWN). The study reported IWN advantages to include reduction of the labor force and increases in mobility and flexibility. Wireless communication technologies in a warehouse are able to organize thousands of goods in a specific space. Moxa use RFID and wireless networks to categorize its products in order to save working time and resources and prevent wire network limitations [15]. Each company has its own unique and particular solution for implementing Industry 4.0. In other words, the solutions and impact of Industry 4.0 would be different between different companies. Since Industry 4.0 technologies have not been well developed yet, significant investment and more research in this area must be carried out [16].

Ref. [17] introduced the key performance indicators (KPIs) to measure which specific areas of the supply chain are affected by the technologies of Industry 4.0. The analysis in the paper showed that order fulfillment is one of the areas which is the most affected by the introduction of Industry 4.0 through tracking products via IoT and RFID tags. More than 50% of the impact of the new technologies on this part of the supply chain certainly leads to opportunities, while the rest could be opportunities or threats, depending on the context of the implication. This ratio of certain opportunities is higher for warehouses—about 67%. Ref. [18] presented online optimization models and showed how they could help cope with real-time challenges. In practice, a time-dependent model can be of great relevance as it allows embedding inventory decisions. Ref. [19] acknowledged that IoT is able to achieve collaborative warehousing by using multi-agent systems, which increase the safety and security of the supply chain. Ref. [20] proposed a manufacturing transportation system via IoT enablers. The system is able to track finished goods and various related items along the supply chain.

Another usage of IoT in warehouses and inventory management is with the concept of zero-warehousing smart manufacturing (ZWSM). IoT-enabled infrastructures are required to achieve a level of visibility that makes the ZWSM concept possible [21]. By using IoT, the smart inventory replenishment system proposed in [22] relies on the point of consumption (POC) data that are gathered from the end customers by extending the vendor-managed inventory (VMI) to the end customers. Assuming that the manufacturer's operational capacity is limited and that customer demand must be fulfilled, the system is designed to focus on inventory control, customer prioritization, and smart decision-making. The system showed that inventory replenishment decisions could be improved extensively. This system can generally enhance the service level and capacity utilization without adding to the customer's inventory costs.

3.2. Structural Implementation Methods and Requirements for IoT

The study by [23] presented the principle and implementation methods of an automated warehouse management system (WMS) in a telecommunication company. This system contains a labeling line in the warehouse and uses Microsoft Visual Studio and barcodes to show the data of access, location, receiving, and expiry in order to enhance utility. The study concluded that the performance of the inventory management system is improved in terms of the operational cost and accessibility of items. Furthermore, the system created extra space in the warehouse for the company.

Ref. [24] indicated that it is essential to use cloud and fog systems for data storage and processing in an IoT-based system when designing a smart warehouse monitoring and control system by using different components such as sensors, network gateways, actuators, etc. Ref. [25] proposed an implementation framework which requires RFID tags, Wi-Fi module (ESP8266-01), Wi-Fi development board (NodeMcu ESP8266-12e), and database (Raspberry Pi 3 as the data receiver and web server—programmed with the Python language).

Ref. [26] mentioned that smartphones can be used in industry to scan and record the data of RFID tags. Doing so would not only save more time, but also enhance inventory management functions. IoT provides real-time visibility and 100% inventory accuracy. This study proposed a framework for smart SCM where inventory is dynamically trackable to managers so that they can connect suppliers and orders in a timely manner via the integrated system. Ref. [27] used a new automatic code acquisition system which replaces the conventional way that a person has to check the inventory before entering the ERP system manually to barcode all the entries. Ref. [28] considered intelligent shelving and pallets as the force for driving innovative inventory management in the case of stocking in warehouses. With this system, tracking and tracing stocks in the warehouse would become faster, more precise, and safer. Ref. [16] presented a model to adopt industry 4.0 in inventory management. An intelligent system is able to measure inventory levels with an RFID shelf. Thus, it is feasible to control the material flow in a smart warehouse via mobile devices.

Ref. [29] discussed the item delivery problems that may be caused by delivery vehicle issues or item accumulation in the warehouse. By using IoT, a smart dispatch system which increases the transparency in the logistics system has been implemented, making visual management of the distribution system possible. In the study by [30], an IoT-based model for decision making in inventory management, which uses RFID, wireless sensors, and other middleware technologies at an enterprise level was introduced. Moreover, an information platform processes the information to ensure that inventory costs remain at their lowest.

The integration of Industry 4.0 technologies requires the various actors and stakeholders of the supply chain to ensure full collaboration and coordination among all stages of the value chain [31]. By recognizing the impact of integration within the whole supply chain on warehouse management systems (WMS), transporters will be able to communicate with the intelligent warehouse management system regarding the location and arrival time to have it select and prepare a docking slot and arrange the just-in-time and just-in-sequence delivery. RFID sensors will reveal delivery data simultaneously. They also send the track-and-trace data to the entire supply chain. WMS can automatically assign storage space according to the delivery specifications and request the appropriate equipment to move the goods independently to the appropriate location. When the pallets are moved to the particular location, the tags will transmit signals to the WMS to provide real-time visibility of inventory levels, which can prevent extra cost from out-of-stock situations and increase the management's ability to make decisions on the settings that might be necessary to increase customers' service level.

The study conducted by [32] demonstrated the possibility of using a warehouse equipped with heterogeneous RFID readers from different manufacturers which is not dependent on a centralized server. Such an implementation could reduce the initial implementation cost and investment. The real-time analysis of RFID efficiency was incorporated with indoor localization and navigation of warehouse mobile robots. With RFID and universal plug and play (UPnP) technologies, [33] recommended a new approach to manage production and logistics processes by turning a product into a smart object, which allows upgrading the products to intelligent objects and services that result in a high level of functional interaction. Using the concept of the industrial Internet of Things (IIoT), another study mentioned a novel approach to the production of smart products and shaped the production line in order to minimize energy consumption [34]. Ref. [35] introduced a communication system in the supply chain for open communication with its electrical professional infrastructure and security to benefit from enhancing real-time properties. The basics of time-sensitive networks (TSN) were explained and compared with the Internet for this communication system. The communication between Industry 4.0 factories which are related or working in parallel or in coordination could be improved. Therefore, these factories can take advantage of the benefits of dynamic inventory aggregation and pooling. A new model in reducing production time, which affects inventory capacity management, has been proposed as well. The paper takes an artistic approach by integrating the fuzzy theory into its model, which results in an optimization in the trade-off between production time and the costs included [36].

Ref. [37] proposed the mechanism that enables objects to communicate via the web in the warehouse. The mentioned warehouse (full of various objects) is smart and works with a system that contains RFID sensors and consists of a data collection module and an administrative module. The paper also simulated and evaluated the proposed system in various scenarios in the context of discovery time, response time, and transmission failure. Its effects, as seen in the warehouse, are performance improvement, quick interaction, and high accuracy. Furthermore, the system was designed and created to be semi-automated. Therefore, with the absence of the user's decision-making, it can work properly. This advantage provides companies more flexibility to shift from their former systems to new technologies and start using the proposed system easily.

Ref. [38] introduced a solution for reverse supply chain management (R-SCM) which is dependent on a heterogeneous IoT network following digital security controls (DSC) objectives. Inventory management utilizes smart containers, while a LoRaWAN (LoRaWAN®is a LPWAN protocol designed to connect battery operated "things'" to the Internet in regional, national, or global networks) context network is liable for checking the industrial facilities by using Bluetooth Low Energy (BLE) and RFID technologies. The four performance tests used to assess this system were data ingest, geographical spread, data size, and network latency. It was found that the testing results are proper for an inventory management setting. However, BLE seemed to be the bottleneck for larger arrangements. Ref. [39] proposed a warehouse management method using mobile robots, which are highly automated and flexible. When a number of such robots operate in the same environment, the challenge is how to manage them. This can be resolved through a cyber-physical system using IoT, which leads to finding a collision-free path for these mobile vehicles.

3.3. Impact of IoT on Inventory Management in Various Industries

3.3.1. Spare Parts Manufacturing

Ref. [40] proposed a smart inventory management system for two types of spare parts: consumable and contingent spare parts for a semiconductor manufacturing company. The system aims to prepare spare parts for the right machine at the right time with the right quantity through IoT technologies. It would lead to making better decisions and establishing transparency and flexibility between fabs and suppliers. Ref. [41] used IoT technologies in the aircraft spare parts inventory system to reduce inventory costs and unavailability risks. Improved fleet management and increased customer stratification were achieved. There are four types of IoT applications in the airline industry: in-house sourcing, ad hoc pooling, cooperative pooling, and commercial pooling. The paper reviewed these four types of applications by using the business model of the KLM Engineering and Maintenance Department. There are numerous challenges with managing inventories of maintenance, repair, and operations (MRO) spare parts. Ref. [42] applied big data analytics, machine learning, and IoT to predict maintenance cycles and spare parts needs. MRO spare part usage in the automotive industry showed the differences in patterns, lead times, and costs, which need to leverage Industry 4.0 technologies to help improve inventory efficiency.

3.3.2. Agriculture Products

For precision agriculture in the agriculture industry, IoT can be used to track detailed information from product production to transportation. It allows stakeholders to receive real-time information about inventory status. With IoT, cloud technologies can be implemented to support the agriculture supply chain [43]. The study by [44] on agriculture logistics suggested RFID-based technology in the agriculture industry. The paper explored the application of RFID in agricultural production and examined the system's efficiency.

3.3.3. Food Industry

The paper by [45] discussed smart inventory management in the food supply chain and used the survey and sequential pattern for prediction with the AHP method. The three factors were presented for measuring the function of the food processing and distribution system on quantity, frequency, and recency (QFR) to indicate the impact of being smart in the food industry. The study concluded that the system's performance could be improved up to 66%. Another IoT application in the food industry is to use an IoT-driven sustainable food security system in which inventory levels are monitored and tracked through the whole logistics process, starting from the farm and ending with consumers [46]. This can also help policymakers monitor food processing, storage, and delivery to end consumers while minimizing food losses in the supply chain by controlling temperatures and planning routines.

Halal food organizations should re-examine their ordinary inventories and influence new innovations. There are many IoT applications in the Halal Food Store Network (HFSC) [47]. The possibilities and opportunities need to be further explored for the HFSC. There are five main areas in which the HFSC can benefit: tracking food items, upgrading supply chain efficiencies, easier livestock management, validation of food's halal status, and observing halal accreditations. Ref. [48] expressed that for special products such as drugs and food, which need specific storage conditions, IoT-based alert systems are beneficial and can lead to more sustainability. Ref. [49] proposed a live IoT-based monitoring system for the food supply chain which shares the information with stakeholders. As an immediate result, the quality of prepackaged food increases. Another example of smart inventory systems in the food industry is the IP-enabled soft drink vending machines that benefit from an inventory system accessible over the internet [50]. It is feasible that by using this technology, one could locate their nearest favorite soft drink in a matter of seconds. This is one of the earliest applications of the internet in inventory systems, which leads to more advanced applications of IoT in warehouses.

3.3.4. Pharmaceutical Industry

The study on pharmaceutical supply chains illustrated that using Industry 4.0 technologies in communication leads to fewer errors in demand forecasting and the improvement of storage space usage in warehouses [51]. RFID can provide expiration date information, which is the main reason for drug returns, and accurately forecast the reverse flow of expired and near-expired drugs. Thus, in the reverse flow, which plays a significant role in pharmaceutical and other perishable product supply chains, information integration is able to reduce wastage and improve sustainability.

3.3.5. People with Disabilities

Ref. [52] introduced an IoT application for people with disabilities. In this study, it was mentioned that RFID via IoT-based inventory management in stores can help people with disabilities shop more easily.

3.3.6. Construction Supply Chain (CSC)

The benefits from RFID tracking implementation in construction supply chains were presented in [53]. The material handling process and inventory counting, searching, and organization in warehouses became more accurate and reliable. In addition to easier measurable benefits, such as alleviating laborious material handling tasks, shipment reliability was improved and supply lead time was shortened in the supply chain.

The concrete stocking-related applications of RFID tracking, e.g., counting, searching, and organizing the inventory, would be most beneficial to the companies with warehouses of construction materials. By using RFID in warehouses, stock recording and balancing would be more accurate. Doing so would result in less out-of-stock materials and less excess stock. Industry 4.0 concepts and technologies have been introduced to the construction industry differently due to the fact that construction supply chains are usually project-driven, and their partnerships are temporary and constantly changing. Ref. [54] defined "proximity" as a concept of distance that can affect construction supply chains. Because of the specific situations at construction sites, delivery lead time and holding cost are the two major factors influencing the entirety of the construction projects' performance. Using RFID can help with tracking and localization and can improve proximity dimensions by solving the problem of late and early deliveries. Eventually, it can lead to reduced inventory cost, more efficient on-way inventory, shortened lead time, and fewer damaged goods [55].

Another example of IoT-enabled material inventory at construction sites is the inventory of the construction materials attached with RFID tags. The RFID tags contain the relevant data of the materials, including the manufacturers, technical specifications, scheduled installation sites and dates, purchase dates, and more. The RFID system plays an essential role in material monitoring and control by using IoT at construction sites. Engineers and managers use portable readers to track material delivery, storage, installation progress, and changes. The data are then transmitted to the dynamic database, which allows real-time information sharing with other project teams [56]. The study by [57] suggested that real-time inventory management can facilitate the construction process. The suggested method is to use long-range RFID readers in the storage area which can track the product-specific information stored on the tag attached to the materials. Doing so would allow the RFID system to read and update the inventory database when the materials move into or out of storage. This can also help the workers to trace the right materials by using the tag data. One good example of using IoT in construction supply chain networks is the use of IoT-enabled devices, augmented reality (AR), and fuzzy-VIKOR-analysis-based inventory management for the construction projects in the China Pakistan Economic Corridor (CPEC) [58].

3.3.7. Retailing Industry

The quick response system is an application of IoT in the retailing industry. RFID facilitates this system by tracking products. It minimizes the backroom inventory and shelf shrinkage of products while improving store security and ability to analyze sales data [59]. The method of product shelf and sales floor bidirectional movements has been proposed by incorporating RFID into the model described in [60]. This model can account for misreading from the RFID readers and avoid the disadvantages of fully automatic inventory control by applying for a simple heuristic extension. An interesting application is the use of RFID tags in fitting rooms.

An example is a German department store in Essen which uses RFID tags on clothes. When clothes are brought to the fitting rooms, a smart mirror will show similar items and suggest complementary clothing choices or accessories based on the information saved on the tag. This system is used in combination with smart shelves [59]. A new model has been introduced to deliver information regarding supply levels from the retailer to the manufacturer using RFID tags which increase the accuracy of the orders based on the retailers' demand based on machine learning [61].

A challenging issue mentioned in [62] is the fact that the inventory data supplied by the point of sale (POS) are sorted out after the sales are closed. It cannot precisely represent the data of the products on the shelves. Using RFID-enabled tags and employing a software agent, an integrated information system is able to overcome the mentioned issue. By being able to telecommunicate the client inventory level to the manufacturer, the installment of an electronic device inside the containers improves the opportunity of just-in-time (JIT) pickups and reduces the chance of late or unnecessary visits to the client site by 50%, as the study [63] indicated. It can also help the supplier to coordinate shipments and rebalance the retailers' stocking positions. A new approach has been mentioned to maximize the profit of a specific retailer by promoting items that will be expired soon, which helps in sales, reducing inventory costs, and prevention of the loss of goods [64].

3.4. Companies' Preparedness for Applying New Technologies

Ref. [65] provided a conceptual framework for assessing sustainability in SCM, which enables companies to understand the preparedness for Industry 4.0 transformation. The framework contains five enablers—business-based smart operations, technology-based smart products, management strategy and organization, collaboration, and sustainable development—with 18 criteria and 62 related attributes. Inventory management was mentioned in two criteria of the framework, including IoT and logistics integration. The study pointed out that concepts such as monitoring, resource management systems, visibility on in-transit consignment, enabling information-driven decision-making, and location, status and allocations could be counted as important attitudes of inventory management.

3.5. New Environmental Insights Impact

Greening is the process of transforming usual activities into more environmentally friendly versions. Integrating environmental insights into supply chain management has important influences on total environmental and economic improvement, which leads to more sustainability in the whole supply chain. The study shows that a green IoT system can improve decision-making in the green supply chain (GSC) and, in the same way, in the green inventory management to achieve greater sustainability [66]. Industry 4.0 capabilities along the supply chain can affect each of the given dimensions. Such capabilities further influence the greening of supply chains [55]. A new methodology has been introduced which helps to significantly reduce carbon emissions, which results in an improvement of the inventory management system [67].

4. Analysis and Discussion

In this section, the findings will be discussed based on the descriptive analytics of the sample literature we reviewed. The sampling process collects 55 papers for our review. The distribution of the articles considered for the survey by publication years is illustrated in Figure 3.

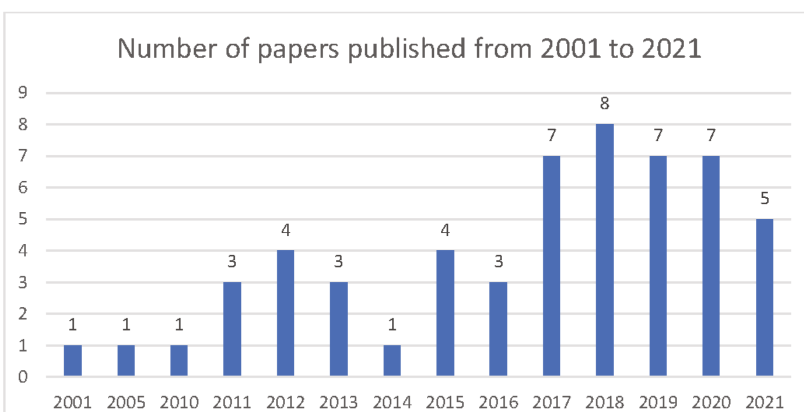

Figure 3. Distribution of the articles reviewed in the study by year.

The majority of papers were published over the last three years. The reason is that the keywords used by the authors to index the articles were relatively new concepts in the first decade of the 2000s. Thus, the research gap between the years 2001 and 2010 seems logical. Figure 4 shows that the interest over time has increased for the above-mentioned keywords around 2010, which supports the reason behind the unavailability of scientific work in the first years of the current millennium.

Figure 4. Interest over time for the keyword "IoT".

Figure 5 shows the increasing interest in this topic over years. In terms of publication types, 11 out of the 55 considered articles in this study were published in conferences and 44 of them were published in journals, as shown in Figure 4. Table 2 presents the details of the journals and conferences we surveyed.

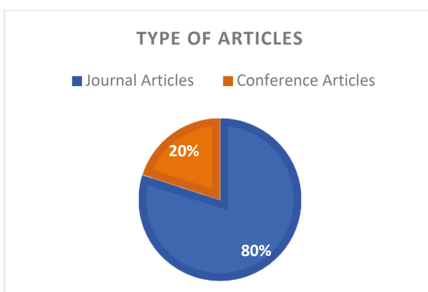

Figure 5. Types of articles.

Table 2. Journal and conference distribution.

Type	Title	Number of Papers
Journal	Advanced Engineering Informatics	2
	Alexandria Engineering Journal	2
	Annals of Emergency Medicine	1
	Automation in Construction Journal	2
	Automation in Construction Journal	1
	Cluster Computing	1
	Computers & Industrial Engineering	1
	Computer Communications	2
	Computers in Industry	4
	Computer Networks	1
	Decision Support Systems	1
	EURASIP Journal on Wireless Communications and Networking	2

Table 2. *Cont.*

Type	Title	Number of Papers
	European Journal of Operational Research	1
	Expert Systems with Applications	1
	Food Control	1
	Future Generation Computer Systems	1
	Industrial Management & Data Systems	3
	International Journal of Advanced Manufacturing Technology	1
	International Journal of Advance Research in Computer Science and Management Studies	1
	International Journal of Business Analytics	1
	International Journal of Production Economics	1
	Internet of Things	1
	Journal of Engineering and Technology Management	1
	Journal of Network and Computer Applications	1
	Journal of Management Science and Engineering	1
	Journal of Supercomputing	1
	Omega	1
	Process Safety and Environmental Protection	1
	PSU Research Review	1
	Resources, Conservation & Recycling	1
	Robotics and Computer-Integrated Manufacturing	1
	Sustainable Operations and Computers	1
	European Journal of Operational Research	1
	Wireless networks	1
	Total	44
Number of journals		**33**
Conference	AASRI Procedia	1
	IFAC Conference	5
	Procedia CIRP—CIRP Conference on MANUFACTURING SYSTEMS	1
	Procedia Computer Science—Information Technology and Quantitative Management	1
	Procedia Engineering -International Conference on Engineering, Project, and Production Management Internet	1
	Procedia Manufacturing—Manufacturing Engineering Society International Conference	2
	Total	11
Number of conferences		**7**

Since this is an emerging underexplored field of research, as shown in Figure 5, 38% of the chosen articles in this study focus on modeling and implementation methodology and principles. About 15% of the articles were on case studies, which could be investigated more. The case study articles present a rich vision of complex phenomena and help to develop theories further.

The percentages in Figure 6 indicate the topic is a niche for both practitioners and academic scholars to apply and improve theoretical methods in inventory management for different industries since it has not been implemented at an integrated level in most supply chains. The cross-sectional data collected by either literature review or surveys constitute 20% of the study. In terms of the conceptual framework, 7% of the articles focus on presenting the frameworks based on IoT systems. However, some literature reviews provide frameworks based on the reviewed papers. The majority of the articles concentrate on modeling and introducing the platforms, and 20% of the articles contain analytical concepts and explanations.

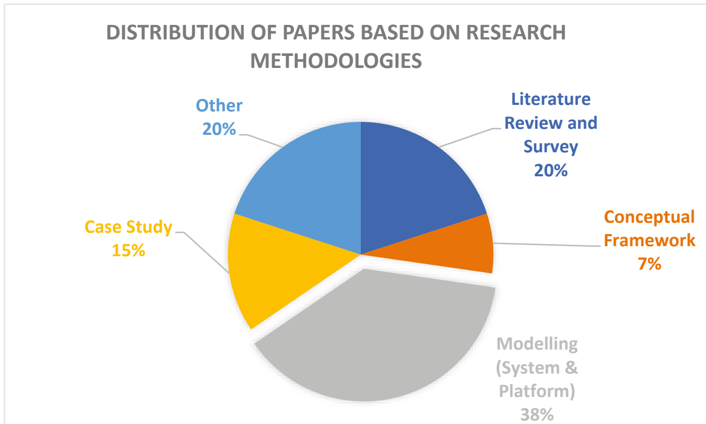

Figure 6. Research methodologies considered in the surveyed articles.

5. Conclusions

In this study, the impact of Industry 4.0 technologies, particularly IoT, on inventory management was investigated. Upgrading a supply chain into an integrated supply chain 4.0 is beneficial. Given the changes in fourth-generation technology compared to previous generations, the approach of conventional inventory replenishment policies seems not responsive enough to new technologies and is not able to cope with IoT systems well.

From the literature analysis, the trend and potential of IoT opportunities available in sustainable inventory management space were explored. Our findings show that the research on this topic is growing in various industries. A broad range of journals is paying particular attention to this topic and publishing more articles in this research direction. The systems and platforms that are applying the new technologies to the organizations are the major parts of this survey. Since each individual company needs its own specific solution for transformation to a greater high-tech level, this topic is expected to be addressed further in the future.

6. Research Gaps and Future Work Recommendations

To bridge the research gaps in the literature, the following are suggested.

- Considering sustainability in inventory management with a focus on the green supply chain as a whole to achieve more sustainability;
- Forecasting future customer demand based on data analytics and market intelligence while reviewing the product selling price and customer satisfaction to improve the accuracy;
- Reviewing suppliers' behavior by leveraging the available data and BI to know which supplier can provide the best quality, price, and response to last-minute orders;
- Establishing an integrative data-driven inventory optimization model instead of the conventional sequential approach by leveraging data about suppliers, customers, and inventory to maximize revenue and customer satisfaction;
- Using AR-enabled headsets to help workers improve storing and finding items inside an inventory and for training purposes;
- Optimization of the placements of items inside a storage facility by applying the results of data analysis from repetitive orders to minimize labor cost and improve efficiency;
- Improvement on decision making systems and lead-time delivery.

In Table 3, the application of IoT in inventory management have been classified in different industries. Based on the literature survey, we propose some future application of IoT technology in inventory management for the different industries discussed in Section 3.

Table 3. Application of IoT in inventory management in different industries.

Industry	Reference
Spare parts	[40–42]
Agriculture	[43,44]
Food	[45–50]
Pharmaceutical	[51]
People with disabilities	[52]
Construction	[53–58]
Retailing	[59–64]

Spare parts: For more risk reduction in maintenance operations and inventory of spare parts, IoT must be connected to cloud computing systems to enable decision support systems (DSSs) to predict orders of new spare parts based on the current rate of consumption.

Agriculture: Future works can enhance the application of IoT in agriculture product warehouses by enabling DSSs to indicate the amount and time and the type of the agriculture products for farming based on the characteristics of the product, such as volume, storage conditions, weather conditions, soil quality, and agricultural land. This would lead to more sustainable agriculture production with minimal waste, optimized use of natural resources, and less emission.

Food: This industry needs some structured frameworks for food product storage and transportation and to control and update the condition of vehicle conditions, such as temperature, humidity, etc. in real time. Additionally, the use of IoT connected to other Industry 4.0 technologies could help order delivery be more efficient based on capacity and the vehicle storage conditions needed for transportation.

Pharmaceutical: Improving the lead time of the delivery is one of the concerns that could be performed more effectively with more progress in use of IoT, especially in emergency situations.

People with disabilities: Establishing and introducing more efficient frameworks of smart houses and smart cities in practice is needed to meet the demand of people with disabilities for full use of smart systems.

Construction: One of the problems of construction sites is that inventory control is more challenging due to the nature of the work because of the lack of dynamically integrated warehouses. Therefore, future application of IoT sensors and equipment could upgrade inventory management for this industry by designing and implementing better sensor systems in the whole construction site, even while working and when the gradual use of resources takes place in different parts of the site at the same time.

Retailing: The use of smart shelves via IoT could progress to the level that refilling the shelves would be possible with the help of smart transportation or integration with robotics in the warehouse.

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logistics

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Review

Moving from Industry 4.0 to Industry 5.0: What Are the Implications for Smart Logistics?

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Abstract: *Background*: Given the importance of human centricity, resilience, and sustainability, the emerging concept of Industry 5.0 has pushed forward the research frontier of the technology-focused Industry 4.0 to a smart and harmonious socio-economic transition driven by both humans and technologies, where the role of the human in the technological transformation is predominantly focused on. Several studies discuss the impacts of disruptive technologies on smart logistics operations in Industry 4.0. However, since Industry 5.0 is a new concept and still in its infancy, its implications for smart logistics have not been discussed. *Methods*: To fill this gap, this paper presents a comparative bibliometric analysis to show the connection and differences between Industry 4.0 and Industry 5.0 and their implications for smart logistics. A thorough content analysis is then given to illustrate the features of smart logistics in Industry 5.0 concerning four areas, namely intelligent automation, intelligent devices, intelligent systems, and intelligent materials. *Results*: The results show that, compared with Industry 4.0, the research of smart logistics in Industry 5.0 puts more focus on the interaction between humans and technology in the digital transition, with the increasing adoption of collaborative technologies, e.g., human-machine systems, collaborative robots, and human-robot collaboration. *Conclusions*: Finally, a research agenda is proposed for identifying future research directions of smart logistics in Industry 5.0.

Keywords: Industry 5.0; Industry 4.0; smart logistics; sustainable logistics; bibliometric analysis; literature review

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1. Introduction

Industrial revolutions, throughout history, are primarily driven by disruptive technological breakthroughs that change the manufacturing paradigms and the way of customer demand satisfaction. With the increasing adoption of advanced manufacturing technologies, digitalization, and information and communication technology (ICT), Industry 4.0, also known as the fourth industrial revolution, aims at achieving a higher level of automation and intelligence [1]. Through leveraging the effectiveness and efficiency of manufacturing processes, Industry 4.0 predominantly emphasizes the paradigm shift led by new technologies, but less attention has been paid to the human aspects [2–4]. This is, however, argued as a threat to the sustainable development of humans and society [5], which requires more attention and effort from both industrial practitioners and academia [6]. Although this concern can be partially addressed by incorporating Industry 4.0 within the context of sustainability [7], circular economy [8], green supply chain [9], and so forth, it is still important to have a systematic conceptual development to fill the missing points of Industry 4.0. Thus, given the importance of human centricity, resilience, and sustainability [10], the concept of Industry 5.0 is proposed to complement the existing Industry 4.0 [11] in order to better meet the industrial and technological goals without compromising the socio-economic and environmental performance [2,3]. Among others, personalization, human–machine collaboration, bioeconomy, and sustainability are the most important pillars in Industry 5.0 [12]. As argued by Di Nardo and Yu [13], the increasing adoption of Industry 5.0 technologies will not hinder human value, but rather promote a dual integration between human intelligence and machine intelligence in a collaborative environment [14].

Logistics, as a key function of a company or a supply chain, has been significantly affected by recent technological advancements and innovation [15]. Smart logistics operations are enabled by the increasing use of new technological solutions, which lead to the emergence of intelligent warehouse management [16], smart transportation [17], digital twin [18], and so forth. By comparing the development of logistics operations with the four industrial revolutions in history, Wang [19] proposed the concept of Logistics 4.0, which integrates Industry 4.0 technologies into various logistics operations to improve smartness and automation. This concept is further developed to adapt to the characteristics of specific industries, e.g., food logistics [20] and forest supply chain [21].

Even though significant research effort has been given to understand the impacts of new technologies on smart logistics operations and management, no effort has been directed to the human and environmental aspects brought by Industry 5.0. A recent literature review has put forward the concept of supply chain 4.0 to supply chain 5.0 [4], but no research has been done to provide a comprehensive understanding of the implications of Industry 5.0 for smart logistics. To fill this gap, this paper presents a comparative bibliometric analysis to show the connection and differences between Industry 4.0 and Industry 5.0 and smart logistics. A thorough content analysis is then given to illustrate the features of smart logistics in Industry 5.0 concerning four areas, namely intelligent automation, intelligent devices, intelligent systems, and intelligent materials. Finally, a research agenda is proposed for identifying future research directions of smart logistics in the era of Industry 5.0.

The rest of the paper is organized as follows. Section 2 presents the theoretical backgrounds of Industry 4.0 and Industry 5.0, and it also identifies the gaps related to smart logistics and the contributions of this paper. Section 3 introduces the research method. Section 4 formulates the research questions and illustrates the procedures of the literature search. A comparative bibliometric analysis is given in Section 5. Section 6 presents the content analysis and discussions. Finally, the conclusions are given in Section 7.

2. Literature Review

2.1. Industry 4.0

Industry 4.0 is undeniably one of the most important industrial phenomena to have occurred in the last decade, which has drawn significant attention from both industry and academia. The advent of this industrial paradigm has shaped the ground for extensive research topics since its introduction in 2011 at the Hannover fair by highlighting two major concepts: internet of things (IoT) and cyber–physical systems (CPS) [22,23]. The high-speed internet connectivity within manufacturing and logistics systems, i.e., industrial internet of things (IIoT) [24], potentially favors these industries by improving their intelligence and integration levels [25–27]. In this regard, combining automation and intelligence in a highly integrated CPS shows the maturity level of an Industry 4.0 system [1,28]. Through a combination of disruptive technologies and intelligent analytics, e.g., IoT, CPS, big data, artificial intelligence (AI), etc., Industry 4.0 will not only change the manufacturing industry but also impact all sectors of economic cycles. Figure 1 illustrates the nine most important enabling technologies of Industry 4.0, which are considered the pillars of the fourth industrial revolution.

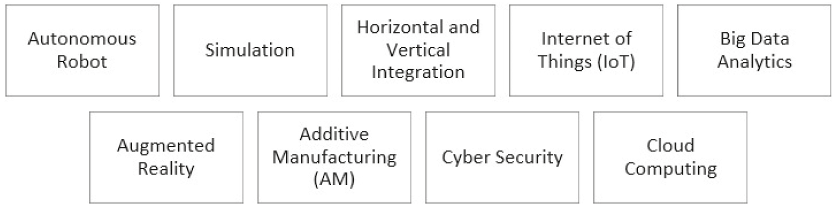


Figure 1. Nine pillars of Industry 4.0.

By integrating these technological pillars into an organized framework, Industry 4.0 is considered a technology-driven paradigm shift that aims at higher productivity through the better utilization of resources [2]. This technological framework incorporates all operational layers and streams of a factory and possesses a high level of intelligence similar to a human's brain. From a holistic point of view, this evokes a fully automated production system that is operated by internet-connected smart machines and robots with minimum human intervention. However, realizing such an objective needs the adoption of several enabling technologies through both vertical and horizontal integrations [1]. For instance, additive manufacturing (AM), e.g., 3D printing, has not only been used for the rapid prototyping of complex designs but has also been widely adopted in the manufacturing processes in several industries, e.g., aviation [29]. It may change the manufacturing paradigm through direct digital manufacturing (DDM), which can better satisfy highly personalized demands. However, on the other hand, it may proportionally increase the sophistication of production management. To this aim, virtual technologies and simulation can be used to evaluate the operational aspects and performance of incorporating AM into a manufacturing plant [30], which can provide comprehensive insights into the technological updates. Thus, the technological integration in a CPS has been categorized into five levels to measure the maturity of an Industry 4.0 system, namely connection level, conversation level, cyber level, cognition level, and configuration level. At the highest level, the system can achieve bi-directional communication and control, intelligent decision-making, and autonomous operations [28].

2.2. Industry 5.0

The primary focus of Industry 4.0 is a technology-driven industrial paradigm transition, but less attention has been given to the human aspects and society. One concern related to this industrial revolution is the possible layoff and job security with the increased adoption of autonomous systems [31]. Thus, it is of great importance that the technological transition must be done in a sustainable way and comply with the socio-economic development goals [3]. The concerns of humans and society in the industrial transition led to the emergence of Industry 5.0, which was raised by Michael Rada [32] in 2015 to put forward the concept of "Industrial Upcycling". This idea emphasizes the cooperation between humans and new technologies, i.e., industrial robots, 3D printers, etc., in production with the purpose that "*we use these tools as tools, do not give them the function and brain to WORK FOR US, but WORK WITH US*" [15]. This concept is closely linked to the technological pillars that have already been employed, and thus studies are carried out to distinguish the scopes, goals, and approaches of Industry 5.0 as a new stage of the industrial revolution. Following the footprints of this paradigm shift, the Japanese government (Keidanren, the most important business federation of Japan) proposed "Society 5.0" based on the high digital transformations in society. This concept aims at protecting societal and environmental benefits along with the direction of economic growth by taking advantage of technological improvements [33,34]. It attempts to turn the novel solutions around for the benefit of society and human life.

With a predominant focus on the role of the human in the technological transition, substantial attention has been paid to human–robot collaboration in Industry 5.0 during the last couple of years [2,3,35–37]. In addition, several studies investigate the human's role from various perspectives, i.e., technical, ethical, operational, societal, safety, etc., which has become one of the mainstream research directions to shape this new industrial revolution [6,34,38]. Hence, Industry 5.0 aims at establishing a comprehensive framework by adopting disruptive technologies and innovative solutions to tackle the emerging human- and societal-related challenges and achieve sustainable development. In this regard, the European Commission (EC) officially defined the concept of Industry 5.0 in January 2021 [33], which presented a systematic approach in the context of technological and methodological improvements. It establishes a synergy between the main technological drivers and societal development in Industry 5.0, and six major categories are identified, including human–machine interaction, bio-inspired technologies and smart materials, digital twins and simulation, big data analytics, artificial intelligence, and energy efficiency and renewable energies.

2.3. Literature Gaps and Contributions of This Research

The technological breakthroughs in the recent industrial revaluation have provided opportunities for smart logistics management and operations. A recent survey has clearly presented the technological implications of Industry 4.0 for smart logistics operations, including production and purchasing, transportation, warehousing, and digitalization and system integration [15]. In addition, research shows that blockchain, AI, and unmanned aerial vehicles (UAV) are the three widely focused enabling technologies for smart logistics [39–41]. Even though significant efforts have been devoted to research to understand the implications of disruptive technologies in smart logistics [15] and supply chains [9,42,43], warehouse management [44], goods transportation [39], as well as other relevant topics, the primary focus has been given to the technological sides and not to the main characteristics of Industry 5.0. A recent study has presented a comprehensive discussion by connecting Industry 5.0 and supply chain management [4]. However, to our knowledge, no research effort has been made to link Industry 5.0 in the context of smart logistics. Thus, this paper aims at filling this gap by providing an overview to understanding the implications for smart logistics moving from Industry 4.0 to Industry 5.0.

3. Research Method

Considering the rapid advancement of industrial paradigms stemming from technological leaps and the significant socio-economic impacts, it is of significance to analyze the status quo of the literature and project the future landscape of smart logistics in Industry 5.0. This paper presents a systematic literature review (SLR) to thoroughly understand the main characteristics of smart logistics in Industry 5.0. Literature review studies could be distinguished by two taxonomies according to their domain of contribution [45,46], namely conventional and stand-alone literature reviews. The former is broadly known and used by scholars serving as a background study that highlights a literature gap as the basis of a research project. The latter, however, is a solid study that assesses the entire “body of existing knowledge” in a particular field to shed light on the current research status and frame the potential directions. This concrete method was reshaped by Fink in 2005 by outlining the main features of the stand-alone review study [47]: systematic, explicit, comprehensive, and reproducible. To be more precise, such a study ought to accommodate a solid methodology with clear notations on the procedures encompassing deep insights into the corresponding research materials, which can be reproduced by other scholars. Based on this framework, the SLR was defined as [45]: “*a systematic, explicit, comprehensive, and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners*”. An SLR can benefit from both qualitative and quantitative methods by exploiting the meta-analysis, which takes place prior to the qualitative evaluation of the selected articles, and thus neutralizes the impact of selection bias pertaining to a narrative literature review [45,48].

The procedures of an SLR were initially developed by eight steps [45,49]: formulating the problem, validated review protocol (eliminate the conflicts of interest for studies including more than one reviewer), literature search, screening, quality assurance, data extraction, synthesizing the findings, and reporting. These steps were further aggregated into four logical categories to represent a more transparent overview of the stages involved in this research method [45,50,51]:

1. **Problem Formulation:** Entails the identification of the research goals and scopes by defining relevant research questions. It is worthy to note that, for studies including more than one reviewer, there should be a consensus over the questions to avoid evaluation bias.
2. **Literature Search and Screening:** This stage commences with a precise search within the selected databases according to the identified keywords for each research question. The resulted papers are to be filtered out through the inclusion and exclusion of relevant criteria, which are further narrowed down by the screening procedure.
3. **Bibliometric Analysis:** According to the meta-data associated with the extracted papers, a quantitative analysis is conducted to reveal the relations between various characteristics of the research articles, i.e., publication trend, keywords focus, involved journals, etc.
4. **Content Analysis:** Qualitative analysis that aims at a thorough evaluation of the selected papers to explore the current status of the research area and to highlight the future research agenda.

4. Problem Formulation and Literature Search

The initial step of this research is to formulate the research questions. According to the main objective of this study, we aim at providing a thorough understanding of the transition of smart logistics operations in the fifth industrial revolution. To this aim, three research questions are defined to shape the ground of this stage:

- Research Question 1 (*RQ1*): What are the connection and differences in smart logistics between Industry 4.0 and Industry 5.0?
- Research Question 2 (*RQ2*): What are the main characteristics and enabling technologies of smart logistics in Industry 5.0?
- Research Question 3 (*RQ3*): What is the research agenda of smart logistics in Industry 5.0?

The second stage is the literature search, which aims at finding and extracting the most relevant research articles for further quantitative (Comparative Bibliometric Analysis) and qualitative (Content Analysis) analyses. This stage consists of four steps, namely keyword search, inclusion/exclusion of criteria, first screening (investigation of titles, abstracts, and keywords), and second screening (full-text investigation). In this paper, we used the following steps to identify and select the most relevant articles for answering the research questions:

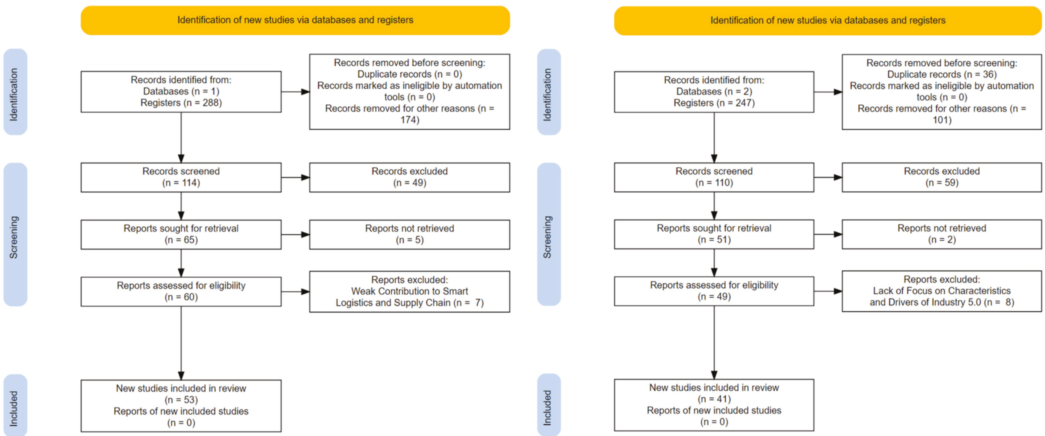
1. **Keyword Search.** This step employs two search techniques: (1) using a double quotation for an exact match with regard to phrase search; and (2) taking advantage of Boolean operators (OR/AND) to combine various taxonomies of keywords. To thoroughly reveal the connection and differences in smart logistics between Industry 4.0 and Industry 5.0, we searched the respective literature in two groups. The first group emphasized the connection between Industry 4.0 and smart logistics, which primarily yielded two contextual categories connected with "OR", as shown in Table 1. The second group was to explore the literature that discussed the characteristics, implications, driving factors, and definitions of Industry 5.0-enabled smart logistics. The primary database for the literature search was Web of Science (WoS), which is the most extensively used platform [52]. However, due to the limited number of papers related to smart logistics and Industry 5.0 in WoS, Scopus was also used to yield a reasonable sample for analysis. The literature search was conducted in late December 2021, and the initial search for the first group yielded 288 papers, while it resulted in 247 for the second group (91 and 156 in WoS and Scopus, respectively).

Table 1. Identified keywords for smart logistics in Industry 4.0.

Main Category ('AND' Boolean Operator)	Sub-Keywords ('OR' Boolean Operator)
Smart Logistics	smart logistics; logistics 4.0; smart supply chain; supply chain 4.0; operator 4.0
Industry 4.0	industry 4.0; i4.0; fourth industrial revolution; cyber-physical system; internet of things; cloud computing; augmented reality; big data analytics; artificial intelligence; virtual technology; simulation; additive manufacturing; autonomous robots; cyber security; digital twin

2. **Inclusion/Exclusion of Search Criteria.** This procedure attempts to narrow down the collected papers from the previous step by either including or excluding particular criteria. Primarily, the language of the research items was selected as 'English' to emphasize the international contributions. To ensure the quality of analysis, the papers were restricted to journal articles and conference proceedings. As also outlined, the introduction of Industry 4.0 was traced back to 2011 [22,23], while the literature had recorded 2017 for Industry 5.0 despite its initial introduction being in 2015 [2,53]. Thus, the next criterion was to set the publication years of the two groups of papers to be after 2011 and 2017, respectively. Another key filter that remarkably impacts the search results is the publication categories, which seeks to eliminate articles with the least correspondence in terms of their scientific fields. Based on the applied filters, there were 114 and 146 in the two groups. Ultimately, a duplicate check for the second group was essential due to the use of two databases, which, in turn, decreased the results to 110.
3. **First Screening (investigation of titles, abstracts, and keywords).** The initial consideration in this stage was to exclude review articles, which were respectively recorded as 6 and 9 papers for the two groups. This was followed by a thematic investigation that aimed at filtering out the papers with weak conceptual relevance associated with the research questions. Throughout this process, the titles, abstracts, and keywords of the articles were investigated. This process led to the exclusion of 49 and 59 papers in the two groups.
4. **Second Screening (full-text investigation).** During this process, the selected papers from the previous step were entirely read to filter out the ones that were incapable of addressing the research questions directly. After the full-text investigation, 12 papers were eliminated from the first group, and 10 papers were eliminated from the second group.

As shown in Figure 2, the first group was addressed by two categories of keywords, by which the initial search within WoS resulted in 288 articles. This figure, however, was reduced to 53 research items after setting the essential filters and completing the screening procedures. Combining both WoS and Scopus, the second group yielded 247 papers in the initial search. After considering the inclusion/exclusion criteria, the duplicate check, and screening, the final set of research articles was narrowed down to 41 papers. It is noteworthy that, during the second screening, 20 papers were identified to be relevant to understand the implications of Industry 5.0 for smart logistics.



(**a**) (**b**)

Figure 2. Flow diagrams of literature search: (**a**) smart logistics in Industry 4.0; (**b**) smart logistics in Industry 5.0.

5. Comparative Bibliometric Analysis

A bibliometric analysis is a quantitative evaluation of the collected research articles [45], which enables scholars to statistically study the available bibliometric data from different perspectives. In this paper, we focus on the connection and differences of smart logistics in Industry 4.0 and Industry 5.0, so a comparative bibliometric analysis was performed based on the two groups of articles. Following the procedures and recommendations by Donthu and Kumar [54], we present both performance analysis and science mapping of the sample of articles, including the publication trend, co-citation analysis, and keyword co-occurrence analysis.

5.1. Publication Trend

The publication trends are represented in Figure 3. For smart logistics in Industry 4.0, the numbers recorded affirm that increasing attention from academia has been drawn from 2015, and peaked in 2019, with 19 research items accounting for 36% of the accumulated articles. This trend reflects that the incorporation of emerging Industry 4.0 technologies into logistics operations and decisions has become more attractive, which may largely affect this industry by adopting automated guided vehicles (AGVs), UAVs, AM, autonomous robots, etc. Although this rising trend is retrieved after a sharp decrease in 2020, the number of research items in 2021 is not comparable to 2019, which shows a shift in research attention to this area within the last couple of years. Contradictorily, the trend of research activities within the area of Industry 5.0-enabled smart logistics has drastically increased in this period, which boomed in 2021 with 22 articles.

The most significant inference in this regard is the incorporation of sustainability, which has recently emerged among the main objectives of Industry 4.0 and the application of its technologies. Based on previous review studies [15], there is an increasing trend in sustainable logistics beginning from 2019. This trend is aligned with the general goals of Industry 5.0, which puts forward the significance of socio-economic and human-centric activities.

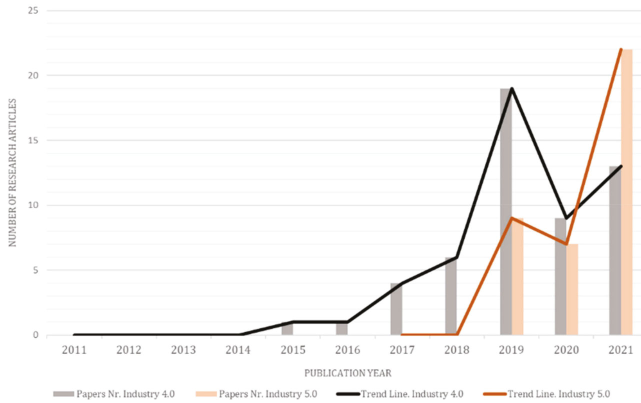


Figure 3. Publication trends.

5.2. Sources Contributions, Interactions, and Co-Citation Analysis

5.2.1. Source Contributions

International journals and conferences are the primary platforms that pave the way towards fostering innovative solutions and ideas. Therefore, it is of significance to evaluate the contributions and interactions of the sources within the sample set, which, from a general scale, gives insights into the active and leading sources of a research topic. Table 2 shows the sources and the number of papers contributing to smart logistics in Industry 4.0 and Industry 5.0, respectively.

Table 2. Distribution of top contributing sources.

Technological Enabler of Smart Logistics	Source Title	No. Items
Industry 4.0	IFIP Advances in Information and Communication Technology	7
	Computers & Industrial Engineering	5
	IFAC-PapersOnline	5
	Procedia Manufacturing	3
Industry 5.0	Lecture Notes in Mechanical Engineering	4
	Applied Sciences Switzerland	3
	Sensors	3
	Journal of The Knowledge Economy	2

Table 2 highlights the four most important sources related to smart logistics in Industry 4.0 and Industry 5.0. With seven articles published, 'IFIP Advances in Information and Communication Technology' is the most contributing source within the context of Industry 4.0 and Logistics 4.0 by signifying the technological topics, e.g., computer applications in technology, systems modeling and optimization, artificial intelligence, etc. 'Computers & Industrial Engineering' is the following journal, which has contributed to five publications in this field and focuses on computerized approaches in response to industrial problems. In parallel, five research items are published in 'IFAC-PapersOnline', which tightly focuses on, but is not limited to, automation and control. Given the importance of manufacturing processes, automation, robotics, and so forth, 'Procedia Manufacturing' is another important source that has contributed to three research items. The main focus of these sources is technological advances, e.g., robotics, automation control, etc., and advanced computerized approaches, which not only are the inevitable components of Industry 4.0 but also play an important role in developing smart logistics systems. On the other hand, Industry 5.0 is listed four times in 'Lecture Notes in Mechanical Engineering', which covers broad scientific topics including control, robotics, engineering design, automotive engineering, and engineering management. 'Applied Sciences Switzerland' and 'Sensors' are the following sources, publishing three papers each and majorly focusing on computer science and engineering along with human–computer interaction. According to the significance of social and technological aspects of knowledge creation and innovation, the 'Journal of The Knowledge Economy' has supported Industry 5.0-enabled smart logistics by publishing two research articles. The endeavor from these top four sources depicts that although technological subjects contribute to the development of Industry 5.0, the human-centric and social aspects must be emphasized.

It is worthwhile to note that the investigation of the entire list of sources reveals that smart logistics and the industrial revolutions are commonly studied in six of them, i.e., IFIP Advances in Information and Communication Technology, Computers & Industrial Engineering, Advances in Intelligent Systems and Computing, Journal of Industrial Information Integration, Lecture Notes in Mechanical Engineering, Procedia CIRP. The aims and scopes of these journals and book series are majorly technology-driven, which shows the connection between I4.0 and I5.0 from this perspective. In comparison with a recent review of technology-driven sustainable logistics operations [15], the result shows that Applied Sciences Switzerland, IEEE Access, Procedia CIRP, and Computers & Industrial Engineering serve as common platforms for this topic. This conjunction indicates the role of socio-economic and environmental factors within the roadmap of smart logistics in Industry 5.0.

5.2.2. Interaction and Co-Citation Analysis

The co-citation analysis intended to investigate the sources cited by the research items and their influence on the published documents. For this purpose, VOSviewer software was used to assess and visualize the interactions between the involved sources (see Figures 4 and 5). Compared with other software for bibliometric analysis and mapping, VOSviewer is an off-the-shelf solution that focuses predominantly on visualizing large bibliometric maps in an easy-to-interpret way [55]. The co-citation network is interpreted as a graph in which the nodes (vertex) represent the sources, and the link between the nodes (edge) shows the connection between them. Based on the visual variations in each network, the evaluation is twofold: (1) the size of nodes indicates the number of citations associated with each source; and (2) the thickness of links demonstrates the number of times each pair of sources is cited together. In addition, the aggregation of the links associated with each node is called total link strength (TLS), and this criterion implies the influence of each source on the published articles. To prevent a substantially congested network formed by all the sources, the minimum number of citations that a source received needs to be determined to eliminate the insignificant ones. This figure was set to be 10 and 5 for the two groups of papers, which yielded 25 and 21 sources, respectively.

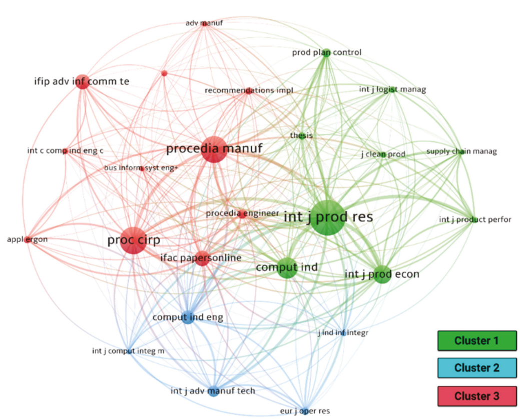


Figure 4. Co-citation analysis network of smart logistics in Industry 4.0.

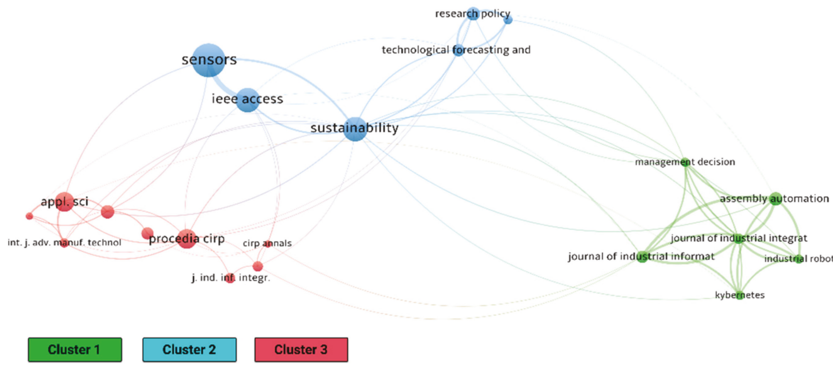


Figure 5. Co-citation analysis network of smart logistics in Industry 5.0.

Figure 4 reveals that the most influential source for smart logistics in Industry 4.0 is the 'International Journal of Production Research', which yields 65 co-citations and its TLS weight equals 1176. Given TLS as the comparison criterion, the impact of six more sources is determined to be significant, including 'Procedia Manufacturing' (780), 'Procedia CIRP' (671), 'Computers in Industry' (641), 'International Journal of Production Economics' (625), 'IFAC-PapersOnline' (544), and 'Computers & Industrial Engineering' (541). Table 3 shows the clusters of these highly influential journals related to smart logistics in Industry 4.0 and their primary focus areas. Based on the features of the sources in each cluster, there is an interweaving connection between sources, which emphasizes the role of technological methods and drivers to advance the smart logistics paradigm in Industry 4.0.

Table 3. Co-citation clusters of smart logistics in Industry 4.0.

Cluster	Source Title	TLS	Features
Cluster 1	International Journal of Production Research Computers in Industry International Journal of Production Economics	1176 641 625	The application of computerized technologies in manufacturing and operation research
Cluster 2	Computers & Industrial Engineering International Journal of Advanced Manufacturing Technology	541 390	Role of technology in manufacturing and logistics
Cluster 3	Procedia Manufacturing Procedia CIRP IFAC-PapersOnline	780 671 544	Manufacturing engineering, processes, and automation

The newly emerged topic of Industry 5.0-enabled smart logistics, however, yields different attributes through the quantitative analysis of the sources. Based on the co-citation analysis, 'Assembly Automation' entails the highest TLS value, which is equal to 241. This is followed by eight sources, which generate considerable influence according to their TLS weight, including 'Journal of Industrial Information Integration' (224), 'Journal of Industrial Integration and Management' (217), 'Sensors' (195), 'Industrial Robot' (192), 'IEEE Access' (184), 'Sustainability (Switzerland)' (171), 'Kybernetes' (166), and 'Management Decision' (156).

In the outlined list, 'Sensors' is the source that is also involved in Table 2 amongst the most contributing journals. Additionally, it is the most referred source in the literature. This applies also to 'Sustainability (Switzerland)' and 'IEEE Access', both of which are the second most cited sources, with a record of 16. This reveals the inter-disciplinary nature of the research and the importance of socio-economic factors and sustainability in the direction of Industry 5.0. Another finding from this list is that six sources (out of nine in total), as shown in Table 4, are cross-functional, with a primary focus on manufacturing technologies and information systems and management. Similar to that of Industry 4.0, these sources have shown that technological advancements and innovation also play a significant role in smart logistics in Industry 5.0 through the adoption of big data analytics, AI, simulation, etc. Figure 5 shows the interaction and influence of these clusters. As demonstrated, there is a weak connection between cluster 1 and cluster 2, while they have intensive cooperation with cluster 3. This indicates that there is an interest in improving manufacturing technologies and information systems with a major focus on social, economic, environmental, and sustainable issues. Through the comparison of the co-citation analysis of articles between the two groups, we find that the paradigm change of smart logistics, from Industry 4.0 to Industry 5.0, must meet the socio-economic and sustainable requirements. In this regard, journals with this feature seem to play an increasingly important role.

Table 4. Co-citation clusters of smart logistics in Industry 5.0.

Cluster	Source Title	TLS	Features
Cluster 1	Assembly Automation Journal of Industrial Information Integration Journal of Industrial Integration and Management Industrial Robot	241 224 217 192	An inter-disciplinary combination of manufacturing technologies and information management
Cluster 2	Sensors IEEE Access Sustainability (Switzerland)	195 184 171	An inter-disciplinary readership with a focus on engineering, social, human, economic, and environmental aspects
Cluster 3	Applied Sciences Switzerland Procedia CIRP Computers & Industrial Engineering	102 69 66	Manufacturing engineering and technology management

5.3. Keyword Co-Occurrence Analysis

The co-occurrence analysis of keywords calculates the number of times each keyword is used along with the interaction between pairs of keywords. This examination is visualized in Figures 6 and 7, where the keywords are represented by nodes and their size is dependent on the number of occurrences of the respective keyword. The links correspond to the interaction between keywords and their thickness indicates the usage frequency of each pair of keywords together. Thus, TLS in this context is the accumulation of links' magnitude associated with each keyword. To yield sufficient and reliable results, 'all keywords' is considered for network generation, which includes indexed keywords as well. Last but not least, the minimum number of occurrences to generate the visualization is set to 2, which leads to 46 and 42 results for the two groups.

Table 5 shows the top 15 keywords related to smart logistics enabled by both Industry 4.0 and Industry 5.0. Concerning Industry 4.0 and smart logistics, the most referred keywords are Industry 4.0, Internet, Operator 4.0, and Logistics 4.0, which identify the general framework of conceptual development. The other keywords, however, show the bond between new concepts and new technological drivers, i.e., big data, augmented reality, internet of things, etc. On the other hand, the keywords from the second group of literature highlight the significant role of Industry 4.0 as well as its enabling technologies within the roadmap of Industry 5.0. The primary finding is that, from a technological perspective, smart logistics in Industry 5.0 is concretely based on that from Industry 4.0. It is worth noting that, apart from a single technological perspective, socio-economic and sustainable issues are better considered and embedded in the smart logistics enabled by Industry 5.0 through the inclusion of human–robot collaboration, collaborative robots, and man–machine systems.

Table 5. Top 15 keywords.

No.	Industry 4.0			Industry 5.0		
	Keyword	**Occur.**	**TLS**	**Keyword**	**Occur.**	**TLS**
1	Industry 4.0	32	123	Industry 5.0	33	116
2	Internet	13	58	Industry 4.0	20	84
3	Operator 4.0	13	42	Industrial Revolutions	6	30
4	Big Data	5	31	Robotics	5	29
5	Future	4	30	Artificial Intelligence	6	25
6	Design	5	27	Manufacturing	4	25
7	Industry	4	27	Smart Manufacturing	4	23
8	Logistics 4.0	10	26	Internet of Things	5	22
9	Internet of things	6	24	Human–Robot Collaboration	4	21
10	Things	6	24	Industrial Research	4	18
11	Logistics	6	23	Collaborative Robots	3	16
12	Framework	3	21	Design and Development	3	16
13	Performance	4	21	Man–Machine Systems	3	16
14	Smart Logistics	6	19	Manufacture	2	16
15	Augmented Reality	3	17	Technology	3	16

Figure 6 illustrates the six clusters of keywords related to smart logistics in Industry 4.0. The most influential one is cluster 6, which shows a strong connection between the internet of things (IoT) and Industry 4.0. Cluster 2 addresses the main focus of Logistics 4.0 and smart logistics, as well as some main enabling technologies, i.e., AR, etc. Cluster 3 indicates the importance of internet-based AI and machine learning in smart logistics and smart supply chains. Cluster 5 has a remarkable interaction with cluster 6 and signifies the role of the smart logistics transition, which yields the concept of operator 4.0. Cluster 1 emphasizes digital tools, i.e., simulation, in manufacturing operations and sustainability. Cluster 4 depicts the importance of Industry 4.0 technologies in smart manufacturing and logistics, i.e., cyber–physical systems (CPS), big data, digital twin, etc. In general, the keyword co-occurrence network of these clusters shows that the research focus has been predominantly given to the technological drivers for smart logistics solutions in Industry 4.0. However, cluster 5 shows that increasing effort has been given to the connection between technology and humans, which shows the motivation for a transition from Industry 4.0 to Industry 5.0. Finally, it is obvious that several advanced technologies, i.e., digital twin, simulation, AI, etc., have major contributions to this concept.

Figure 7 illustrates the four clusters related to smart logistics in Industry 5.0. Cluster 3 is by far the most influential category, showing that the root of Industry 5.0 is from Industry 4.0. As discussed earlier, these two concepts have an interweaving connection in which the technological drivers play an undeniably important role. However, the elaboration of the links associated with smart logistics in Industry 5.0 reveals the footprints of social and environmental issues in this context. Cluster 1 comprises topics that immensely study CPS and smart manufacturing based on industrial robots according to the social impacts. Cluster 2 shows the links between the concept of society 5.0 and intelligence systems, human–robot collaboration, and collaborative robots. Cluster 4 evokes the existence of operator 4.0 and elaborates the significance of human factors, human engineering, personnel training, and so forth, in Industry 5.0-enabled smart logistics. On the one hand, Industry 5.0 is tightly linked to the technological drivers of Industry 4.0 in the current digital era, while, on the other hand, Industry 5.0 places predominant attention on socio-economic development, sustainability, and human issues. To this aim, the result of the keyword co-occurrence analysis shows the potential for smart logistics in Industry 5.0 by adopting new technologies while considering the human side in the transition, e.g., enhancing human–robot collaboration.

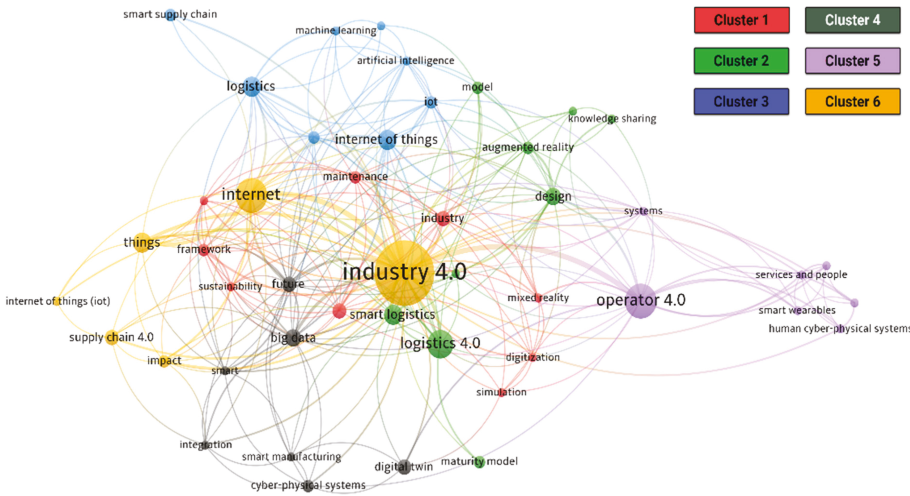


Figure 6. Keyword co-occurrence analysis of smart logistics in Industry 4.0.

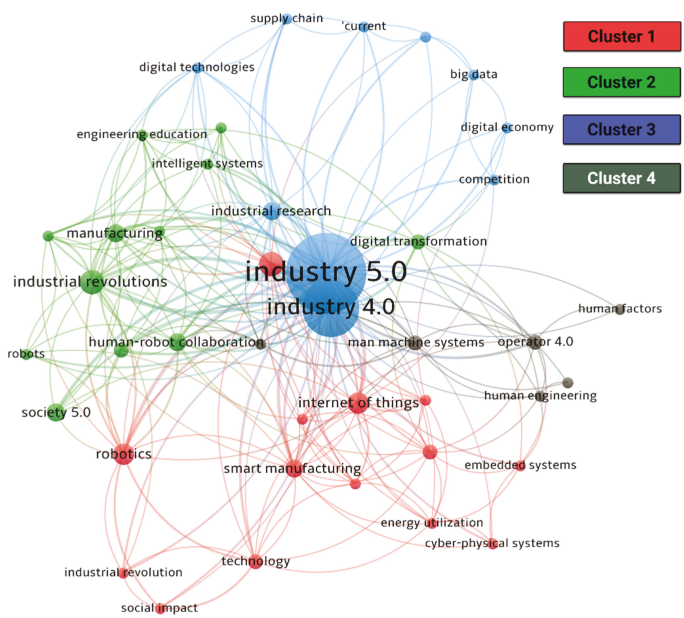


Figure 7. Keyword co-occurrence analysis of smart logistics in Industry 5.0.

6. Content Analysis and Discussion

The results of the comparative bibliometric analysis of the two groups of literature demonstrate that there is an increasing trend in addressing the societal, human, and sustainability aspects, which are the key elements of smart logistics in Industry 5.0 [6], to highlight the harmony between technological development and human-centric socio-economic transition. The evaluation of the most extensively used keywords reveals that smart logistics in Industry 4.0 focuses purely on the technological pillars. However, on the other hand, Industry 5.0 not only emphasizes the adoption of new technologies in smart logistics operations but also substantially stimulates the interaction among humans, technology, and the environment through human–robot collaboration, collaborative robots, man–machine systems, etc.

6.1. The Three Key Elements of Industry 5.0

As rooted from Industry 4.0, Industry 5.0 embraces similar technologies and a clear distinction between these two industrial revolutions is thus of significance. The official introduction of Industry 5.0 underpins the evolution of this novel paradigm with respect to a trinary concept to pinpoint its corresponding core values [33]: human-centricity, resilience, sustainability.

1. **Human-Centricity.** Conveys the fact the production and logistics system must be improved with solid attention to human benefits and needs, by which the human is transformed from 'cost' to 'investment' [2]. From the operational aspect, this urges the promotion of hybrid alternatives in response to the industrial challenges, where the human power and human brain are involved not only in maintaining the surveillance but also in incorporating more intelligence and innovation and, to some extent, making decisions [3,35]. Industry 5.0 emphasizes research and development (R&D) activities to translate information into knowledge and meet sustainable social goals by upskilling humans through formal education or training schemes [2,6,36,56,57]. From the social and economic point of view, Industry 5.0 shapes the ground to not only prevent the elimination of human labor engaged in the manufacturing industry but also create more job opportunities in the supportive industries, which provide technological solutions, i.e., robot manufacturing, sensor manufacturing, etc. [3,34,36]. Hence, based on these objectives, Industry 5.0 is a human-centric paradigm that transfers the human back to the center of production cycles.
2. **Resilience.** Represents the flexibility and agility that a production plant needs to maintain in response to market change [36,58]. Today, customers are strikingly bombarded with high-tech innovations and products, and according to the constant changing in the market, personalized demands are one of the most significant challenges to the manufacturing industry [35]. To a larger extent, manufacturing systems are expected to transform from mass customization to mass personalization [36]. From a tactical perspective, this is realized by incorporating the customers into the design phase to build up the personalized product from scratch [34,59]. To improve the operational flexibility in this regard, human–robot collaboration has significant potential, which conducts versatility of fabrication in a more efficient time [36,37]. It is worthwhile to highlight that while the main task is accomplished by the robot, human collaboration facilitates the problem solving of the work and process flows, and improves intelligence and innovation [35,37].
3. **Sustainability.** The concept of sustainable development was initially introduced by Brundtland in 1987 and defined as the "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [60]. While the social- and human-related issues are an integral part of this concept, they are merely discussed within human-centricity in the context of Industry 5.0. This approach emphasizes reverse logistics [61,62], circular economy [2], value chains, and so forth [63]. Sustainable development seeks the protection of the environment through sustainable products and logistics systems to approach the zero waste objective [34]. In addition to waste prevention, the manufacturing processes must be environmentally friendly—for example, by using renewable resources and green computing [37].

6.2. Smart Logistics in Industry 5.0

The core elements of Industry 5.0 show that following the technology-centric transition of Industry 4.0, the societal, environmental, and human perspectives require more attention, which will yield significant impacts on logistics operations and management. For instance, the personalization of demands implies a personalized delivery system [56]. Incorporating customers into the design requires highly intelligent CPS and system integration [37].

Human–machine interaction triggers the interaction of various topics such as safety, human behavior, etc. [35]. Thus, there exist various challenges and approaches to addressing smart logistics issues in Industry 5.0. With a focus on the interaction between technology and humans in smart logistics, we present discussions through a quadripartite intelligence framework [3,36], namely intelligent automation, intelligent devices, intelligent systems, and intelligent material.

6.2.1. Intelligent Automation

The major focus of Industry 5.0 is human-centricity, which, from a pragmatic aspect, puts forward the presence and high importance of the human in a system. However, there is a trade-off between human integration and automation to satisfy the goals of Industry 5.0, and this concern resides in the context of intelligent automation [35,36], e.g., human–robot collaboration. It impacts the resilience of a logistics system and thus requires special attention and intelligence to achieve a lean collaboration [64–66]. The human's role in a logistics system was initially investigated in 2016 under the concept of 'Operator 4.0′, which aims, by taking advantage of technological advancements, at maximizing the human's contribution from three functional aspects [67,68], namely assisted work, collaborative work, and augmented work. The first function highlights the tasks that are mainly completed by human operators with the help of assisting technologies. The second requires collaboration between machine/robot and human. The last relies on technologies that could extend the human's physical and visional capabilities. Considering logistics operations at different stages, e.g., production, warehousing, etc., material handling and information flow are two operational categories that significantly benefit from these applications [69].

Industry 5.0 paves the way to extending this framework by considering both resilience and human-centricity. Romero and Stahre [70] introduce the concept of 'Operator 5.0′ as "*a smart and skilled operator that uses human creativity, ingenuity, and innovation empowered by information and technology as a way of overcoming obstacles in the path to create new, frugal solutions for guaranteeing manufacturing operations sustainable continuity and workforce well-being in light of difficult and/or unexpected conditions*". In the context of Industry 5.0, this paradigm encourages technological development in two main directions: self-resilience and system resilience. Self-resilience emphasizes human sustainability from biological, physical, cognitive, and psychological dimensions and focuses on human-centricity in the technological transition, i.e., work ethics, social impacts, legal issues, etc. [38,71–73]. System resilience, however, signifies the functional collaboration between humans and machines in terms of sharing and trading control [74].

Human–robot collaboration in Industry 5.0 also plays a vital role in reacting to highly unexpected events, e.g., the COVID-19 pandemic, which requires high production agility and flexibility to fulfill the rapidly increasing demands of medical supplies [70,75,76]. In this regard, collaborative robots (cobots) are one of the most discussed enabling technologies in Industry 5.0. However, two important issues, namely the human skills and the behavior of cobots, need to be taken into account when cobots are integrated into a production or logistics system. As the main lever of Industry 5.0, through proper training, humans must be capable of working together with cobots [31,73,77–79]. For this purpose, the use of several supportive technologies, i.e., virtual reality, augmented reality, and simulation, has been extensively investigated [3,76,80]. For instance, operators can learn and understand the cobot motions under specific conditions without compromising safety measures and productivity [3,76]. On the other hand, cobots can be programmed or trained to establish a lean collaboration with the operators, which may lead to an increase in the productivity and efficiency of the workflow [81]. Human–robot collaboration not only requires hardware capabilities, i.e., sensors, etc., but also implies the essence of cognitive and intelligent behaviors of the cobot [81]. In this regard, the latest computation methodologies, i.e., machine learning (ML), deep learning (DL), clustering, regression, etc., have become increasingly important for the development of versatile applications [3,76,82–86].

6.2.2. Intelligent Devices

Machines, robots, and other facilities that are used in the production and logistics systems must be improved and equipped with smart technologies to maximize functionality and performance through physical and cyber connections with high monitoring and controlling capacities [87–90]. Considering the scopes of Industry 5.0, this objective signifies the interaction between humans and robots/machines. On the one hand, these intelligent devices, e.g., intelligent machines, smart robots, cobots, etc., require cognitive capabilities for decision-making by themselves to not only perform operations alongside the humans but also actively prevent undesired incidents. On the other hand, due to the operators' inherent physical and intellectual limitations, the shortcomings for accessing the information flow and augmented functional abilities can be resolved by intelligent devices [77]. The collaboration between robot and operator raises concerns about human constraints as opposed to machines, which requires extra effort to resolve their integration issues. In this regard, operators' conditions need to be constantly traced with capture motion and eye-tracking devices, wearable biometric equipment, etc., under various workload conditions from both physical and cognitive perspectives [91–93]. This helps to facilitate a resilient workplace in which the environment adaptability can be improved in varied conditions [92].

In addition, Industry 5.0 emphasizes human-centricity through the use of technologies and hardware to improve and support the operators' performance in logistics systems and supply chain operations. In this regard, human wearable devices that boost cognitive and operational capacities are increasingly being utilized and improved in manufacturing industries [93]. Exoskeleton refers to augmenter equipment that gives extra strength and physical capabilities to protect the operator from the adverse effects of heavy workloads [94–97]. Benefiting from virtual technologies, i.e., smart AR glass, spatial AR projector, etc., are viable and novel gadgets that facilitate flexible operations and technical guidance through information transmission and virtualization [70].

Moreover, the latest improvements in unmanned aerial vehicles (UAVs) have radically altered the intralogistics and material handling systems in a highly novel manner, and this additionally represents significant potential for personalized delivery systems [56,98,99]. Furthermore, Auto Identification (Auto-ID) and RFID have been extensively investigated in smart logistics and supply chains, which support traceability, warehouse operations, and inventory management [78,100].

6.2.3. Intelligent Systems

The systematic approach of Industry 5.0 requires information transmission for individualized and case-based tasks in the production system and enhanced interaction with better decision-making processes throughout the whole supply chain [101–105]. This characteristic urges improved data and information exchange among different stakeholders, which largely affects the agility and intelligence of a smart logistics system. This aim can be realized by a network of data interoperability, where sensors exchange and process information in a big data environment [3,56,106–109]. In the context of Industry 5.0, a Smart Cyber–Physical System (SCPS) can be established for promoting data transmission and the sustainability of production and logistics systems [110,111]. This digital transformation, however, must be energy-efficient by taking into account green procedures, i.e., green production, green recycling/disposal, green IoT (G-IoT), etc., to facilitate a lean circular economy (CE) [112,113].

A digital transition to Industry 5.0 and Society 5.0 triggers the development of blockchain computing [34,114–118]. In addition, it benefits the supply chain by enabling demand customization and personalization through recommender systems, which capture customers' preferences using social networks, text recognition, and analytical techniques [119]. Benefiting from internet-based connectivity, the transparency of information and manufacturing traceability can be drastically enhanced [56,78]. Real-time decision-making and high-quality visualization form the foundation of a virtual smart logistics system in Industry 5.0 [120], which facilitates the emergence of the smart digital twin for logistics systems [3,108,121–123].

6.2.4. Intelligent Materials

One of the revolutionary improvements in Industry 5.0 is the development of smart materials. The characteristics of these new materials may significantly impact the supply chain activities by serving multiple functionalities and capabilities under certain conditions. For example, manipulating the shape and properties of the material and/or product according to varying physical conditions, e.g., temperature, light, stress, etc. [123–126]. The primary implication is related to additive manufacturing, where the 4D printing method strongly benefits from smart materials [36]. Compared with traditional 3D printing, 4D printing employs similar technology that fabricates parts and components through the layer-wise adhesion of a corresponding material. However, the major difference lies in the material type [124,125,127,128]. By using smart materials, the products can maintain various shapes and functionalities according to the environmental condition to improve the durability, adaptability, and reliability of the product. Various examples exist in medical science, aerospace, semiconductors, etc.

6.3. Discussions and Research Agenda

6.3.1. Analysis of Enabling Technologies

Industry 4.0 has proposed a technology-driven evolution during the last decade, with a major focus on network connectivity, intelligence, and automation. However, the autonomous attribute of this industrial revolution disregards the role of humans in the operation loops, and thus, the new concept of Industry 5.0 is developed to use the technology in favor of humans, not as a substitute. According to the established automation level and massive utilization of industrial robots in manufacturing plants, human–machine/robot collaboration offers the best potential to approach this goal. The human and robot symbiosis, however, triggers various technological, operational, and strategical challenges that require particular attention from both industrial practitioners and academia to achieve a lean collaboration. Furthermore, Industry 5.0 embraces new technologies and platforms that facilitate the achievement of socio-economic and environmental objectives. In this regard, through the analysis of the literature related to smart logistics in Industry 5.0, we have summarized the most extensively focused enabling technologies in Figure 8 and Table A1 (Appendix A).

As shown, artificial intelligence has shown remarkable viability, being addressed in 59% of the research. This innovative solution with broad applicability, i.e., human–robot collaboration, Society 5.0, etc., is one of the most promising technologies that successfully fulfills the socio-economic requirements of Industry 5.0 within the context of smart logistics. Given the human-centricity attribute of Industry 5.0 and the significance of the interaction between humans and machines/robots, 49% of the research has highlighted the advantages of cobots, which are unarguably the main technological driver in this regard. Although operators are empowered by a variety of new tools and equipment, cobots facilitate a resilient and sustainable logistics system. To improve the utilization of cobots, 24% of articles argue the importance of sensor technologies that not only favor better and safer human–robot collaboration but also improve the connectivity and intelligence of intralogistics and supply chain operations. Moreover, machine learning and deep learning methods (maintaining 16% of research activities) are emphasized methods to increase the intelligence and cognition level of either humans or cobots as well as the entire logistics system. To account for the sustainability and human-centricity features, biotechnologies have been studied in 14% of articles. This category of technologies is enriched by machine/deep learning methods for better utility and applicability. It is noteworthy that smart materials are also included in this category. Additive manufacturing and mobile transportation are the least discussed topics. Given 8% and 5% for AM and UAV/AGV, respectively, there is a lack of attention from scholars to these categories considering their potential impact on smart logistics in Industry 5.0.

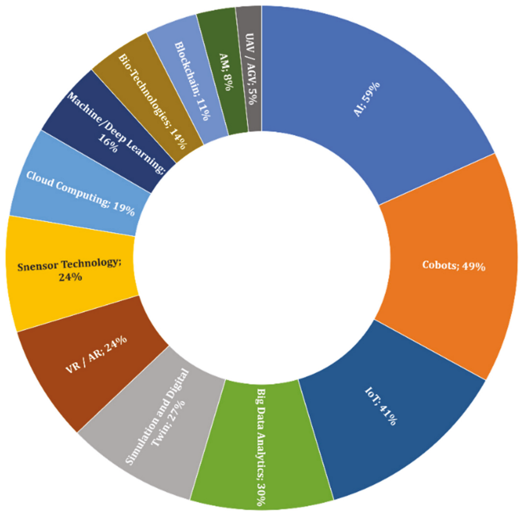


Figure 8. Supporting technologies in smart logistics of Industry 5.0.

IoT, big data analytics, and cloud computing, which are the most important Industry 4.0-enabling technologies, have drawn academia's attention by 41%, 30%, and 19%, respectively, which implies the significance of the digital transition in the fifth industrial revolution. These components, which are widely discussed in various topics, i.e., operator 5.0, society 5.0, and so forth, not only establish connectivity and intelligence but also improve the information transparency throughout different actors in a logistics system. In addition, blockchain is discussed in 11% of the research, which has a notable role in achieving socio-economic goals. Given this digital transition, smart logistics operations have shown a strong connection with virtual technologies in recent years, where 51%, 27%, and 24% of research highlights the role of simulation, digital twin, and virtual reality and augmented reality, respectively.

6.3.2. Similarities and Differences between Industry 4.0 and Industry 5.0 for Smart Logistics

Industry 5.0 is still in its infancy and under both conceptual and methodological developments by practitioners and the research community. From the conceptual development perspective, Industry 5.0 is not considered a radical technological revolution from Industry 4.0 but essentially shifts the focus from technology to the development of human and society driven by new technologies. Thus, it can be seen that Industry 4.0 technologies are still the most important technological enablers for smart logistics in Industry 5.0. For example, IoT, AI, big data analytics, simulation, and digital twin are still the focus of smart logistics transformation.

However, there are significant differences between Industry 4.0 and Industry 5.0 in their core focuses. Given human-centricity, resilience, and sustainability as the main drivers of Industry 5.0, the transition in logistics, which is a labor-intensive sector, toward a more harmonious balance among economic, environmental, and societal sustainability is crucial. For example, the focus of the smart logistics transformation in Industry 4.0 is to replace human operators and improve productivity through the adoption of new technologies. However, in Industry 5.0, the balance is shifted to human and environmental sides, and new technologies are used not to replace the human operators but to support their operations in a more effective way to better achieve highly personalized products and services. In this regard, many logistics providers are undergoing a smart transformation of Industry 4.0, but this smart transformation should not be hindered but be repurposed to achieve better cohesion among economic, environmental, and societal sustainability in Industry 5.0.

6.3.3. Research Agenda

The following directions are raised to inspire further research of smart logistics in Industry 5.0.

- *Smart and sustainable logistics network design.* Logistics network design is one of the most important strategic decisions. The human-centric and technology-driven paradigm shift will largely affect the smart logistics operations in Industry 5.0; however, this leads to more challenges in strategic logistics network design to accommodate these configurational and operational changes within the whole planning horizon. Thus, research focus needs to be given to smart and sustainable logistics network design considering both human and technological factors in Industry 5.0.
- *Mobile transportation.* Intralogistics operations and material handling systems are some of the most significant challenges related to manufacturing logistics, which significantly impact the system's flexibility and agility. In this regard, smart mobile transportation means, i.e., UAVs, AGVs, have shown significant capabilities with intelligence and connectivity utilities. These pave the way for a smart collaboration with the operator, which not only satisfies the resilience goal but also takes human centricity into account. Given the least attention from the literature, it is of significance to devote more effort in this direction.
- *Additive manufacturing.* Due to its high adaptability and flexibility, additive manufacturing would significantly influence the sustainable supply chain and logistics operations compared with other techniques in Industry 5.0. Various logistics operations and supply chain activities can benefit. For example, in warehouse management, digital inventories of a large variety of products with low and irregular demands can be held with the help of additive manufacturing, which reduces both costs and environmental impacts. Thus, research attention needs to be given to AM in smart logistics of Industry 5.0 to improve both economic and environmental performance while maintaining a high service level.
- *Intelligent materials and supply chain.* Biotechnologies and intelligent materials are among the primary technologies for Industry 5.0. Given its low rate of attention from scholars, it is of significance to invest more research effort in this direction. In addition, it is highly beneficial to study the impact of intelligent material on smart and sustainable logistics systems, i.e., green logistics, reverse logistics, circular economy, etc.
- *Warehouse and inventory operations.* Although plenty of technological discussions exist within the context of manufacturing industries, some other logistics activities are neglected in the agenda. Warehouse and inventory operations could be investigated from various aspects considering both new technologies and human-centric operations—for instance, the use of virtual technologies to improve the information transparency and cognitive skills of warehousing or inventory activities. In addition, innovative human–robot solutions along with advances in sensing technologies potentially serve as valuable topics to be studied further in this context.
- *Human-centric manufacturing and logistics.* On the one hand, the human operator, supported by technologies, is the most important element in an Industry 5.0-enabled manufacturing and logistics system. On the other hand, the diversified human demands drive the way of technological breakthroughs and paradigm changes in manufacturing and logistics. Hence, it is substantially important to understand the interplay between humans and technologies in the transition by, for example, studying the impact of cobots and other human-centric technologies on manufacturing and logistics.
- *Smart logistics solutions for unexpected events and disasters.* Recently, the world witnessed several catastrophic events and humanitarian disasters, e.g., the COVID-19 pandemic, the war between Russia and Ukraine, etc., which require more smart and responsive logistics solutions. For example, satisfying the rapidly increasing demand for personal

protective equipment (PPE) [129] and properly dealing with infectious medical waste are among the most critical logistics challenges during the pandemic [130]. In this regard, Industry 5.0 may play an important role by providing innovative solutions through autonomous logistics solutions, human–robot collaboration, etc. Thus, future research in this direction is suggested.

It is worthwhile to mention that the above list is not a binding research agenda according to the structure of Industry 5.0; however, it seeks to highlight the most important topics in the context of smart logistics. In addition, the identified research agenda does not neutralize the significance of other technological drivers that have been extensively discussed in the literature. For instance, simulation and digital twin are inevitable parts of Industry 5.0, facilitating digital transmission.

7. Conclusions

Based on the technological breakthroughs in Industry 4.0, the emerging concept of Industry 5.0 has put forward the research frontier from technology-driven to human- and society-driven paradigm changes that will potentially and drastically influence many industries. Embedding human-centricity, resilience, and sustainability in smart logistics requires a rethinking and reconsideration of the technology matches, and in this regard, the role of the human in the technological transition needs to be predominantly focused on to ensure sustainable development in economic, environmental, and societal dimensions. To understand the implications of the coming Industry 5.0 for smart logistics, this paper presents a comprehensive analysis of the existing literature with both quantitative and qualitative methods.

We sought to answer the following research questions:

- *RQ1*: We conduct a comparative bibliometric analysis to thoroughly present the connection and differences in smart logistics between industry 4.0 and Industry 5.0.
- *RQ2*: We thoroughly evaluate the characteristics and key enabling technologies of smart logistics in Industry 5.0.
- *RQ3*: We propose a research agenda with seven directions to inspire future research on smart logistics in Industry 5.0.

The results show that smart logistics in Industry 5.0 is deeply rooted and benefited from the technological breakthroughs in Industry 4.0. However, in Industry 5.0, more emphasis has been given to the human side, with increasing research that focuses on human–machine systems, collaborative robots, and human–robot collaboration. Moreover, besides manufacturing journals, research related to smart logistics in Industry 5.0 is also published by inter-disciplinary journals that focus on the interplay among technology, society, and sustainability. Through a detailed content analysis, it is shown that IoT, cobots, and AI are the most investigated Industry 5.0 technologies in smart logistics. Finally, a research agenda is given to guide and inspire future research.

The paper has three limitations related to the sample selection. First, Industry 5.0 is a new and rapidly developing concept, so the papers presented in this review are restricted by the time of the literature search, and some important papers published after 2022 are not included. Second, some papers may be published in another language, so they are excluded from this review, but these papers may also present important information for smart logistics in Industry 5.0. Third, only the peer-reviewed papers published in scientific journals and conferences are focused on in this research, but, as an emerging topic, many studies may be published in other forms or may still be in the review process, so they are not included in the analysis of this paper. Thus, the results of this literature review are not exhaustive and are affected by these limitations.

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Appendix A

Table A1. Industry 5.0 technologies in smart logistics.

Author [Ref. No]	AI [a]	Cobot	Sim. and DT [b]	Sensor Tech	Cloud. Comp [c]	Big Data	ML/ DL [d]	VR/ AR [e]	UAV/ AGV [f]	Bio-Tech.	IoT	AM [g]	Block. [h]
Callaghan [6]	√												
Nahavandi [3]	√	√	√	√			√	√					
Xu, Lu [2]	√		√			√				√			
Patera, Garbugli [63]	√			√	√	√							
Pathak, Pal [37]	√	√									√		
Gaiardelli, Spellini [35]	√	√											
Duggal, Malik [131]	√	√					√			√		√	
Kumar, Gupta [56]					√			√	√		√		√
Javaid and Haleem [36]	√	√	√	√	√	√	√	√		√	√	√	
Saptaningtyas and Rahayu [34]		√	√	√				√			√		√
Demir, Döven [38]	√	√			√	√					√		
Doyle-Kent and Kopacek [75]		√											
Gürdür Broo, Kaynak [132]	√		√										
Rega, Di Marino [76]		√	√					√					
Brunzini, Peruzzini [91]			√	√				√		√			
Thakur and Kumar Sehgal [110]				√									
Fraga-Lamas, Lopes [113]	√				√						√		
Zhang, Hu [133]	√		√										

Table A1. *Cont.*

Author [Ref. No]	AI [a]	Cobot	Sim. and DT [b]	Sensor Tech	Cloud. Comp [c]	Big Data	ML/DL [d]	VR/AR [e]	UAV/AGV [f]	Bio-Tech.	IoT	AM [g]	Block. [h]
Golov, Palamarchuk [111]	√		√		√								
Resende, Cerqueira [71]		√											
Ávila-Gutiérrez, Aguayo-González [92]	√			√			√				√		
Doyle-Kent and Kopacek [80]		√											
Bathla, Singh [119]	√					√					√		
Romero and Stahre [70]	√	√				√	√	√		√			
Jabrane and Bousmah [81]	√	√				√	√						
Fraga-Lamas, Varela-Barbeito [100]			√	√							√		
Fornasiero and Zangiacomi [78]				√				√			√		
Carayannis, Dezi [59]						√					√		
Carayannis, Christodoulou [117]	√										√		√
Hol [73]	√	√						√	√			√	
Doyle Kent and Kopacek [79]													
Longo, Padovano [93]		√						√					
Doyle-Kent and Kopacek [31]		√				√							
Martynov, Shiryaev [57]	√												
Martynov, Shavaleeva [53]	√					√					√		
Mihardjo, Sasmoko [58]											√		
Welfare, Hallowell [72]		√											
Rahman, Muda [118]	√				√	√					√		√

a. Artificial Intelligence. b. Simulation and Digital Twin. c. Cloud Computing. d. Machine Learning/Deep Learning. e. Virtual Reality/Augmented Reality. f. Unmanned Aerial Vehicle/Automated Guided Vehicle. g. Additive Manufacturing. h. Blockchain Technology.

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Review

Impact of Additive Manufacturing on the Supply Chain of Aerospace Spare Parts Industry—A Review

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Abstract: *Background:* Additive manufacturing (AM) applications in producing spare parts are increasing day by day. AM is bridging the digital and physical world as a 3D computer-aided manufacturing (CAM) method. The usage of AM has made the supply chain of the aviation spare parts industry simpler, more effective, and efficient. *Methods:* This paper demonstrates the impacts of AM on the supply chain of the aircraft spare parts industry following a systematic literature review. Hence, centralized and decentralized structures of AM supply chains have been evaluated. Additionally, the attention has been oriented towards the supply chain with AM technologies and industry 4.0, which can support maintenance tasks and the production of spare parts in the aerospace industry. *Results:* This review article summarizes the interconnection of the industry findings on spare parts. It evaluates the potentiality and capability of AM in conceptualizing the overall supply chain. Moreover, MROs can adopt the proposed framework technologies to assist decision-makers in deciding whether the logistics hub with AM facilities is centralized or decentralized. *Conclusions:* Finally, this review provides an overall view to make critical decisions on the supply chain design of spare parts driven by new and disruptive technologies of industry 4.0. The next-generation supply chain may replace the logistics barriers by reducing waste and improving capability and sustainability by implementing AM technologies.

Keywords: additive manufacturing; spare parts; aircraft industries; industry 4.0; supply chain; efficiency; performance; systematic literature review

1. Introduction

Additive manufacturing (AM) is a digital technology of layered fabrication by adding material where no cutting tool is required as in the case of a subtractive manufacturing process. In the earlier time, the application of AM was confined to rapid prototyping for physical product validation in the product development process. However, AM has been turned into a form of direct manufacturing technology due to the emerging advancement of its technological capability. It is estimated that AM industry will reach 35.6 billion USD by 2024, which was 7.34 billion USD in 2017 [1]. One of the top prospects behind the scenario is the capability of AM for mass customization of the product [2], fabrication of complex parts, on-demand product fabrication, cost-minimization, and waste-reduction [3,4]. Such characteristics of AM not only permit complex shape or customization in products but also are capable of fabricating high-performance aerospace components [5] and low volume production in the aerospace industry [6,7]. Hence, AM has become a potential fabrication process for the aerospace industry [8]. However, strategic implications have been adopted to apply AM in various applications, such as automotive, aerospace, and engineering by exploiting the potential and advantages of AM [9].

In Aircraft industries, high quality, safety standards and preventive maintenance are the dominant factors. Moreover, these industries require highly valued spare parts in larger volumes due to uncertain and unpredictable demand [10]. The unprecedented demands for spare parts occur when preventive maintenance has taken place, or any components fail randomly during the part life cycle [11]. Therefore, spare parts management has become crucial; and it incurs a higher holding cost [12]. Nevertheless, high shortage costs and obsolesce risk are inevitable for the spare parts [13]. Therefore, suppliers face an unpredictable barrier in their business investments as they need to produce older spare parts for a short life cycle. High stock levels can be a solution for this issue but it can increase obsolescence cost risk, holding cost and barriers to cash flow. Furthermore, a shortage of spare parts may lead to a lack of reliability, slow responsiveness, and poor cycle service level (CSL), which finally results in poor supply chain performance [14].

The aircraft industry also consists of maintenance, repair, overhaul (MRO) and original equipment manufacturers (OEMs) with MROs and OEMs being the prime service providers. GE aviation, Airbus, Boeing, and Rolls-Royce are notable OEMs in the aircraft industry [15]. MRO organizations manage the facilities to run the aircraft company's processes and facilities smoothly [16]. Aircraft companies require MROs to deliver much-needed spare parts with high responsiveness and a higher fulfillment rate at a low cost [17]. Therefore, MRO services face significant challenges in aircraft spare parts supply chains to minimize costs [18]. Moreover, both the MROs and OEMs struggle to optimize the design and production processes to minimize the production lead times and waste by implementing lean manufacturing approaches [8]. Very few OEMs like BAE System, Raytheon, and Lockheed Martin are associated with manufacturing and designing aircraft's main component systems due to the high market entrance barriers [19]. With computer-aided designs, advanced automation in AM has improved the products and services that are currently taking center stage in this endeavor [20]. With the advancement of AM, OEMs expect the spare parts manufacturing facility to locate near service areas [13]. The benefits of AM can reduce inventory, transportation, safety stock, uncertainty, and the overall supply chain costs. Accordingly, the complex supply chain of the aerospace industry needs to be more agile and efficient through the integration of AM. Therefore, extensive analysis is required with respect to the existing work in this field. To understand the current state of the literature, contributions of related research are summarized in Table 1.

Table 1. Summary contribution of related articles.

Author name	Supply Chain	Additive Manufacturing	Industry 4.0	Spare Parts	Material Selection	Aircraft Industry
(Khajavi et al., 2014) [17]	✓	✓		✓		
(Frandsen et al., 2019) [21]		✓		✓	✓	
(Ceruti et al., 2019) [22]		✓	✓			✓
(Kalender et al., 2019) [23]		✓			✓	✓
(Li et al., 2017) [24]	✓	✓		✓		
(Caesarendra et al., 2018) [25]			✓			✓
(Zijm et al., 2019) [26]	✓	✓		✓		
(P. Liu et al., 2014) [27]	✓	✓		✓		✓
(Chekurov et al., 2021) [19]		✓		✓	✓	✓
(Mehrpouya et al., 2019) [28]		✓	✓	✓		
(Yusuf et al., 2019) [29]		✓			✓	✓
(H. Khajavi et al., 2018) [30]	✓	✓		✓		✓
(de Souza et al., 2011) [31]	✓			✓		✓
This Paper	✓	✓	✓	✓	✓	✓

Despite the increasing number of publications in this field, there are currently insufficient techniques and models that thoroughly address and organize this topic. There exists a gap in the proper extensive literature review in this field. To the best of our knowledge, there seems to be a lack of review papers in additive manufacturing of spare parts concentrating on the aviation industry, compared to many other topics in AM. Through a survey of relevant literature, the authors hope to make tangible fundamental and technical contributions. The goal is to use the findings of this research to develop new scientific methodologies and models for assessing and enhancing the supply chain of the spare parts (SP) industry through AM.

The framework of core subject areas, explained in this paper, is illustrated in Figure 1. The shared portions of the frameworks are described in this paper through a systematic literature search and literature review. Consolidation of information from various literature was induced towards bringing proper value to the research.

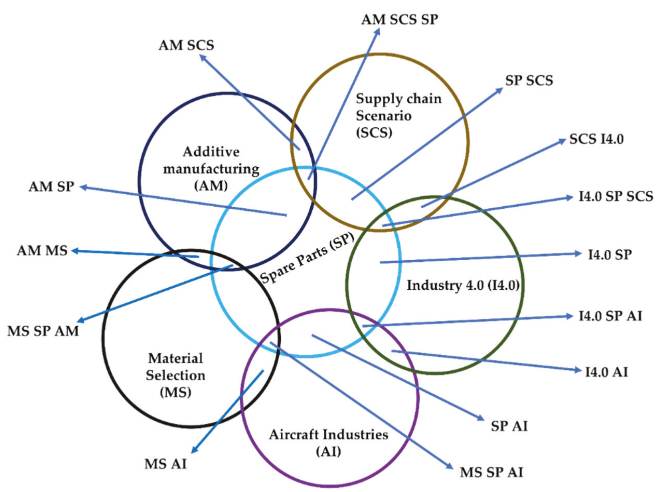

Figure 1. Framework of Core Subject Areas Mapping.

This paper is outlined in different sections. After the introduction, Section 2 presents a systematic literature review on how the study has been carried on. Section 3 identifies the impact of additive manufacturing on the aerospace spare parts industry. It also discusses the current and future trends of AM in spare parts of the aviation industry. Section 4 focuses on deriving several parameters, such as material selection criteria, part consolidation, quality, and standardization for AM spare parts. Section 5 analyzes the supply chain design and strategies for spare parts in the aircraft industry. Next, Section 6 relates AM of spare parts in the I4.0 context. Then the managerial implications are presented in Section 7. Finally, concluding remarks and future research directions are provided in Section 8.

2. Systematic Literature Review (SLR)

The framework illustrated in Figure 1 indicates the research areas covered in this study. As there remains a gap in proper data integration in these areas, this study conducts a systematic literature review (SLR) towards covering those gaps. Initially, a conceptual model was developed for SLR (Figure 2), which shows that the study was conducted in several steps toward acquiring reliable research outcomes. This SLR was developed based on the proposed methodology of [32].

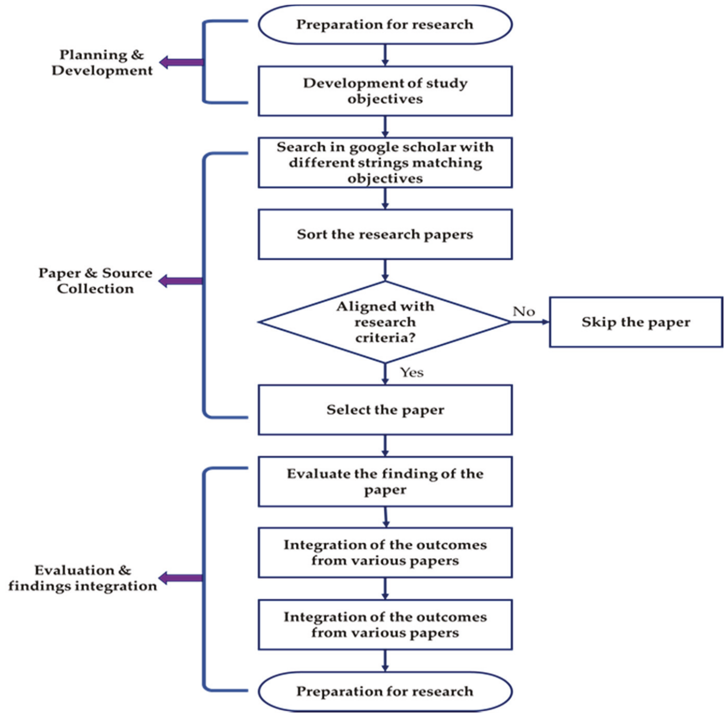

Figure 2. Steps of Systematic Literature Review.

Based on the review gaps, a set of research questions (RQs) were identified to fulfill the study. The questions are stated as follows:

RQ1: What are the states of the supply chain scenario in additive manufacturing (AM) of spare parts?

RQ2: What is the basis for selecting a particular AM supply chain strategy in Aircraft's spare parts industry?

RQ3: How does AM bring changes in spare parts of the aerospace industry?

RQ4: Which strategies are trending in the aircraft industry's spare part supply chain?

RQ5: How industry 4.0 helps different aspects of spare parts manufacturing?

RQ6: What are AM's major challenges, constraints, and considerations to use in the aerospace spare parts industry?

The planning and development phase of this research set the area of study and different questions. RQ1 and RQ2 focus on the functionality of the spare parts (SP) supply chain in the aerospace industry. It addresses how SC works and a comparison of SC scenarios in this sector. RQ3 is concerned with the impact of additive manufacturing on the SP industry on moving toward changing conventional manufacturing in every term. RQ4 focused on SP's current and future trends in the aviation industry. RQ5 deals with the effect of industry 4.0 on different aspects of the digitalization of SP industries. There remain challenges and influences of different factors. RQ6 is concerned about these factors and constraints for AM in Aircraft SP industries. Nevertheless, there remains a lack of systematic reviews that answer these questions in an organized manner.

After the planning and development phase, the researcher moved on to the source and collection. This section required critical attention to the study. A complete examination of scholarly articles in the field of AM in SP was conducted in order to address the research questions to be answered. The goal was to include a wide variety of facts in order to minimize prejudice and assure the research's neutrality and validity. High-quality publications were identified based on the selection criteria focused on answering the research questions. Google scholar database was used to find peer-reviewed publications published in academic journals. The selection of published journals was restricted from 2005 up to 2022. Various keywords were used to select papers that helped in discovering the most relevant papers associated with AM, SP, and aviation industries. In this step, mainly the research criteria are set for the SLR. The search goal was to answer the research question and attain the research objectives. The reviewing source is peer-reviewed journals, review papers, conference proceedings, etc., Google Scholar's advanced search option has been used as Google Scholar is a free and accessible search engine with scholarly literature across all kinds of publishing formats and disciplines. During the search period, the publications in the English language were selected only. Finally, the preferable timeline for filtering scholarly articles was 2005–2022, following the changes with the advancement of the research field. The search criteria for this research are listed in Table 2.

Table 2. Search Criteria of the study.

Criteria	Description
Contribution	Importance observed in the review area
Relation to the research	Must align with research questions
Source	Journal, Review, Official Website, Proceedings
Timeline	2005–2022
Search Engine	Google Scholar
Language	English

Search strings have been identified via an unstructured literature review. The main aim of this review lies in exploring the supply chain of aerospace spare parts from AM and I4.0 perspectives. Boolean operators combined with synonyms of additive manufacturing, spare parts, aerospace industry, supply chain, industry 4.0, material selection, etc., have been used to form the word string for searching. The strings for each domain are shown in Table 3, and a relevant word-cloud is illustrated in Figure 3.

Table 3. Word Strings for publication search.

Subject Area	Word String Used
Supply chain	'Supply chains' OR 'supply chain'
Additive manufacturing	'Additive manufacturing' OR '3D printing' OR 'Three-dimensional printing' OR 'Direct manufacturing' OR 'Digital manufacturing' OR 'Rapid prototyping' OR 'Rapid manufacturing' OR 'Additive fabrication' OR 'Solid free form fabrication' OR 'Generative manufacturing'
Spare parts	'Spare part' OR 'Service part' OR 'Repair part' OR 'Replacement part'
Industry 4.0	'Industry 4.0′ OR 'I4.0′ or '4IR' OR 'Fourth Industrial Revolution' OR '4th Industrial Revolution'
Material Selection	'Material selection' OR 'Material application' or 'Material segmentation'
Aircraft industry	'Aircraft industry' OR 'Aerospace industry' or 'Aircraft' OR 'Aerospace application' OR 'Spacecraft' OR 'Aviation industry' OR 'Aviation'

Figure 3. Keywords for the literature search.

The resulting word string has been merged with the framework of core subject areas mapping (Figure 1) using the Boolean and Operator. Then, the search results in a total of 4788 articles. The criteria are based on the abstract, title, and keywords of the articles. The results from the selection of titles, abstracts, and keywords are shown in Table 4.

Table 4. Subject area wise publication.

Core Subject Area	Short Form of Core Subject Area	No of Papers (Abstract, Title, Keywords)
Spare parts AND Supply chain	SP SC	2050
Industry 4.0 AND Supply Chain	I4.0 SC	538
Spare parts AND Industry 4.0	SP I4.0	1
Aerospace industry AND Industry 4.0	AI I4.0	30
Aerospace Industry AND Spare parts	AI SP	1710
Material Selection AND Aerospace Industry	MS AI	34
Additive Manufacturing AND Material Selection	AM MS	13
Additive Manufacturing AND Spare parts	AM SP	103
Additive Manufacturing AND supply chain	AM SC	299
Additive Manufacturing AND Supply Chain AND Spare parts	AM SC SP	3
Industry 4.0 AND Spare parts AND supply chain	I4.0 SP SC	1
Industry 4.0 AND Spare parts AND Aerospace Industry	I4.0 SP AI	5
Material Selection AND Spare parts AND Aerospace Industry	MS SP AI	1
Material Selection AND Spare parts AND Additive Manufacturing	MS SP AM	1
Total		4789

The resulting articles achieved from the search process are either excluded or included for further assessment [33]. The exclusion or inclusion procedure has been divided into subsequent stages with specific criteria. Firstly, the 4789 papers have been identified via the combined search strings and duplicate results have been removed. Next, the abstracts of the papers have been studied and non-relevant papers were excluded. After that, a full-read assessment was performed, and non-relevant articles were removed, resulting in about 238 articles. Finally, 136 articles qualified for the content analysis in the systematic literature review. Therefore, articles that had been identified to be related to the research of core subject areas. The inclusion and exclusion procedure have been illustrated in Figure 4.

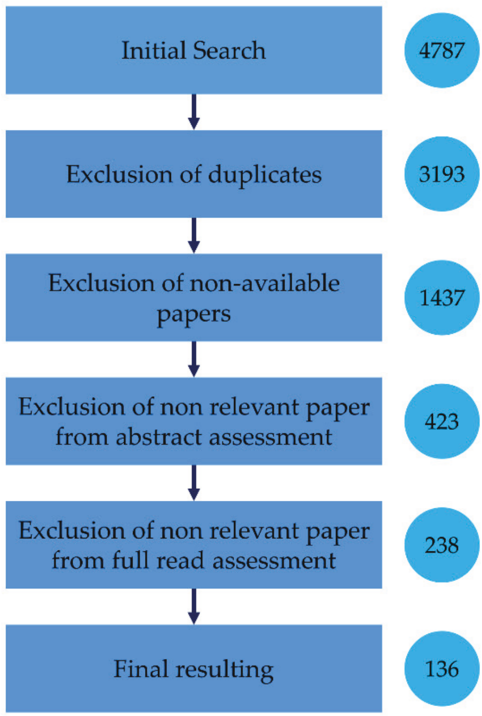

Figure 4. Screening mechanism of Paper selection.

Finally, the findings from these selected papers were evaluated, and the information was compiled for building the research paper.

3. Additive Manufacturing of Spare Parts

Additive Manufacture (AM) is the general term for the collective advanced manufacturing technologies, which construct components layer by layer. Instead of removing the material, they are made by adding material rather than by subtracting manufacturing like machining. Additive manufacturing technology has the freedom for creating complex geometry components, efficient waste minimization and highly customized products. Among other advantages, AM has a very impressive effect on the environment by increasing sustainability in the production line with respect to traditional manufacturing processes [28]. AM processes can be classified into seven categories: powder bed fusion, material jetting, material extrusion, vat photopolymerization, directed energy deposition, sheet lamination, and binder jetting [34].

The material addition or fusion is regulated by G codes directly generated from the 3D CAD models. AM has taken up the role of complex parts manufactured in small to medium sized batches in many areas of engineering and industry, with increased competition in the international economy and evolving market trends, such as increasing production rates, increasing demand for personalized and customized goods, reduced lead time and the implementation of new business models [35,36].

The rate of AM innovation is increasing every day, and the equipment is becoming less expensive and more efficient. Parts made with new materials can match, if not exceed, the qualities of traditional production. However, it has some disadvantages as well. The advantages and disadvantages of the AM over CM are given in Table 5, respectively.

Table 5. The advantages and disadvantages of AM over CM.

	Attributes	Explanation	References
Advantages	Flexible design	AM process can overcome the limitations of not producing complex shapes in the conventional process. The parts do not need further fabrication or operator to produce complex parts.	[3,37–47]
	Low cost	Because of AM, rapid prototyping is easier based on time and monetary budgets. Compared to CM, a CNC milling setup is much cheaper with AM.	[37,47–49]
	Customized products	As AM does not have limitations over shapes, it can produce customized products massively.	[3,38,41,43,47]
	Efficient use of materials	3D printing means methodically adding materials until a part is created. Since AM starts laying down a base layer of material and then adds subsequent layers until the part is ready, the overall waste is minimal. Additionally, consolidating parts for manufacturing can save energy and manufacturing costs.	[42,44,47,48,50]
	Increased part reliability	As newer materials, such as polymers, metals, and composites become available for the AM, replacing parts with improved materials gets easier to improve the parts' performances.	[51,52]
	Reduction in on-hand inventory	Unlike the traditional manufacturing that sticks to a warehouse packed with premade parts, AM needs a virtual inventory that saves warehouse space, personnel, and obsolete parts.	[37,40,42,53]
	Small production runs often prove faster and less expensive	Almost nothing beats AM for speed and economy for a handful of products. It will be faster to print those. Gathering design files, printers, and materials are all we will need.	[44]
Disadvantages	Not preferred for mass production	The process of AM is slow, and it allows mass customization, and thus till now, it is not being able to be used for mass production.	[3,37,40,45,47,48]
	Size limitation	Industries are slow to adopt AM and consider it a niche process even in 2021, probably because 3D printing is not an efficient method of producing a considerable quantity of parts.	[42,43,53]
	Low range of material	Unlike CM, AM have fewer materials to be used.	[44,47,53]

3.1. Current Trends Additive Manufacturing in Aerospace Industry with Example

GE aviation (Ohio, United States): GE aviation has produced a leap engine fuel nozzle (Figure 5) by combining 20 parts into a single-part with cobalt-chrome materials using Laser AM that weighed 25% less than the conventional one. After getting certified by the FAA (Federal aviation administrator) in 2015 [54], GE has fulfilled a target of more than 30,000 additive fuel nozzles to be produced by 2018 [55]. Before that, GE also additively manufactured housing components of the T25 engine sensor for retrofitting GE90-94B engines.

NASA-Rocket injector (Glenn Research Center, Cleveland, United States): NASA has considered a Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) to adopt AM for fabricating rocket engine parts with metal powder and lasers. The method of fabricating the powder with lasers is named 'blown powder directed energy deposition' to minimize lead time and cost for manufacturing complex engine components like combustion chambers and nozzles. The nozzle was fabricated within 30 days, whereas it would require about a year with conventional methods [56]. NASA had manufactured a metal rocket injector (Figure 6) with selective laser melting using nickel-chromium powder combining 115 parts into two parts only. The part had gone through hot fire and structural tests and was used in the J-2X engine in 2017 [57].

Boeing (Illinois, United States): Boeing, Inc., has additively manufactured more than 200 different parts for ten aircraft platforms. Boeing has also used roughly 20,000 additively manufactured parts in military and commercial aircraft, including 32 different components for its 787 Dreamliner planes. Boeing has fabricated more than 7500 tools which are additively fabricated and this is increasing [58].

Airbus (Leiden, Netherlands): Airbus has produced a Cabin bracket connector for the Airbus A350 XWB using Laser CUSING technology with Titanium powder, as shown in Figure 6. Previously, the parts were manufactured with Aluminum alloy by milling machining, which produces 95% waste. In contrast, Laser CUSING technology has a waste of about 5%. Furthermore, the component can bear a 20KN fore effect and withstand at 330 °C, without any problem. With the help of AM, Airbus can develop components in a month instead of a 6-month lead time, as projected earlier [59].

Rolls Royce (Westhampnett, United Kingdom): Rolls-Royce has manufactured a Trent XWB-97 engine part having 0.5 m and 1.5 m diameter thick front bearing housing part for holding 48 airfoils using Electron Beam melting of Titanium. By applying AM, Rolls-Royce has reduced the manufacturing time by about 30% [60].

Stratasys (Rehovot, Israel): Stratasys with Aurora flight science has Fabricated an Unmanned Aerial Vehicle (UAV) which is 80% 3D printed with a total weight of only 33 lbs and capable of gaining a speed of 150MPH. With the combination of Fused deposition Modelling and Direct metal laser sintering (DMLS), different parts have been produced by reducing design and build time by about 50% [61].

SpaceX (California, United States): SpaceX has fabricated a hypergolic propellant rocket engine named SuperDraco for passenger-carrying space capsules. It is manufactured additively with Inconel superalloy by direct metal laser sintering. The fabrication process dramatically reduces lead-time compared to the traditional process with fracture resistance, ductility, superior strength and low variability in materials properties [62,63].

3.2. Future Perspective

The future development in AM technology will tend to fabricate larger products. Larger spare parts like airplane wings are expected to be fabricated by AM technology in the future. The current establishments of AM (i.e., flexible and convenient supply chain) are being studied and investigated by Lunar Building, NASA, and 'Made in Space' towards finding the capability and potential of using this technology in zero-gravity environments [5]. With the help of Part consolidation and topology optimization, AM may create multifunctional structures that simultaneously perform several functions. Besides, 4D printing can be an emerging way that will change the part geometry with respect to humidity, heat, or radiation. Currently, repairing a damaged part through AM is time-consuming. Therefore, automation for the preparation process may reduce the time and cost of repairing the damaged part instead of producing a new product. A step has been taken by a European project named RepAIR where the geometrical deviation of the damaged part compared with the original part is identified automatically. This automation process can be extended to prepare the surface and is incorporated into producing large parts. Moreover, the automated process will be able to analyze the condition of the damaged part, whether it is repairable or needs fabrication of a new part on-demand [5,64].

4. Spare Parts with Additive Manufacturing for Aviation Industry

Additive manufacturing (AM) is established as the manufacturing process that increases the revenue of the aerospace industry with the repairing operation and supply chain [27]. AM provides new opportunities to make sustainable, topologically optimized, lightweight spare parts for aircraft. Various sophisticated components and subcomponents assemble them, and a multi-tiered manufacturing structure is required. Therefore, intensive work is needed in the inventory and supply chain to continue smooth operation in the aircraft assembly. However, continuous improvements in process are still required to ensure safety and quality in the aeronautical industry considering the below attributes.

4.1. Quality Assurance and Standardization

Some structural parts and critical components of engines are made of metals using AM, which may bring catastrophic and consequent events if they fail. These components require rigorous assessments to get certified. ISO/TC261 and ASTM F42 have been formed to establish standards on terminology, materials, processes, and test procedures for AM [65]. While SAE International primarily works on aerospace-related AM standards, both ISO and ASTM are responsible for AM standard publications [66]. Therefore, FAA and EASA have established certification and testing protocols to clear any components for service on the required application [67]. Major leading regulatory bodies like ASTM, ANSI, and SAE international have collaborated frequently with aviation regulatory bodies, such as NASA, FAA, and EASA [68,69]. This effort has accelerated the certification process and ensured continued operational safety for adopting AM in the aerospace industry [70]. However, a well-established standardization has not been conducted yet, and the process is quite costly and lengthy.

4.2. Part Consolidation

In conventional machining processes, complex shapes cannot be fabricated easily. Thereby, in CM processes, simple parts are joined together to construct or assemble complex aerospace parts which require different types of joins or fasteners like welds, braze, nut bolts, etc. However, these joining processes are less reliable and sustainable with respect to a single part [71]. Moreover, any error in tolerance, misalignment, or geometric error would complicate the assembly process [72]. Additive Manufacturing can solve this problem by fabricating a complex part combining components that enables feature integration and increases reliability, sustainability, and performance [73]. Moreover, it will reduce inventory, lead time, assembly-line footprint, and supply chain pressure by increasing components' performance [5,74]. For example, a hydraulic housing tank containing 126 parts can be reduced into a single component using AM [64]. Similarly, GE aviation has consolidated conventionally manufactured 855 components into a dozen parts using AM, resulting in a 20% improvement in fuel burn and 10% more power [75].

4.3. Materials Selection for Spare Parts in Additive Manufacturing

Spare parts forecasting is challenging as the demand pattern is intermittent [76]. A higher service level is required to avoid downtime costs, making the spare parts planning more complicated [77]. Therefore, companies need to keep high inventories of spare parts to compete with service-level requirements. AM allows producing low-volume parts away from CM processes. By removing disrupted parts with part consolidation and low volume parts from traditional fabrication methods, AM can maximize the service level for spare parts by availing time [77,78]. AM can increase responsiveness by balancing inventory levels and minimizing carbon emissions and disruptions in the supply network of spare parts [77]. AM reduces the supply risk for spare parts for low-demand parts while conventionally manufactured part is unavailable in low quantity [79]. However, a limited volume of AM, inadequate quality and post-processing requirements are the challenges for this purpose [80]. Additively manufactured spare parts can be used to repair damaged parts without replacing the whole parts, such as repairing the burner tip of a gas turbine by Siemens [26]. Aircraft MROs require fabricating parts in minimal quantities; hence, they face a widely distributed supply chain and unpredictable demand [11]. The demand is often affected by disputable factors like failure rates, type of maintenance, and wear behaviors [81]. Many aircraft spare parts are highly valued, ordered infrequently, and require a long replenishment lead time [82]. Hence, a literature gap remains where the lead time can be simulated for varying AM spare parts percentages in the overall system and its effect on the replenishment lead time can be monitored. Sometimes, repairing tools become unavailable from OEMs [74]. AM may play a recovery role in this perspective. For example, by using AM instead of milling, the lead time and cost to repair a helicopter part have been reduced from 45 days and $2000 to 2 days and $412 respectively [83]. The U.S. air force has collaborated with 'America Makes' to supply on-demand production to reduce the lead time for maintenance and replacement components of aircraft [84]. A summary of factors to be considered for spare parts selection is given in Table 6. Appropriate supply chain and technical factors should be considered to classify spare parts with AM. Moreover, companies are not classifying spare parts with a systematic data-driven way to choose the suitable spare parts for AM, which tends to fail in searching for the potential aspects and is a time-consuming exercise. A data-driven approach and multi-criteria decision-making (MCDM) techniques may assist in prioritizing the factors [85]. Moreover, companies need to avoid evaluating a large number of spare parts covering multiple criteria as it is a time-consuming process. However, understanding the suitability of spare parts with AM is also important. By analyzing additively manufactured part characteristics, Artificial Intelligence (AI) can be a suitable technique according to regulatory bodies' standards [86–88]. AI can ensure feature recognition characteristics for spare parts selection with AM that will not be repeated even if a new spare part is developed. As less research has been conducted in this process, identifying missing classification approaches and promising opportunities can be future research.

Table 6. A summary of factors for spare parts selection.

Spare Parts Selection Parameters	Description	Author Reference
Part size, Build volume	AM machines have limitations of build volume as well as part size which depends on the resolution of the machine.	[79,89,90]
Supplier availability, demand pattern, lead time, predictability of delivery time	Normally AM is a time-consuming process rather than the machining process depending on the process parameters and part quality. Therefore, high resolution products can take large fabrication time rather than machining process, which may result in large lead time and delivery time need to be predicted to supply the spare parts in time	[90]
Appropriate material	Different materials have different mechanical properties, and their application may vary depending on their characteristics.	[91]
Appropriate material, Dimensional accuracy	The formability of complex shapes can affect the product dimension. Hence, proper material needs to be employed depending on material properties.	[92]
Post-production shrinkage; Appropriate material, water, and temperature resistance	The AM fabrication process is conducted in an ambient temperature depending on the material. After producing the parts, it tends to have shrinkage and resulting change in the product dimensions. As accuracy and tolerance is a big factor for aviation spare parts, so the shrinkage, dimensional accuracy and temperature resistance need to be considered for the fabrication process	[3]
Stiffness to weight ratio, Appropriate material, support material, strength to weight ratio	The part mechanical properties like stiffness to weight ratio, and strength to weight ratio need to be considered for better performance under a loading environment. The mechanical properties also depend on the product material and support material to sustain under loading.	[93]

Table 6. *Cont.*

Spare Parts Selection Parameters	Description	Author Reference
Layer thickness, Build speed	Optimized layer thickness, and printing speed needed for better part quality and material consumption.	[94]
Supplier availability, demand pattern, lead time, responsiveness, downtime cost, maintenance type	The spare parts need to be easy to change or repair. Otherwise, it will increase downtime in the maintenance work.	[5,95]
Supplier availability, demand pattern, lead time, Annual consumption value	The annual consumption of materials and spare parts plays a vital role in the MRO's yearly revenue.	[21,96,97]

4.4. Material Criteria

Titanium, Aluminum, Nickel, stainless steel, tool steel, etc., are commonly used in AM for the aerospace industry [98]. However, the most popular materials used are Nickel and Titanium base alloys due to their remarkable properties at elevated temperature which is well suited for aerospace application [99]. Moreover, silver, gold as well as platinum can be used for selective application in the aerospace industry [53]. Furthermore, Ti6Al4V alloy has been used extensively due to its high strength and fracture toughness, low density, low thermal coefficient, etc. [100]. In addition, the titanium alloy is used widely for mass manufacturing of turbine blades for use in commercial aircraft [101,102].

Various cabin accessories in aircraft like seatbacks, entry door parts, transparent headlights, full-size panels, and functional knobs have been manufactured in a highly detailed manner with SLA clear resins [103]. Moreover, Aurora Flight science and Stratasys have fabricated the largest Unmanned Aerial vehicle (UAV) with ULTEM 9085 material with the FDM process [61]. NASA's Mars rover has used 70 Production grade thermoplastic parts in the FDM process. Mainly, plastic materials are used because they are lightweight yet durable and strong enough to withstand stringent conditions [104]. Noteworthy, in CM processes, the fabrication of a part starts with cutting down a large ingot to the desired shape. Therefore, multiple component fabrication requires more ingots and machining, resulting in high wastage of around 90%, and low material utilization, with a high 'buy-to-fly ratio' of nearly 10:1 [105]. The 'buy-to-fly ratio' is an established concept in AM for the aerospace sector that refers to the weight ratio of raw material and the component itself [106,107]. Approximately 70% weight reduction of the original weight is possible in AM process [89,108]. The main advantage of AM is to fabricate the product to near net shape with approximately 1:1 'buy-to-fly ratio' and significantly minimize material waste by nearly 10–20% [109]. Even though the material cost is higher for AM than CM, a lower 'buy-to-fly ratio', minimum wastage, mass customization, and recyclable capabilities significantly reduce the overall manufacturing cost in AM [110]. AM can be considered an economical and better option than CM with added operational, inventory, and supply chain benefits.

Recently, AM has been applied to various complex-shaped spare parts fabrication by showing significant inroads in manufacturing novel components. However, AM's drawbacks remain on maintenance requirements, standardization, part size, geometry accuracy, printing quality, limited materials, and costs for spare parts production in the Aerospace industry. Therefore, further research on design methods, consolidated part configuration, and novel materials are required to overcome the challenges and maximize the applications of AM in the aerospace spare parts industry.

5. Supply Chain Scenario

AM significantly impacts the supply chain transformation as the number of components is reduced. In the case of additive manufacturing, the functionality of different components is integrated into one 3D printed model. This reduces the assembly of components and synchronization efforts, unlike conventional manufacturing. Digitalization of manufacturing through AM reduces inventories compared to the conventional subtraction manufacturing processes. Consider two supply chain scenarios, Centralized and Decentralized, for additive manufacturing in spare parts. Decentralizing increases customer responsiveness, and reduces lead times, transportation time, and cost. The distribution time is significantly reduced if the final product is produced near the customer [26]. In terms of cost, the current condition in additive manufacturing technology found centralized AM cost effective compared to decentralized AM but with increased automation, decentralized AM is predicted to be cost effective [111]. Decentralized manufacturing enables a production system to deal with the unpredictability of demand, including cyber-physical systems automation with improved quality [112]. A case study carried out with six different spare parts in the aircraft industry analyzes the fluctuation of safety inventory with varied standard deviations of the demand. It is seen that the safety inventory of decentralized AM is the lowest, with a standard deviation of up to 30%. Nevertheless, as the standard deviation reaches 30% or more, the safety inventory of centralized AM is lower [27]. A simulation, carried out at a service level within 65% to 95%, implied the decentralized scenario as a prominent strategy [113]. It shows that a decentralized AM reduces the lead time, holding costs, and transportation costs compared to a centralized AM at every service level point [113]. The two scenarios of centralized and decentralized AM [114] are illustrated below in Figure 5.

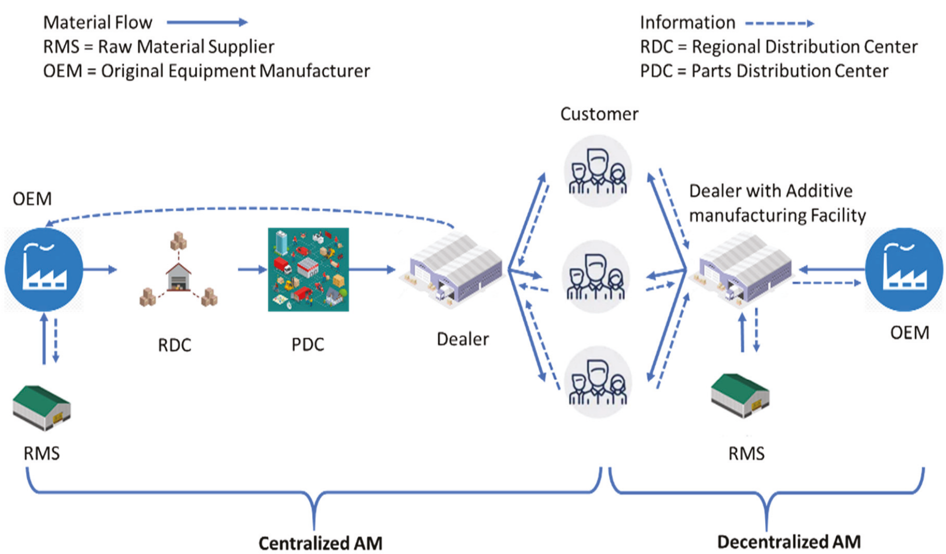

Figure 5. Illustration of Supply Chain Scenarios in Spare Parts Industry (Own illustration based on [114]).

5.1. Spare Parts Manufacturing Scenario

This sub-section discusses five spare parts manufacturing scenarios as illustrated in Figure 6. Personal, Retail, and Mobile industries are proposed to benefit from decentralized manufacturing [115]. Personal manufacturing refers to the owning of AM machines by customers and producing spare parts by themselves by purchasing the licensed model online. In retail manufacturing, an AM facility in the high street will provide an on-site manufacturing facility with access to a digital library. Mobile manufacturing is an in-transit manufacturing method that implies spare parts to be manufactured while shipping towards reducing lead time and stock holding. In bureau manufacturing, regional centers of bureaus are provided by OEMs that reduce reliance on the central warehouse and transportation. In factory manufacturing, AM machines are incorporated with the current manufacturing system that allows mass production with customization flexibility as well [115].

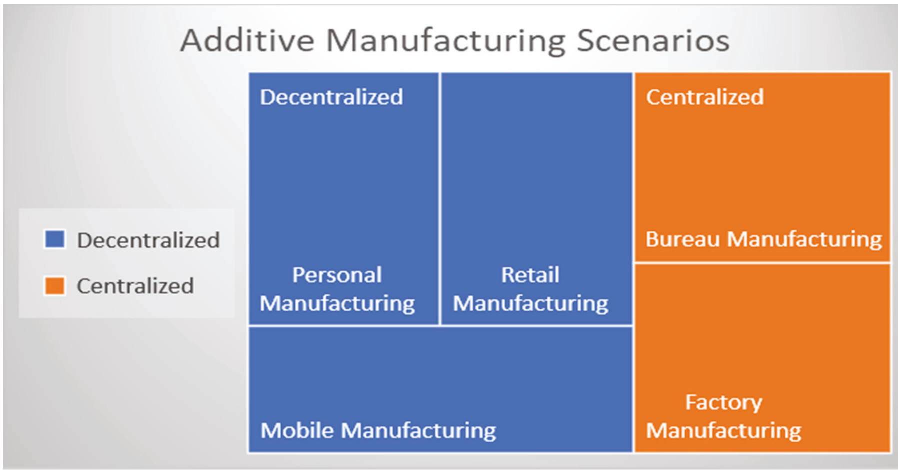

Figure 6. Different Scenarios of Centralized and Decentralized Additive Manufacturing.

5.2. Centralized vs. Decentralized Supply Chain

A comparison between centralized and decentralized supply chains of AM in the spare parts industry is discussed in Table 7.

Table 7. Cost Comparisons of Supply Chain Scenarios among AM Technologies.

	AM machine Technology							
	Current Technology						**Future Technology**	
	SoA-SP [30]		**SoA-MP** [30]		**SoA-2013** [17]		**ReqTecDM** [17,30]	
Attribute	**Centralized**	**Decentralized**	**Centralized**	**Decentralized**	**Centralized**	**Decentralized**	**Centralized**	**Decentralized**
Material Cost	Same	Same	Same	Same	Same	Same	Same	Same
Spare parts transportation cost	High	Nil	High	Nil	High	Nil	High	Nil
Inventory carrying cost	High	Low	High	Low	High	Low	High	Low
Aircraft downtime cost	Low	High	Low	High	High	Low	High	Low
Annual cost of initial inventory production	High	Low	High	Low	High	Low	High	Low
Inventory obsolescence cost	High	Low	High	Low	High	Low	High	Low
Initial investment in AM machines, depreciation cost	Low	High	Low	High	Low	High	Low	High
Personnel cost	Low	High	Low	High	Low	High	Low	High
Total Cost	Lower	Higher	Lower	Higher	Lower	Higher	Higher	Lower

Based on the required chamber capacity, the current technology machines are classified into three sections: "state of art-2013"; "state of art- single part"; "state of art- multi part", that are denoted as "SOA-2013", "SOA-SP", "SOA-MP", respectively. Norge Ice 1 and 9 are two machines referred to as SOA-SP & SOA-MP, respectively [30]. Moreover, the future assumption of hypothetical machine technology is referred to as "Required Technology for Distributed manufacturing", also termed as "ReqTecDM" where the machine has increased productivity and more automation. With the current technology (SoA-SP, SoA-MP, SoA-2013) of additive manufacturing, it is preferred to have centralized manufacturing rather than decentralized manufacturing. Here, the total cost for centralized is always significantly lower except for one case of future hypothetical technology (ReqTecDM) of AM where the operator to machine ratio and the procurement price of machines are reduced significantly. The future technology in AM supports the decentralized structure because the future AM machines are investigated as cheaper, smaller, and with increased automation [17,30].

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Li et al. (2017) [27] simulates the carbon emissions in two scenarios of AM and concludes that a centralized AM has a bit higher carbon emission than a decentralized AM (Figure 7). In a centralized supply chain, 63.7% of its total carbon emission is due to the production of raw materials, which is 68.31% in the case of a decentralized supply chain. For the centralized scenario, the carbon emission due to the manufacturing and transportation of the final product is 22.75% and 13.55%, respectively. In contrast, the decentralized method incurs 22.42% and 7.27%, respectively [27]. Hence, it appears that decentralized facilities reduce the carbon footprint. Nevertheless, further investigation is needed on how component design and AM's weight savings character impacts the life cycle and carbon footprint for spare parts fabrication in the aerospace industry.

In general, OEMs perform turnaround tasks, replace aging and broken parts, inspect and identify broken parts, send out broken parts, as well as stock new spare parts of the aircraft. However, considering the details, the tasks are not as simple as it seems. There are many unique parts in Aircraft that are delivered through several distribution networks. Therefore, various managerial strategies need to be adopted to govern the system. Accordingly, these strategies face various geographical and human barriers. As Aircraft has some highly technical and critical parts, the logistics system is quite complex to make the right decisions in terms of performance, cost, and sustainability [117].

Moreover, logistical disruptions are common in the spare part supply chain when suppliers face low-volume business that is no longer economical. As a result, service providers lose interest in investing in inventories of additional spare parts to fulfill the demand. Such a high uncertainty leads to substantial costs frequently [118]. However, the low-volume production costs can be minimized by utilizing AM due to the lower tooling and setup costs [119]. For instance, AM can be used to repair worn-out spare parts, saving costs and increasing the usage period. Moreover, the total lifecycle costs are minimized as replacement intervals increase with AM.

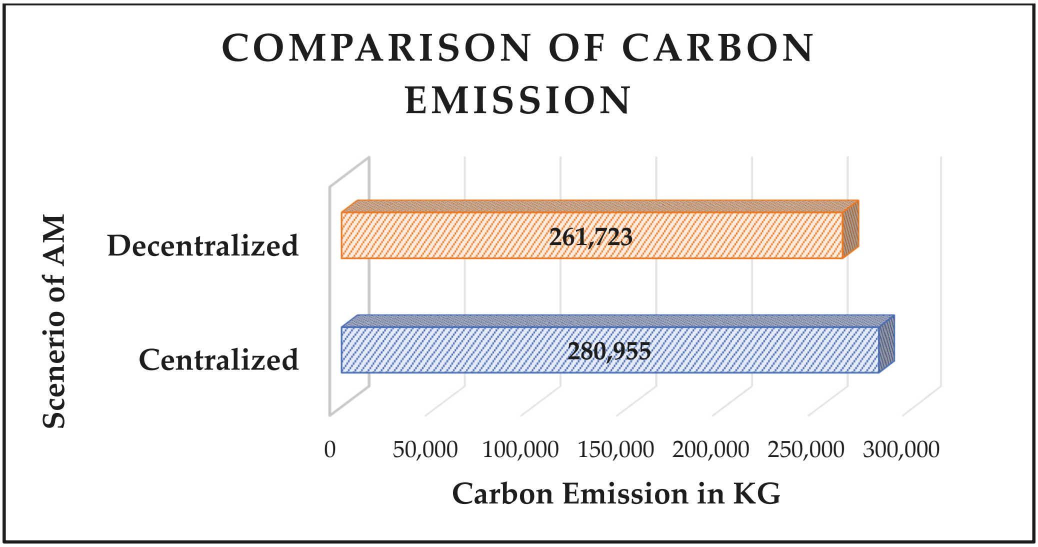

Figure 7. Comparison of Carbon Emission between Centralized and Decentralized Additive Manufacturing [27].

In addition, AM may increase the responsiveness of a supply chain [17]. For example, AM can fabricate on-demand spare parts and lower response time to avoid safety stock costs. Furthermore, order-driven production can minimize the obsolescence risk of stored spare parts. As discussed before, if spare part supply is disrupted, high costs can be incurred, especially for low-volume parts. It is possible to establish a streamlined supply chain relatively cheaply with AM technology [78]. Moreover, this practice may bring more benefits if the demand for spare parts occurs at remote locations or the customer response time needs to be short. On-demand printing of AM can be an alternative to holding high inventory and longer downtimes. This type of application is found in the military, like the US marine corps, to fabricate advanced parts at remote locations [120].

6. Industry 4.0 Context in AM of Spare Parts

The vision of Industry 4.0 (I4.0) is to construct a smart and open manufacturing platform in order to build an industrial networked information application [121]. Mostly, tracking the status and position of products, data-driven manufacturing, real-time monitoring, and control of production processes are the primary needs of I4.0 [122]. Various technologies like Cloud Manufacturing, Internet of Things (IoT), Big Data, Cyber-Physical Systems (CPS), Additive Manufacturing, Artificial Intelligence (AI), Block Chain, etc., have evolved and appeared recently for industry 4.0 [123,124]. Despite increasing research on industry 4.0, it remains stippled and fragmented [125]. For example, there may be a technical similarity, such as adopting a process perspective or decreasing failure in the manufacturing system.

A popular key concept is the Smart Factory, also called an intelligent and digital factory [126]. It consists of machines equipped with different sensors and actors, which can send, process, collect and receive data and act accordingly with the internet connection [126,127]. A smart factory illustrates the future state of a controlled manufacturing system, which operates without any human force [126]. It transfers, generates, processes, and receives the necessary data to complete required tasks to produce various types of goods [128].

Industry 4.0 gives the vision of a new industrialization concept that exploits newer technologies to fabricate spare parts for building smart factories. Smart factories are self-adaptive, making them the heart of Industry 4.0 [129]. A smart factory integrates new technologies like blockchain to improve the overall quality, performance, and transparency of the manufacturing processes. Blockchain helps to monitor printed parts with the secured exchange of data among the stakeholders, improving the process and reducing the logistic costs with the help of a flexible supply chain [130,131]. From a supply chain perspective, smart factories are self-sufficient facilities that source raw materials from local suppliers. Sustainable approaches to building smart factories need to be ensured by 4Vs volume, variety, velocity, and veracity [132]. Yet, more research is needed regarding how to adopt a smart system with the implementation of I4.0 technologies to manage spare parts production in the aerospace industry.

Big data enable process analysis and optimization by generating a large amount of data. It assists in developing an AM integrated data model [133] and benefits manufacturers, the environment, customers, and different aspects of the spare parts manufacturing phase [134]. However, a lack remains to implement big data analysis in spare parts industries to forecast the unpredictable demand, design the inventory system, and consequently minimize the overall supply chain cost.

Furthermore, Artificial intelligence (AI) explores techniques of developing intelligent programs and machinery that can solve issues creatively which has always been regarded as a human attribute. AI can minimize the required workforce to increase output and achieve greater resource efficiency. With AI, local partners and alliances can decrease lead time and inventory and simultaneously increase the customization and responsiveness of the supply chain. Research trends demonstrate that AI supported models are computer-efficient technologies that enable AM processes to achieve a high-quality standard, product consistency, optimized process, and responsiveness in the supply chain [135]. Figure 8 illustrates the AM supply chain digitalization of spare parts with industry 4.0.

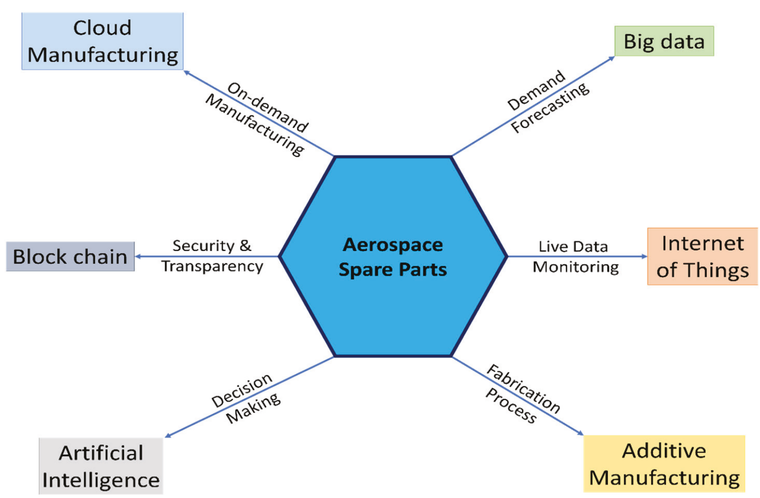

Figure 8. Digitalization of spare parts supply chain with industry 4.0.

Nowadays, additive manufacturing is becoming popular due to the capability of making parts with small sizes, complex shapes, and intricate details at a low cost. Nevertheless, this process is challenging for not determining how many parts should be produced due to inadequate exchange of information where industry 4.0 can be the solution [17,112]. Besides, industry 4.0 helps in proper inventory management. Using a cyber-physical system, more data can be acquired that can be used by sensors to determine failure time accurately [136]. Moreover, increasing types have complicated spare parts' tracking as it moves from one place to another. The blockchain system may ease this issue [137]. Industry 4.0 connects supply chain players (e.g., supplier, manufacturer, distributor, and retailer) with the help of cyber-physical systems that initiate the growth of the 'factory of the future (FoF)' [138]. It also helps to ensure sustainability in the supply chain [139]. This system can also be used to improve flexible AM systems. Apart from these, Industry 4.0 plays a significant role in the maintenance of spare parts [22,140]. Cloud Manufacturing refers to an interconnected virtual space of manufacturing resources, intelligent management, and solution to all consumer queries requiring IoT, cloud computing, service-oriented technologies, and virtualization. In AM processes, cloud manufacturing helps increase resource efficiency [131]. Some key characteristics of cloud manufacturing are flexibility and scalability depending on market demand, multi-tenancy, intelligent on-demand manufacturing, etc. It also helps to achieve a sustainable manufacturing process [130].

In AM processes, parts can be produced with new materials, features, and shapes for better optimization of performance and features. Moreover, another challenge is to obtain the same properties in the parts produced later with feedstock arriving from different vendors, which may harm the supply chain due to more integration of parts. Aircraft spare parts are valuable and expensive products that need to be delivered from one place to another with extra caution increasing delivery time and cost. Consequently, future research can be conducted on expanding AM materials, improving part designs, and maintaining the reliability of the part produced from different feedstocks. Future research can also be conducted on how delivery cost and time of delicate parts can be reduced [141] and how AM impacts the supply chain performance [142]. The AM process is not preferred for mass production. Future research can be conducted on how AM can be used for mass production along with mass customization in the aerospace industry. Nevertheless, AM processes also have limitations on the materials they use. More materials for AM should be discovered so that conventional machining does not need to be used in the aerospace industry. Large parts (like airplane wings) cannot be manufactured using AM, which can be solved in the future. Industry 4.0 concepts should be adapted quickly, which will help to reduce the downtime in the production of spare parts as well as increase gross revenue for the manufacturers of the aerospace industry.

7. Managerial and Policy Implications

The study can play a vital role in AM spare parts supply chain with significant managerial and policy implications in the aerospace industry for the logisticians. As the demand in this field is quite unpredictable, aerospace logisticians need to take measures quickly to satisfy their customers. However, some barriers constrain providing service within the shortest period resulting in revenue loss. Based on the discussion of the review, AM and I4.0 can be potential technologies in the aerospace spare parts industry to solve constraints and problems. By understanding the material selection criteria, policymakers may adopt AM in spare parts productions, which will assist them in utilizing the resources efficiently. With the advancement of AM, logisticians can provide required spare parts in the shortest lead time possible. Therefore, AM can boost spare parts production by coping with the market demand. With AM facilities, spare parts production can be facilitated in remote locations. Logisticians can employ and manage decentralized facilities by using blockchain, big-data analysis, cyber-physical systems, artificial intelligence, cloud manufacturing, etc. Moreover, AM can produce on-demand mass-customized products in the facilities. Therefore, MROs would not require larger facilities for spare parts inventory and it may reduce the safety stock. Finally, AM and I4.0 technologies will help the managers proactively take the right initiatives to minimize lead time, safety stock, inventory, and financial loss in the aerospace spare parts industry. Thus, the outcomes of the study may bring essential guidance for policymakers and different management professionals to adopt the excellence of AM in the emerging field of aerospace spare parts.

8. Conclusions

This research aims at exploring the impact of AM technologies on the aerospace industry's spare parts supply chain. Hence, a systematic review of the literature has been conducted. This paper discusses various aspects of the spare parts supply chain, such as facility location, distribution network, material selection, comparative analysis of AM and CM technologies, and industry 4.0 perspectives. The systematic review of existing literature provides a solid reference to the companies and entrepreneurs in their decision-making regarding AM consideration in the spare parts industry. This article further contributes to the knowledge of supply chain scenarios in different conditions, choices of material for making spare parts, and trends in AM technologies.

It is noteworthy that there are some limitations to this review paper. Since the author has used Google scholar only, using other search engines and databases may affect the review result. Selected papers were published between 2005 and 2022; hence, previously analyzed data in this field are not incorporated. Moreover, changes in word strings other than mentioned keywords may present slight differences in the review outcomes. While this paper reviews the existing literature descriptively and analytically, considering any statistical models or analyzing the engineering impact is out of this study's scope.

Currently, a centralized AM facility is preferred over decentralized AM facilities for total expenses in aerospace spare parts industries. In the future, a decentralized AM is predicted to be less expensive due to increased automation, reduced price, and small-sized machines. Moreover, carbon emission is lower in a decentralized supply chain than in a centralized supply chain due to lower emissions at the manufacturing stage and reduced outbound transportation. Nevertheless, further research on the AM facility location is required. Secondly, part consolidation and quality standardization have characterized AM into a new enabler of spare parts in the aerospace industry. Various complex-shaped nozzles, blades, turbines, and other structures can be fabricated easily under AM processes than CM processes. Thirdly, in the fabrication of aerospace spare parts, the material criteria and other listed factors for spare parts selection can help conceptualize the MRO to improve its supply chain. Industry 4.0 helps to digitalize the spare parts supply chain for transforming intelligent and smart industries. Consequently, AM has good potential in the aerospace industry for spare parts production and new parts fabrication. However, there are still some constraints to adopting I4.0 technologies to make the supply chain stable and responsive. Such constraints need to be identified by engaging the manufacturer and MROs. The future requirements for AM can be critical to resolving the current limitations of the spare parts supply chain scenario in the aerospace industry.

Overall, a research gap still remains in the aerospace industry due to the commonly lower usage of AM and industry 4.0 in spare parts service logistics. A realistic explanation can be that logisticians are less aware of the capability, sustainability, and technologies of I4.0 and AM than design engineers and operations teams. Conversely, design engineers and operations teams may not be aware of the importance of logistical characteristics to satisfy the gap. Unfamiliarity from both parties may lead to the underestimation of AM potentiality. The future perspective of the spare parts supply chain should consider AM and I4.0 technologies to overcome supply chain uncertainties. Hence, it may lead to a more responsive and economical supply chain by meeting the uncertain customer demand and making a smooth path in the logisticians' decision-making. Moreover, future research may explore the impact of AM on certain phenomena like the bullwhip effect in the spare parts industry. It is hoped that this review article will further inspire researchers and industry practitioners to explore and adopt AM in the aerospace spare parts supply chain.

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Power in the Context of SCM and Supply Chain Digitalization: An Overview from a Literature Review

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Abstract: *Background*: Within highly complex supply chain networks, driven by the trend of digitalization, supply chain relationship management becomes one of the central enablers in increasing supply chain performance. While the influences of globalization and digitalization on the supply chains are increasing, the power allocation within several markets is centralized to a small number of companies. The objective of this paper is to investigate the research gap concerning the impact of power asymmetries on the supply chain, in addition to the trend of digitalization. *Methods*: A literature review on power, in the research area of supply chain management and logistics, is used to synthesize the current state of the art in this research field and to provide a comprehensive definition of the concept of power. *Conclusions*: While this paper provides an overview of the impact of power allocations, according to supply chain digitalization and in the present research of supply chain management, it also develops a definition of Power in Supply Chain Management in general. Linked to this definition, this research elaborates on the research gap between power allocations and the digitalization of the supply chain.

Keywords: power; bargaining power; digitalization; innovation; supplier management; supply chain digitalization; supply chain management

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1. Introduction

Digitalization can be determined as one of the driving forces influencing inter-organizational relationships in the supply chain [1]. "The ability to combine massive data collection, previously unimagined information connectivity and visibility, and ever-improving analysis capabilities, combined with a physical network consisting of broad geographic network coverage, local fulfilment presence and parcel/postal delivery, have positioned these twenty-first-century retailers as leaders of the digital supply chain era" [2]. With the technological development, however, the cooperation of the actors within the supply chain [3] and the structure of the markets is changing [2,4]. Due to the multitude of players, the possibility of collaborative, cross-company cooperation is becoming increasingly important for the success of the supply chain in competition. Furthermore, the interaction of suppliers, customers and logistic providers on different tiers is creating a network of different patterns of dependency or influence. Depending on the network structure and other factors, such as company size, switching costs or resource dependencies, the ability of influencing is not equally partitioned along the chain, which leads to an asymmetry in the allocation of power according to every strategic decision which has to be taken along the chain [5].

Based on the growth of digital leaders and the increasing influence of digital technologies, market power within digitalized chains is increasingly centralized among a few players [4]. This change leads to a change in the distribution of power among the supply chain actors, in which small- and medium-sized enterprises, in particular, can become dependent on larger companies, so their own corporate goals have to take a secondary priority to those of their customer or supplier [6]. The increasing market share of companies such as Amazon, ALPHABET INC or Alibaba can be used as a first indicator for this trend. In 2021, eight of the ten largest companies in the world were using digital business models [7]. Amazon also can be used as an example to describe the power shift, induced by its digital business models, which are restructuring the traditional structures in the retail sector and changing the power structures in the market by creating new patterns of dependency from the analysis of data or the implementation of data interfaces [8,9], as well as focusing the logistic infrastructure on a small number of warehouses and logistic infrastructures, instead of previous end-customer-orientated logistic processes. On the one hand, the analysis of customer data or data interfaces are creating new patterns of dependency and inducing a new level of resource dependency. On the other hand, the increasing market share of Amazon, based on their digital and centralized business model, allows Amazon to influence the decisions of their suppliers. In summary, Amazon is reaching a position of power, where it will be able to dominate its suppliers decision variables [10].

Digitalization projects, such as the implementation of block chain platforms from companies such as MAERSK and IBM or Walmart, which are creating a dependency on the data interface, data analysis and the fulfillment of the requested guidelines, are also representative for the structural changes in the value chain. The definition of guidelines and data interfaces furthermore creates market standards, which increase the level of dependency and market entry barriers. Further mechanisms can be illustrated in the industry standards of Microsoft OS. The increasing market share of Microsoft enables the company, next to the resealing of different software products, to define industrial standards and influence the whole IT infrastructure of several industries. So, server infrastructure, as well as its security and further IT processes and software applications, are often related to Microsoft OS [11]. The highly variable environment of digitalization is influencing the classic value creation processes and relationship structures [12]. In this increasingly complex environment, digitalization is inducing dependencies between different suppliers, whose effects are unidentified and thus represent an unidentified variable with regard to strategic decisions. Based on this development and the huge impact of buyer–supplier relationships on supply chain decisions [13], this research offers the first theoretical contributions for dealing with these challenges and complex transformation processes. To reach the research objectives of this review, the following research question was formulated: How is the concept of asymmetric power allocations discussed in the scientific literature, in the context of supply chain digitalization and supply chain management? According to the overall objective, this research closes the gap between the present supply chain digitalization research—which highly focused on technical implementation—and the research about supply chain relationship optimization.

2. Literature Review: Methodology and Descriptive Analysis

Referring to the previous section, the following sections will present the research method of a literature review about power, digitalization and innovation processes within the supply chain, in a comprehensible systematic and scientific structure, and it will present the current state of the art [14,15].

To generate a clearly structured review, the analysis is split into two main parts: (a) First, this research is developing a general overview of power in the research area of supply chain management and elaborating a definition of power in the research area of SCM. (b) The further research focus of the review is closely aligned to the title of the research and closes the research gap between supply chain digitalization and power allocations. The objectives of this review are to summarize state-of-the-art research about power in SCM, as well as the influences of power in supply chain digitalization, and to point out further research recommendations.

2.1. Methodology

The study is conducted according to Fink [14], who has proposed a seven-step, step-by-step approach, to generate a comprehensible scientific review. The different steps of the analysis procedure are highlighted in Figure 1. The methodical approach is identical in both parts of the review, so the structure will only be described one time. Further considerations of this research will be carried out in addition to this split. The first step is the formulation of the research question, which guides the screening of the literature and is a superordinate of the review in the achievement of the goal [14].

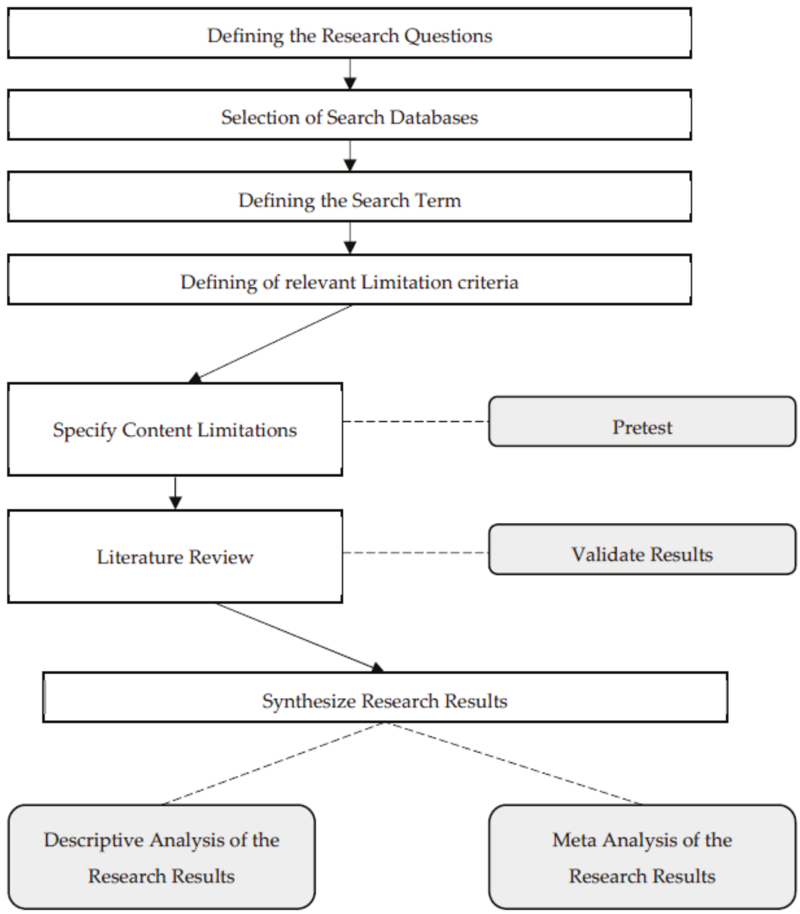

Figure 1. Steps of the literature review [14].

In addition to the objective of the research, three leading questions can be formulated:

1. How is the term of power defined in state-of-the-art research on power within the supply chain?
2. How does the existing research capture the impact of power on supply chain management?
3. How does the existing research capture the impact of power on the digitalization of the supply chain?

Further relevant databases were defined and the publishing period was selected. The review was conducted in the scientific databases Web of Science and Scopus, which offers a wide scope of publications. Denyer and Tranfield [15] suggest that the search term is defined, which, in addition to Fink [14], is necessary for the localization of relevant literature, based on the theoretical background of the research area. The search terms, including synonyms of power, supply chain and digitalization, and all variants, are summarized in

Table 1. The different synonyms of each column are summarized by the logical operator of "and", and the synonyms of each row are connected by the operator of "or". According to the two different parts of this research, two different search terms resulted from this structure. In a first stage, only the first two columns of Table 1 were used, in a second stage, this was extended by the third column. As an example, for the database Web of Science, this results in the following search string: (TS = ("Supply Chain" OR "Supply Chain Management" OR SCM OR "Value Chain" OR "Supply Chain Relationship" OR "logistics") AND TS = ("Power" OR "Bargaining Power" OR "Buyer Power" OR "Customer Power" OR Legitimacy OR Reward OR Coercion OR Referent OR Informational)). This definition of the search term is fundamentally based on more general terms/synonyms of power, digitalization or supply chain to develop a wide overview about the research field. In doing so, different synonyms of power were defined on the basis of social researchers, such as Weber, French/Raven [16], Olsen [17], Popitz [18] or Sofsky and Paris [19], who developed a bright understanding of the term of power, whereby the main challenge for this review was the transformation of this understanding to the SCM area. Furthermore, the different synonyms of digitalization, as well as the synonyms of supply chain, were selected on a superficial level to not restrict the research by a technological focus and develop the broadest possible understanding. For example, terms such as Industry 4.0 or big data were deliberately excluded to reduce any technological focus from this part of the search term and offer a more general overview. In addition to the search terms, this review was limited to journal publications and conference proceedings which were published between 1990 and 2021 in the English language. The period of the last thirty years is, on the one hand, quite broad, but on the other hand, it offers a large framework, so both publications from the beginnings of supply chain management research and more recent research results about digitalization can be considered. The criteria of further limitations, except of the categorizations, are summarized in Table 2. In addition, both databases only consider publications that were published within the framework of an economic categorization, thus having a direct connection to supply chain management research.

Table 1. Definition of the search terms.

Power	Supply Chain	Digitalization
bargaining power	Supply Chain Management	Digitalization
customer power	SCM	Innovation
buyer power	Supply Chain Relationship	Technology
legitimacy	Value Chain	Information
reward	Logistics	Automation
coercion		
referent		
informational		

Table 2. Criteria of inclusion and exclusion.

Criteria	Inclusion	Exclusion
Document type	Journals, conference proceedings	Any other publications, such as reports or reviews
Publications stage	Final	Article in process
Language	English	Any other language

Entering the search term into the selected databases, the research results highlighted 8574 hits for the database Web of Science in July 2021, and 22,661 hits were found in the Scopus database. These first results were narrowed down by using different levels of limitations. For the Web of Science database, the search was narrowed down to the following categorizations: Management, Operations Research Management Science, Business, Economics, Business Finance, Transportation and Transportation Science. All other categories were excluded. Based on these restrictions, the search result reduced to 1481 hits. The same restrictions were made for the Scopus database. Here, the search result was limited to the categories Business, Management and Accounting, as well as Economics, Econometrics and Finance, and all other categories were excluded, which led to a search result of 953 hits. Other subject areas were excluded. A further narrowing based on an analysis of titles and abstracts finally reduced the search result to 68 publications in Web of Science and 46 results in the Scopus database. This step was based on a scanning of the title and abstracts according the any connection to the search term, based on qualitative reading. Finally, this result was considered with regard to duplicates and access authorization to the publications, so that 67 publications were considered for the final analysis.

A similar procedure was used for the specific literature analysis on power in the context of digitalization within supply chain research. In July 2021, the Web of Science database yielded 2004 hits, whereas Scopus yielded 5872 hits. The further restrictions regarding the categorizations are identical to the first for this second analysis. Thus, narrowing down based on categorization reduced the results to 361 results in Web of Science and 240 hits in the Scopus subject database, respectively. Further narrowing down of the results based on an analysis of titles and abstracts yielded a final result of three publications in Web of Science and three results in the Scopus database. These were also checked for duplicates and access permission, leaving four publications for the final analysis. If this review was carried out without the synonyms introduced for the term digitization (technology, information, automation, innovation), then two hits were found in the Scopus database and only three hits for the subject database Web of Science. Similar to the generally very low search result, this result also shows the so-far low extent of power research in the context of digitization. For further consideration, therefore, the synonyms of the term digitization were consulted, and the synthesized results were interpreted in the context of digitization.

The gradual limitation of the search result is summarized in Table A1. The further steps of the review (content analyses) are presented in the following sections.

2.2. Descriptive Analysis: Characterising the Research Results and the Literature Surrounding Power in SCM

After the selection of the relevant literature, the next steps comprised the detailed analysis of the literature [14,15]. In addition to the small number of publications in the research area of power and digitalization, a separate descriptive presentation was dispensed, and the results are presented summarized. As illustrated in Figure 2, the consideration of power structures has become increasingly important in recent years. The maximum number of publications was reached in 2017, with a total number of 13 publications per year. The overall number of publications between 2014 and 2020 was an average of 3.4 publications per year. Next to the small average number of publications, the increase in the number of publications that has be taken in recent years proves the previously low but increasing significance of the research area.

Figure 3 illustrates the number of publications in addition the publisher. The research result shows a huge number of publishers which have only published a small total number of publications. Only a few journals have published more than two publications per year. The maximum number of eight publications per year was accounted by the journal *Supply Chain Management*, and other journals, such as Industrial Marketing Management, European Journal of Operational Research and the Journal of Supply Chain Management, have published six papers. By taking into account this small number of publications per year, the huge number of publishers proves the low significance of power research in the research area of the supply chain.

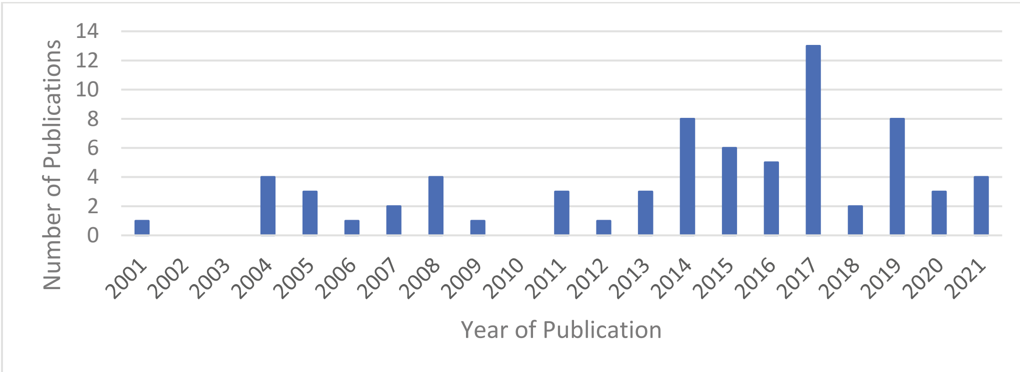

Figure 2. Number of publications per year.

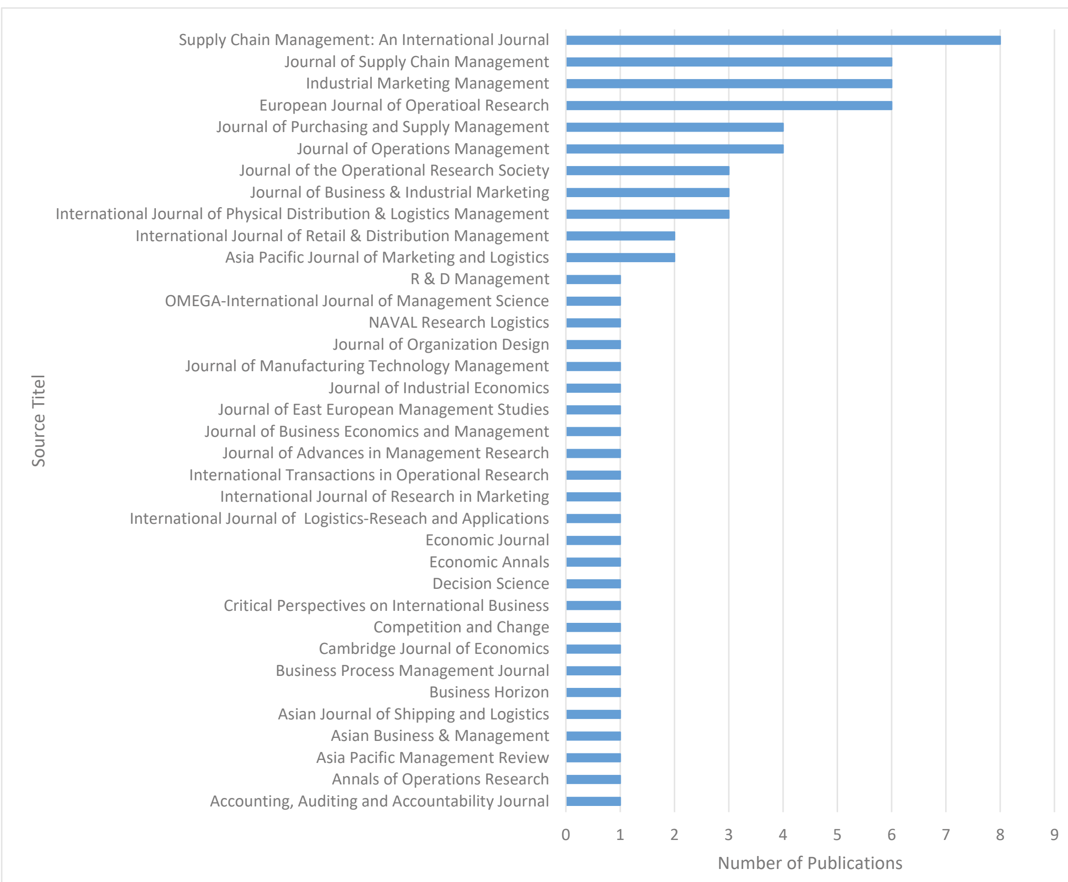

Figure 3. Number of publications per source.

The following section will illustrate the content analysis in more detail. It will present a general definition of power in the research area of SCM and also giving an overview about the state of the art of the present research about the influence of power the digitalization of the supply chain. This analysis will have two parts: the presentation of the general review result, and the illustration of the overview about the impact of power on supply chain digitalization.

3. Power within the Supply Chain: An Overview

The following section presents an overview of the research about power in supply chain management and digitalization in SCM. To do so, this section is structured according to the three research questions, presented in the beginning of this paper. It starts with a general overview of the definitions of power used in the research subject and a development of a general definition of the approach to power in SCM, followed by a categorization of the results, ending with and an overview of the subjects of power and digitalization in SCM.

3.1. Development of a Power Definition Approach in SCM

According to this research objective, it was necessary understand the concept of supply chain power and to develop a general power definition in supply chain management. In a first stage, it can be summarized that authors are referring to the definitions of El-Ansary/Stern [20] and Emerson [21], or referencing the theoretical contributions of French and Raven [16]. To develop a more general definition of the approach to power, any publication of both reviews was analyzed according to the used definition of the term of power. Summarizing these considerations and refer it to SCM power in context of this research is defined as: *Power is the ability to influence the* ***decision variables*** *of other supply chain participants, based on a* ***mutual dependency relationship****, regarding to the* ***participants' individual preferences****.*

This definition forms the basis for all further considerations in this research. Power is based on an individual ability, which is mostly based on a resource dependency, to influence decision variables of other supply chain actors, towards which power is applied in order to promote the achievement of one's individual cooperate goals [22–34]. The goals of this exertion of influence can range "from quality and delivery requirements to prices and contractual terms, through to issues of strategic direction, product development and competitive intelligence" [28]. The ability to exert influence here is anchored in the relationship between the actors and is rooted in the use of different influence strategies. An overview of the different influence strategies and influence mechanisms is outlined in Table A2 According to this definition of power, equal and symmetric relationships cannot be characterized by power. The term of power itself requests an asymmetric allocation in the ability of influence [5]. Referring to this, an asymmetric distribution of power can be understood as the unilateral capability of influence, so one actor in a dyad is in position to reach its individual goals by influencing the decision variables of the other.

According to the power bases theory of French and Raven [16], these influence strategies can be subclassified by mediated and non-mediated power strategies. Mediated power strategies are here considered to be constraints or legally based legitimations. Non-mediated power strategies include information power, expert power and referential power [22,35–38]. Following Benton and Maloni [22], the influence mechanism of reward should be listed separately under the categorization of reward-mediated power.

The analysis of the publications proved that a large part of the influence strategies is based on a resource dependency of the respective partners. Thus, 24 of the publications are directly related to the resource dependency theory (RDT), according to Pfeffer and Salancik [39]; in addition, other publications also describe an influence strategy that is based on resource dependency, which is described as a mechanism of influence with regard to the influence strategies coercion, reward, informational power and expert power. Legitimate power and referential power, on the other hand, are not justified on the basis of this dependence.

In addition to resource dependence, various authors refer to the incurrence of transaction costs or transaction cost economics (TCE) as an influential mechanism with regard to various influence strategies. Ireland [40] cites the creation of switching costs and the resulting costs for the change of supplier. Cox et al. [41] describe the occurrence of transaction costs as part of a negotiation process and link the goal of economic action with the avoidance of such costs. Based on these costs, they also refer to the number of alternatives and the development of switching barriers [22,24]. Furthermore, TCE can be found in the evaluation of the supplier relationship [23]. In addition to the RDT and the TCE, few other mechanisms of influence can be found in the literature. Ref. [42] referring to the influence of power through process integration and the resulting ability to influence decision-making processes through information/expert knowledge. Wang et al. [43] cite the same definition of power, but break down influence into market dominance and channel dominance. The resulting influence strategies increasingly refer to influencing price or channel strategies and are, however, also linked to the use of financial resources.

In summary, it can be highlighted that the term of power is composed on three different levels: the definition approach itself, influence strategies and influence mechanisms. The Figure 4 highlights these different dimensions of power, which could be used as a theoretical approach to analyzing the influences; for example, digitalization can have on the power allocation of the supply chain. Furthermore, this first analysis can highlight the variety of different definition approaches and the necessity to develop a more SCM-specific and empirically validated definition. This research offers a first concept, which can be used for further validation.

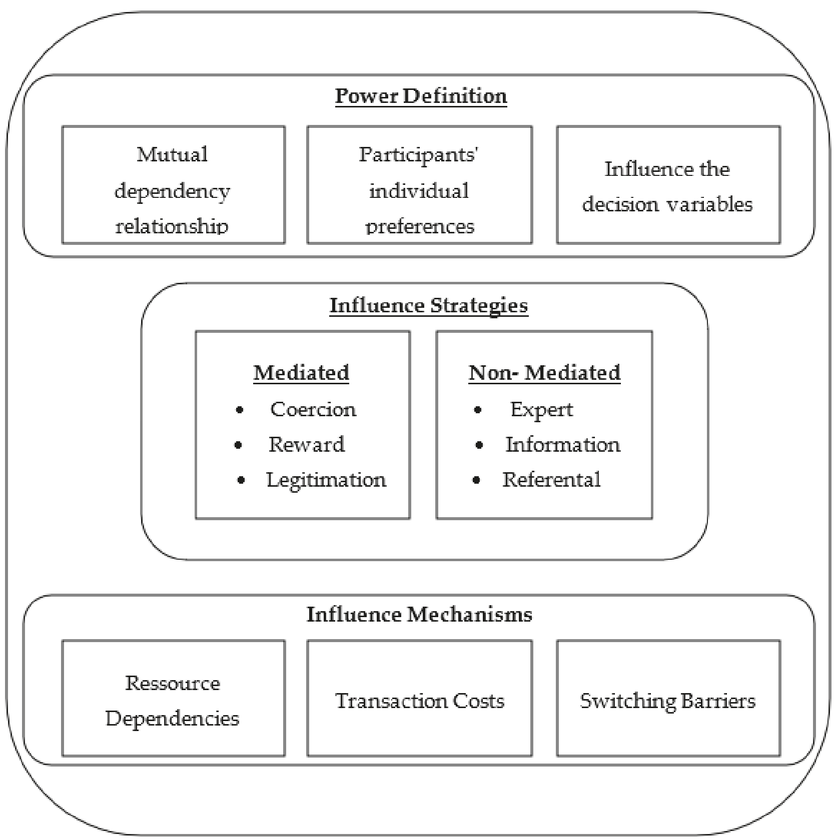

Figure 4. Dimensions of power.

3.2. Power as a Research Subject in SCM

According to the objective of this review, the results will be categorized and outlined in order to provide an overall picture of the research topic. Six superordinate categorizations of the research result, which are developed based on the research topics of each publication, can be highlighted. Every publication was assigned to the category it matches the most, which led to an overlap in some categories content. These focal points are presented in Table 3, which also presents the main keywords of this category.

Thus, various definitions of power repeatedly reference a resource dependency as the basis of individual power, although the respective emphases of the individual studies are set differently. The aspect of opportunism was a recurring element in the power research. It can be found in the considerations about bargaining power by Sheu and Gao [32] or Fabbri and Klapper [44], but was also taken up in the analysis of power strategies of the construction industry in the UK by [45], who linked power with the term of individual opportunism—the ability to assert one's individual goals in the face of resistance from others. An opportunistic behavior is, in this context, understood to be very closely connected, with a minimization of the total benefit, which can be seen as the cumulative benefit of all parties [46].

Table 3. Categorization of the research results.

Categories	Keywords	Author
Bargaining Power in the Supply Chain	Bargaining power; Dominance; Channel coordination; Negotiation; Buyer–supplier negotiation;	[25,27,32,47–49,59,60]
Power Structures along the Chain	Power Structure; Power dominance; Power Asymmetry; Chain Structure; Business networks; Influence Strategies; Resource Dependence Theory; Control power; Principal–Agent Paradigm	[29,42,45,50–54,61–69]
Influences of Supply Chain Design on Power Structures	Channel Dominance; Competition; Global sourcing strategy; Relationship initiation; Supplier attractiveness; Supplier selection; Channel selection	[55–57,70–73]
Strategies of Power and Supply Chain Relationship Management	Relationship; Relationship marketing; Supplier satisfaction; Power use; Sustainable supplier management; Customer value; Supplier value; Buyer–seller relationships; Channel relationships; Power; Power-imbalanced relationships; Market power; Power-dependence management	[22,24,28,30,33,34,36–38,46,58,61,74–81]
Collaboration and Power	Collaboration; Contractual Governance; Relational Governance; Supplier relationship; Dependence; Supplier orientation; Logistics triad	[78,82–87]

As well as the negative effects of an opportunistic behavior, the superordinate focus of symmetric power allocations in the chain can be highlighted in several publications and categorizations. Concerning the construct of power, the influences of opportunism and the influence of symmetric power allocations, there are only minor differentiations between all publications; furthermore, these categorizations are overlapping in several considerations, theories and results. However, differences can be found in the respective approaches to the topics of power, within the supply chain.

In a first superordinate category, the literature highlights an analysis of bargaining power or negotiation power in the supply chain. Based on the derivation of the bargaining power, different manifestations on the supply chain and the enforcement of individual goals can be justified. This category overlaps in content with the categories of power structures and power strategies discussed below. The availability of resources is associated with the bargaining power of individual partners in the supply chain and will have an influence on the negotiation process. Hereby, resources include material, financial resources and even the availability of information [25,27]. Another possible bargaining position can be generated by the creation of switching barriers. The respective negotiation strategy, the choice between reward or coercion strategies, has a decisive influence on the success of a negotiation situation. The enforcement of corporate goals, such as the enforcement of a pricing strategy, is positively influenced by the respective bargaining power of the contracting parties [47,48]. The transparent sharing of one's own negotiating position reduces the negative effects that can result from premature action [49].

The analysis of different dominance structures within dyads along the chain pointed out that opportunistic behavior will negatively influence the supply chain. Mutual dependencies between respective partners or a shift of power structures towards the customer side reduces opportunistic influence, which leads to a minimization of the total benefit [50]. Similar to the collaborative approach, the highest benefit is reached by a symmetrical distribution of power. Symmetric power relationships and strong ties between the parties can foster the will of individual suppliers/customers to invest in expanding these relationships and increasing total benefits [29,51]. Individual dominance strategies increase opportunistic benefits, but simultaneously it can negatively influence the supply chain's overall success [51]. In addition to the positive influence of innovative solutions—in this context understood as IT solutions—Deitz et al. [52] used this example by analyzing the influence of forced IT integrations. The empirical analysis shows the positive correlation of company liquidity on the implementation of forced measures, such as the introduction and integration of RFID chips in production. This power allocation can only be narrowed down for isoelastic demand, which induced a shift of the distribution of power towards the traders. In non-price-sensitive markets, in which the customer is strongly dependent on product availability, the total benefit can be increased more strongly by, e.g., pricing on the part of retailers than by process optimization on the part of manufacturers [53,54].

The analysis of different market structures or supply chain designs and their influence on power structures and supply chain performance forms the third category, which shows that the individual benefit can be maximized through an appropriate power position [55]. For example, a power position of the manufacturer can lead to an increase in production volume, a decrease in the "retail price and the largest expected surplus for an individual buyer" [56], on the other hand, the total "channel profit and the total consumer surplus" [56] can increase due to a power position of the retailer [56]. So, the market power structure will have a noticeable influence on the resale pricing strategy within multichannel service supply chains [57]. Due to the influence of the more powerful actor, the objectives and target achievements of the entire chain continue to differ, but the chains targets are often influenced by the most powerful member.

In addition to examining the power structures within the supply chain, further publications focus on the analysis of power strategies or strategies of exerting influence. These considerations also take up the investigation of the relationships along the supply chain and their influence on the performance of the supply chain. Although there is a major overlap with the previous section in terms of content, these publications differ in their focus on relationship management and power strategies. Cox et al. [41] highlight the meaning of individual power strategies, leaned against the power base theory, and a corresponding resource dependence. They emphasize the complexity of the various supply chain structures and suggest that each power strategy must be evaluated to the background of the individual requirements. Individual power strategies exhibit varying degrees of positive or negative effect on the supply chain relationships. Strategies of coercion, overriding mediating strategies, can significant negatively influence supply chain relationships, whereas non-mediating strategies have a significant positive effect. Strategies of reward turn out to be largely positive in terms of relationship quality within the supply chain and thus performance, but do not show a significant impact [22,25,37,58]. Assuming that power structures exist within each dyad, Maglaras et al. [34] and Takashima and Kim [24] show that corresponding factors of asymmetry negatively influence the respective relationship structures and performances, as well as the negative effect incompatibility of one's own objectives with those of the respective partners will have on the success of the supply chain by the mechanism of dependency, whereby Chicksand and Rehme [46] refer to value creation, which is based on the individual objectives and power strategies. Contrary to this, Hingley [58] point out that power is not to be seen negatively throughout, but asymmetries are present as a basic condition of all interactions, and only the use of a dependence leads to negative effects.

As part of supply chain relationship management, the factor of power is an effective tool for managing suppliers and customers. Symmetrical power relationships can be highlighted as one driving forces to maximizing benefits along the supply chain. Considering collaboration and the effects of symmetrical power structures within the supply chain, forms another, overarching research focus. Several publications take up the collaborative approach to supply chain design, in the context of analyzing power effects on supply chain performance. Referencing the power mechanisms Benton and Maloni [22], the literature pointed out the positive influence mechanisms of non-mediated power strategies on supply chain success. Similar to non-mediating power strategies, which positively influence supplier relationships quality, a collaborative strategy also has a positive effect on supply chain performance by aligning strategic goals [86]. Collaboration, however, does not change the power structures in the chain, rather it creates a shared decision horizon and joint strategies, in which decisions are made for mutual benefit. Resource dependencies, the monetary strength of individuals and the asymmetric information relationships remain, but can be softened with regard to the joint achievement of goals. Therefore, it is necessary to know about one's own individual market position, the market as a whole and possible influence strategies, and to include this knowledge in the strategy development [36,61,62].

The final categorization forms the element of trust and its influence on power structures and supply chain performance. This category increasingly overlaps with the topic of collaboration. The recognition of an authority increases the confidence in the respective power position, from which an increase in the respective influence results, whereby this is not regarded as negative or opportunistic. Creating a common identity has a similar effect. This also increases trust among the different supply chain members and strengthens the power structures along the supply chain. Inter-organizational interfaces also have a trust-building effect; for example, they promote the exchange of information and thus increase the degree of trust and the associated benefits for the supply chain. Finally, perceived equity is asserted as an influencing factor on trust within the supply chain by [88]. According to supply chain governance approach, the level of trust is positively influenced by the degree of information sharing and thereby increases the common benefit. Trust here represents the basis for creating long-term strategic partnerships, across the presence of asymmetrical power distributions [26,89]. The more trustworthy a supplier/customer is, the better the individual's respective competitive position. The size and market power of a company increases the corresponding trustworthiness [35].

3.3. Power and Supply Chain Digitalization

The following section analyzes the reviewed literature, linked to the research area of SCM and digitalization. The concept of supply chain digitalization in this review is associated with technological improvements, such as IoT, CPS and smart products, as well as being driven by technologies such as big data, etc.; however, to avoid technological specialization, this review focusses on general terms, such as digitalization, etc. Including the preceding considerations about supply chain digitalization, the collection and analysis of data will become a critical resource in the chain. Overall, it can be concluded that the concept of power is only addressed in a very rudimentary way in relation to supply chain digitalization. Several publications are dealing with the impact of information availability on collaboration or relationship quality. Further results can be mentioned in the impact of new business models, such as e-Commerce, on supply chain structures and supply chain design. Based on the induced restructuring of the chain and value creation, first approaches about the relation between digitalization and supply chain power structures can be elaborated.

Based on this assumption, information sharing can be used as an influence mechanism of power; furthermore, it will have an impact on the level of collaboration, by influencing the level of trust. Vendrell-Herrero et al. [10] hereby lead a bidirectional perspective on the theorem of power: digital servitization can strengthen the power position of downstream companies, if they gain control over the connection channels to consumers; furthermore, a strengthening of the position of upstream companies can be demanded by regaining a resource dependency. In addition to the use of information as an influence mechanism of power, Vendrell-Herrero et al. [10] link the concept of digital disruptive technologies and business models to the analysis of enterprise collaborations within supply chains. The use of digital technologies enables companies to introduce new products or distribution channels, leads to a change in value creation, such as corporate processes, and ultimately changes competition in the market [8,90]. By considering the availability of information and the capability of data analysis, data processes have become another central resource of the chain, which influences the power allocations.

Referring to the principal–agent theory, power asymmetries in the chain can be deduced in dependency to information's availability. The allocation of information is asymmetric allocated on side of the agent, who can decide which information it is willing to share with the principal. However, informational availability or expert knowledge can be understood as mechanisms of coercion or reward. Information sharing, depending on the individually chosen corporate strategy, can on the one hand promote the consolidation of collaborative strategies, but on the other hand, only the withdrawal of information availabilities or knowledge can be used as a strategy to expand asymmetric power distributions [89]. As an example, this development in value creation, induced by digitalization, can be located in the more original, end-customer-oriented sales landscape of stationary retail, where the final customers make their procurement decisions in the stationary store, which also takes over the functions of the warehouse logistics. One of the main objectives of the stationary trade concerns the reduction in transaction costs. This creates a corresponding power position of stationary retailing—on the one hand, there is a customer proximity, and their purchase behavior can be analyzed, on the other hand, further instances and tasks of the supply chain takes over. With the growth of e-commerce platforms or mobile shopping, the supply chain expands to include another actor. The power structures within the chain shift accordingly. Like brick-and-mortar retail, e-commerce platforms meet the needs of the end customer and expand their market share. Similar to stationary retail, the platforms receive information about the customer's preferences, but at the same time they reduce transaction costs on the customer side through significantly increased transparency and comparability. Distinctions are primarily found in logistics—the transport of products to the customer. In addition to the reduction in transaction costs, they point out various influencing factors that distinguish digital commerce from analog commerce and establish added value for the customer. Furthermore, they cite customizability, spatial independence and corresponding interaction as added value. In these factors, Reinartz et al. [9] justify the increase in power that digital sales models gain over analog sales models.

Digitalization leads to changes in value creation and competition, further to a growth of digital monopolies, and so it is influencing the allocation of power in the chain [90]. Similar to the approaches of Reinartz et al. [9], Subramaniam [90] shows that digitalization creates value when processes or collaborations can be made faster and more easily due to digital measures, thus creating a competitive advantage in the market. Market entry barriers, such as physical availability of products and raw materials or product developments, are no longer the only limiting factors. The analysis and availability of data is becoming increasingly important. Following Subramaniam [90], it can result in a monopoly position that is both product-associated and data-driven. With regard to the consideration of digital monopolies, he concludes that the original definition of a monopoly, tied to the respective market shares, is no longer sufficient.

4. Concluding Discussion

The objective of this research was to analyze the scientific literature according to the merge of power in SCM and the research field of supply chain digitalization; therefore, assertions about the influences of asymmetric allocations of power, in addition to the trend of digitalization of the supply chain, can be made. The accomplishment of this objective is based on three basic elements: by developing a general definition of power, this research identifies RDT and TCT as the main influencing strategies of power on supply chain power allocations. Digitalization changes the competitive environment and the channel structures, so it can lead to emphasized asymmetries of power. Thereby, information technologies offer opportunities to reduce barriers in communication or information sharing.

4.1. Theoretical Implications

This literature review pointed out that research concerning objective power is becoming increasingly important in supply chain research, but these results are often theoretical and based on model assumptions. The research field of power overlaps with the research of collaboration, supply chain relationship management and supplemental, often simulative, game theoretical analysis about the impact of different dominance structures in supply chain management. The present research mostly focused on the influence of opportunistic behavior, not the influence of power structures, and its impact to the total supply chain benefits. Further superordinate research focusses can highlight the effects of asymmetric power allocations and how these will influence supply chain design or strategy. Thus, the research indicates a clear objective regarding the monetary influences that power can have on the supply chain. This review provides the first overview highlighting a few research gaps.

Basically, on this first level, the necessity for developing a general, SCM-specific definition approach about power and proving it on an empirical level can be highlighted. The present research offers a huge variety in the number of definitions and matches with other research areas in SCM.

In summary, the influences of asymmetric power allocations and strategic considerations are rarely considered within current research, but can derived from the influences of opportunism or symmetric power allocations. On this second level, the research about power in SCM is developing, but most results are grounded in the considerations of collaboration or opportunistic behavior, so there is also a lack of empirical confirmation and further theoretical research. Further research should to prove the results and definition approaches of this review on an empirical level, or could use the results presented here for some theoretical improvements. The main problem for this research area will be the delimitation of the concept of power in order to be able to elaborate actual further results. Possibilities for this are likely to be provided by qualitative research.

Thus, in this second level, it can be highlighted that the concept of power is frequently used, but is not detailed elaborated and empirically proved; accordingly, however, the first theoretical results overlap with collaboration, etc., so this can be used as a foundation for further concepts.

Although informational power is already used as one of the power bases of French and Raven [16], the influences of digital technology and its disruptive influence on the power structures of the supply chain are only superficially elaborated. The trend of digitalization and the changed competitive environment is considered but is only researched on a rudimentary level.

Further considerations of the influence of digital power and the derivation of strategic implications are completely lacking within these discussions. In particular, further research can, for example, focus on the influence of digitalization on the different levels of the power term, which has been developed in this paper. It will be the main challenge to deduce how the digital environment influences the different dimensions of power in SCM. Table 4 highlights the various research gaps that can be identified in this review, and further its outlines a basic research framework.

Table 4. Research gaps concerning power in SCM.

Research Focus	Research Gap
Generalizable SCM Power Definition	Empirical validation
Influence Strategies	Empirical validation of Power bases in SCM
Influences of Power on SCM Strategy	Theoretical contributions and empirical validation
Similarities of Collaboration/Opportunism and Power research	Theoretical contributions
Power and SC digitalization	Theoretical contributions and empirical validation

4.2. Managerial and Political Implications

From a management point of view, the knowledge about the influences of different power structures on the chain can be helpful tool for risk or resilience management and the strategic supply chain design. As shown before, the trend of digitalization is inducing huge changes in the markets and processes. In this more complex, competitive environment, every actor must deal with an increasing amount of information, interfaces and increasingly complex requirements of the market. The knowledge about these challenges and influences of power will improve the performance of every single actor and the whole supply chain. So, it can be useful to analyze the companies and the supply chain perspectives separately. On the company tier, it will be necessary to define your own market position and influence variables, which other companies can use to influence your decisions. This information will help you to increase your market share and decrease the influence of other participants on your behavior. Additionally, the knowledge about the individual long-term company goals will be helpful to deal with these market challenges. From a supply chain point of view, the knowledge about the power structures, different individual goals and the overall supply chain goal will be helpful to improve the overall supply chain benefits and create a long-term-orientated chain. Opportunistic influences of individual companies can be reduced or blocked, reducing the opportunistic behavior which can be implemented.

4.3. Limitations of the Research

The objectives of this research were to investigate the research gap concerning power in supply chain research in the context of digitalization and to develop a research framework for further research. To do so, a literature review was conducted. Fundamentally, the term of power in SCM is only used on a superficial level and defined qualitatively. In a first stage, it can be highlighted that the results about power in the state-of-the-art research are characterized by a degree of fuzziness, which negatively influenced these results; furthermore, it is one of the main objectives of this research to develop a general SCM-specific definition approach to decrease this degree of fuzziness for some further research. Furthermore, the definition of a search term for this review is influenced by this degree of fuzziness, as well as the lack of empiricism and the fact that all results are based on theoretical constructs reinforces this impression.

This review is primary limited by the subjective influences of the researchers in the selection of the search term and the limitation criteria, as well as the degree of fuzziness in the definition of the term of power in the overall research and the selection of relevant papers based on abstracts/titles. Fundamentally, the search term selection is based on the systematic classification of the subject area in the scientific foundation, but this classification is characterized in its design by subjective influences of the research process and the researchers. Based on this fact, as shown in the results and in the fact that most publications in this subject refer to just a few of the same theoretical contributions, this subjective influence can be minimized. All these limitations and categorizations have to be reviewed according to these possible subjective influences, and have to be verified in further research. Further research must verify the selection process of the papers to increase the objectivity by, for example, using larger groups of researchers and carrying out pretest validations.

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Appendix A

Table A1. Research results per limitation stage.

Review 1		
	Web of Science	**Scopus**
First research results	8574	22,661
Limitation based on categorizations	1481	953
Limitation based on title and abstract	68	46
Limitation based on accesses and duplicates	67	
Review 2		
	Web of Science	**Scopus**
First research results	2004	5872
Limitation based on categorizations	361	240
Limitation based on title and abstract	3	2
Limitation based on accesses and duplicates	4	

Table A2. Influence mechanisms and strategies of power.

Author	Resource Dependency Theory	Further Influence Strategies
[76]	X	Transaction Costs Theory
[45]	X	
[22]		Transaction Cost Theory/Number of Alternatives
[23]		Transaction Costs Theory
[58]	X	Transaction Costs Theory
[25]	X	
[88]	X	
[26]	X	
[86]	X	Transaction Costs Theory
[65]	X	
[81]		
[32]	X	
[91]	X	
[89]	X	
[33]	X	
[66]	X	

Table A2. *Cont.*

Author	Resource Dependency Theory	Further Influence Strategies
[35]	X	Transaction Costs Theory
[36]	X	
[24]	X	Transaction Cost Theory/Number of Alternatives
[47]		
[74]	X	
[63]	X	
[82]	X	
[38]	X	
[64]	X	Transaction Costs Theory
[46]	X	
[83]	X	
[70]	X	

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Review

From Supply Chain 4.0 to Supply Chain 5.0: Findings from a Systematic Literature Review and Research Directions

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Abstract: The main purpose of this paper is to present what the Industry 5.0 phenomenon means in the supply chain context. A systematic literature review method was used to get evidence from the current knowledge linked to this theme. The results have evidenced a strong gap related to Industry 5.0 approaches for the supply chain field. Forty-one (41) publications, including conference and journal papers, have been found in the literature. Nineteen (19) words, which were grouped in four (4) clusters, have been identified in the data analysis. This was the basis to form the four (4) constructs of Industry 5.0: Industry Strategy, Innovation and Technologies, Society and Sustainability, and Transition Issues. Then, an alignment with the supply chain context was proposed, being the basis for the incipient Supply Chain 5.0 framework and its research agenda. Industry 5.0 is still in an embryonic and ideal stage. The literature is scarce and many other concepts and discoveries are going to emerge. Although this literature review is based on few available sources, it provides insightful and novel concepts related to Industry 5.0 in the supply chain context. Moreover, it presents a clear set of constructs and a structured research agenda to encourage researchers in deploying further conceptual and empirical works linked to the subject herein explored. Organizations' leadership, policymakers, and other practitioners involved in supply chains, and mainly those currently working with Industry 4.0 initiatives, can benefit from this research by having clear guidance regarding the dimensions needed to structurally design and implement an Industry 5.0 strategy. This article adds valuable insights to researchers and practitioners, by approaching the newest and revolutionary concept of the Industry 5.0 phenomenon in the supply chain context, which is still an unexplored theme.

Keywords: Supply Chain 5.0; Supply Chain 4.0; Industry 5.0; Industry 4.0; literature review; research agenda

1. Introduction

The Industry 4.0 phenomenon has fostered several discussions among both academics and practitioners. The theme of Industry 4.0 was initially introduced in 2011 at the Hannover Fair—Germany [1]. Nowadays, Industry 4.0 is being considered as one of the main topics of the World Economic Forum's agenda and many countries' government agendas [1–5]. Industry 4.0 strategy impacts directly on the global competitive market, being a true source of value creation [6,7].

In the wave of Industry 4.0, several discussions and developments have been deployed through different countries and industry sectors [8–11]. Additionally, many topics of research have been deployed to create a better understanding of how this revolutionary phenomenon relates to other knowledge areas. Among these are included the themes of product development [12], performance measurement [13], small and medium enterprises—SMEs—in Industry 4.0 [14], production planning and control [15], strategic management [16], organizational structure [17,18], servitization [19], sustainability [20,21], and lean manufacturing [22,23].

Especially in the supply chain context, few studies have been deployed to get evidence regarding the influence of Industry 4.0 and its disruptive technologies on the supply chains.

Research that stands out with regard to this specific subject has been communicated by [24–32]. Some of these authors denominate the relation between Industry 4.0 and supply chains as Supply Chain 4.0. In their studies, there is a certain consensus that Industry 4.0 in supply chains means much more than only technology adoption. It involves understanding the capabilities required (e.g., infrastructure, people skills, coordination) to effectively implement Industry 4.0′s technologies as well as generate the impact of these technologies on supply chains' performance criteria (e.g., transparency, responsiveness, efficiency, flexibility) and strategic goals.

Although Industry 4.0 is still in an initial stage, some concerns have been raised by researchers and practitioners concerning the role of humans amid this new technological environment. Some researchers have recently approached the role of humans in the Industry 4.0 context (e.g., Refs. [33–38]. Specifically, for the context of supply chains and logistics, Ref. [39] have discussed this issue, taking into consideration the role of logistics operators amid the surge of Industry 4.0′s technologies context. Hence, the still visionary idea of Industry 5.0 has emerged in contrast to the paradigm that robots will dominate the industry environment. For instance, Ref. [40] argue that the highly automated environment allowed by Industry 4.0 puts humans at risk of no longer playing a valuable role. According to these authors, there is a relevant consensus that the era of robotics and automation in previous industrial revolutions brought about paradigm shifts in the manufacturing industry worldwide. Yet, they reinforce that although Industry 5.0 has still to be materialized, the same will occur with this new revolution, mainly because the set of technologies established with the Industry 4.0 phenomenon has been implicated in new paradigms.

This new trend defends a conciliating perspective of human–robot collaborative work [41,42]. Ref. [43] argues that policymakers and CEOs are overestimating the power of disruptive technologies (e.g., artificial intelligence, internet of things—IoT), since they are not focusing on the real innovation and effective potential of those technologies when properly interacting with human skills. In parallel with the Industry 5.0 concept, an approach proposed by Japan called Society 5.0 has also attracted attention from the scientific and practical audience. The terminology Society 5.0, also known as Super Smart Society, has been initially presented in the Fifth Science and Technology Basic Plan, which has been elaborated by the Japanese Council of Science, Technology and Innovation in 2016 [41].

Some authors have tried to clarify the interplay between Industry 4.0, Industry 5.0 and Society 5.0. For instance, according to [44], while Industry 4.0 is more concerned with the application of disruptive technologies, Industry 5.0 is focused on allowing a Society 5.0, with a sustainable human-centered society, by the use of those technologies from Industry 4.0. These authors also emphasize that it is challenging to create a Society 5.0 by incorporating the disruptive technologies from Industry 4.0. For [45], a Society 5.0 goes beyond the boundaries of technological and organizational transformation of the industrial system. It involves considering social and human aspects to achieve a sustainable environment in this technological context. Ref. [46] point out that Society 5.0 uses advanced technologies and products to connect people and things, share knowledge and information, and then create new social and business chains and values in society. From the industry aspect, these authors state that a Society 5.0 environment frees humans from exhausting routine work by exploring the advantages of Industry 4.0′s technologies. Society 5.0 also helps in overcoming social problems by eliminating several social constraints.

Ref. [47] emphasize that Industry 5.0 combines robots with human brains, which enhances the potential for developments quickly. Thus, the 'cobot' concept is one of the key elements of the upcoming industrial revolution. This concept of the cobot means working intelligently in the factory environment by the application of artificial intelligence, big data analytics, IoT, and other disruptive technologies, implying productivity improvement, wastes reduction, and the enhancement of sustainable goals. The main purpose of the Industry 5.0 idea is to foster the role of human beings in the manufacturing environment [47]. Moreover, some authors have affirmed that Industry 5.0 will allow personalized products on a mass scale, adding high value to the customers [47–50]. Additionally, intelligent robots and systems will influence supply chains to an unprecedented level [51,52] point out that Supply Chain 5.0 is a trend which will involves three main perspectives: collaborative work between humans and robots (cobots), mass customization, and personalization to customers, and a super smart society (Society 5.0).

Although Industry 5.0 may still appear a premature and visionary idea, and the literature about it is scarce, this new revolutionary phenomenon is already being discussed by some of the organizations that are just now implementing Industry 4.0′s programs. While Industry 4.0 creates the foundation for the smart factory, Industry 5.0 is the era of a social smart factory, because every single cooperative building block of a CPPS (cyber–physical production systems) will be able to develop communication with humans through the enterprise social networks. Actually, humans will be asked to collaborate with CPPS and complement the virtual and robotic elements of the automated production systems by the use of disruptive technologies, fostering faster and intuitive workflows [42].

Differently from the Industry 4.0 phenomenon, regarding Industry 5.0, there is a large gap related to what this fifth industrial revolution will mean to supply chains. In a search conducted in the Scopus and Web of Science databases, it was possible to identify that, although there are already papers approaching Industry 5.0 and Industry 4.0 relations, with regard to the supply chain subject the Industry 5.0 phenomenon is completely unexplored. Besides the lack of available knowledge regarding Industry 5.0 in the supply chain context, the gap relates to the fact that supply chains play a crucial role by providing services and products to society and the advancements of the Industry 5.0 phenomenon are going to certainly affect supply chain processes and members. Therefore, a proper understanding in respect to the relationship between Industry 5.0 and supply chains becomes paramount.

Therefore, this paper aims to present a novel perspective based on evidence obtained through the systematic literature review method. This new approach is herein called Supply Chain 5.0. Based on what has been contextualized in this Introduction section, this research aims to investigate the interplay between Industry 5.0, Industry 4.0, and Supply Chains as demonstrated in Figure 1. Figure 1 also links the research gap, as presented in this section, with the research questions′ formulation.

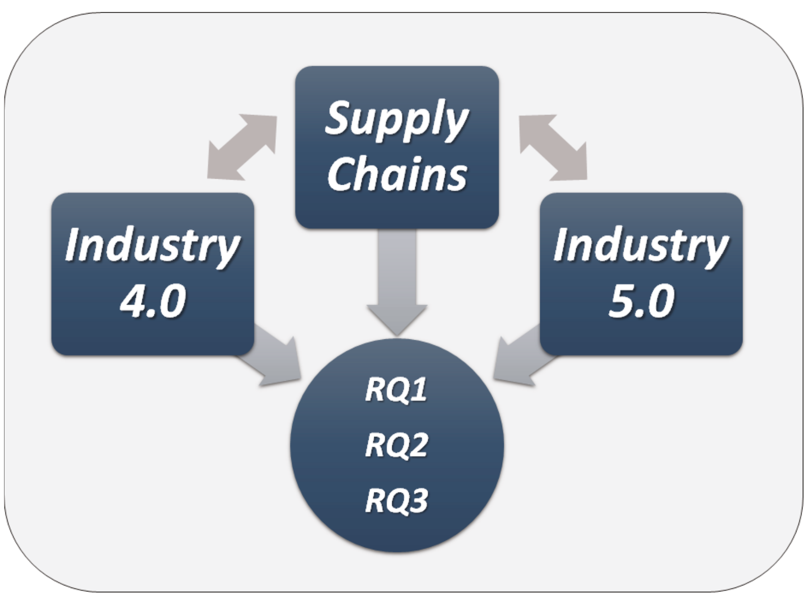

Figure 1. Research scope.

Therefore, with the purpose to guide this research, three research questions were established as follows:

RQ1—What are the constructs which form the concept of Industry 5.0?

RQ2—How can Industry 5.0′s constructs be aligned with the supply chain context?

RQ3—What are the main research questions related to Supply Chain 5.0, which should drive further research deployments?

Firstly, a systematic literature review focused on Industry 5.0 knowledge is conducted, to find any papers addressing the relationship between Industry 5.0 and supply chains. This aimed to understand the constructs related to this new phenomenon (**RQ1**). Then, an alignment between those constructs and the current knowledge about supply chains and Industry 4.0 interaction (i.e., Supply Chain 4.0) is proposed, with the purpose to provide a novel vision related to the relationship between Industry 5.0 and supply chains—SC 5.0 (**RQ2**). Based on this, some research questions are proposed to establish an initial research agenda regarding the relationship between Industry 5.0 and supply chains (**RQ3**).

This paper is structured as follows. This Introduction section contextualized and introduced the theme, motivation, and research gap of the present paper. The second section covers the systematic literature review method. The third section presents the findings gathered from the literature review. The fourth section presents the alignment between Supply Chain 4.0 and Supply Chain 5.0 as well as a research agenda with some research pathways related to Supply Chain 5.0. The fifth section ends this paper with conclusions containing theoretical and practical implications.

2. Systematic Literature Review

The systematic literature review is a robust method that effectively supports the exploration of unknown research issues. It is crucial to establish constructs and build theories that give support to empirical works [53]. According to [54], a systematic literature review can be divided into three steps: planning, conducting, and reporting. The planning phase refers to the establishment of search keywords, search databases, and search period. In the first phase, the search is undertaken, involving the screening of the first sample of articles. In this phase, inclusion and exclusion criteria are applied; the conduction of data analysis and elaboration of syntheses closes the phase. In the last step (reporting), results are structurally presented based on the relevant articles' sample analysis. With regard to results presentation, Ref. [55] suggest the matrix technique, which is an effective manner to properly make the transition from an author-centric to concept-centric approach. This research followed the three steps of [54] approach. Additionally, in the reporting phase, the technique suggested by [55] was used.

2.1. Planning the Literature Review

In the planning phase, two databases were chosen: Web of Science and Scopus. These are the most relevant search databases, covering the majority of scientific journals. In the sequence, keywords and their combination for the search were defined: "Industry 5.0", "Supply Chain", "Society 5.0" and "Industry 4.0". The chosen places for search in the articles were in the title and abstract and only journals and conference papers were considered. The period for the search of articles was from 2015 up to 2021. The year of 2015 was chosen as the start of the period because it was in this year when the Industry 5.0 theme has commenced to be discussed.

2.2. Conducting the Literature Review

In this step, the first sample of articles was identified. A total of 330 articles were first extracted from the databases. Then, the inclusion and exclusion criteria were applied by reading articles' abstracts. The exclusion criterion was articles out of the scope and duplicated articles. There were articles which only mentioned one of the keywords; however, they did not reflect the main approach aim for this research. The inclusion criterion was articles that had as the main subject a combination of the keywords defined for the search (i.e., Industry 5.0, Supply Chain, Society 5.0, and Industry 4.0).

It is important to emphasize that it was not possible to identify articles addressing the relationship between Industry 5.0 and supply chains, confirming the gap which this research aims to cover. Then, after the screening of the sample of 330 articles, 41 articles were considered as relevant for the study herein considered, as demonstrated in Table 1. Figure 2 details the conduction of the systematic literature review process, considering the planned criteria.

Table 1. Forty-one relevant articles were extracted from the Web of Science and Scopus databases.

	Authors	*Source Title*	*Purpose*	*Database*
1	[56]	Journal of The Knowledge Economy	The purpose is to investigate the implementation of a smart environment for Industry 5.0 and Society 5.0. The case investigated is in the aviation industry sector.	Web of Science and Scopus
2	[43]	AI & Society	This paper discusses the aspect of human interaction with Industry 4.0's technologies and the trend towards Industry 5.0.	Web of Science
3	[44]	Sustainability	Its purpose is to study the use of OD (open data) in Industry 4.0, enabling a Society 5.0. They discovered that the bridge between Industry 4.0 and Society 5.0 is focused on technologies supporting the creation of a physical-to-digital-to-physical loop to ensure the sustainable development of a human-centered society.	Web of Science and Scopus
4	[57]	IPSI BGD Transactions on Internet Research	This research aimed to identify challenges and opportunities for implementing the concepts of Industry 4.0 and Society 5.0 in Russia, using a case study method.	Web of Science
5	[58]	IOP Conf. Series: Earth and Environmental Science	This paper brings a discussion regarding the benefits of Industry 4.0 and Society 5.0 for the real state and construction industries.	Scopus
6	[59]	Sustainability	This work refers to a survey carried out in Turkey, which investigates the relationship between Industry 4.0 and Society 5.0 in the context of Sustainable Development Goals—SDGs.	Scopus
7	[40]	Lecture Notes in Mechanical Engineering	This article is an investigation regarding human skills required for synchronization of robots in the Industry 5.0 environment.	Scopus
8	[60]	Lecture Notes in Mechanical Engineering	This research investigated the enablers for Industry 5.0 in the Indian manufacturing sector.	Scopus
9	[61]	Lecture Notes in Mechanical Engineering	This article presents the main conceptual differences between Industry 5.0 and Society 5.0.	Scopus
10	[62]	Journal of Industrial Integration and Management-Innovation and Entrepreneurship	This paper explores major technologies of Industry 5.0 which can be applied to the COVID-19 pandemic in the health sector.	Web of Science and Scopus
11	[63]	AATCC Review	This article presents the development of functional fiber computing for the textile industry in the context of Industry 5.0.	Web of Science and Scopus
12	[64]	Sustainability	This study examines how Industry 4.0 features and enabling technologies can support the transition to Society 5.0. It also investigates the roles of both open innovation and value co-creation within this transition.	Web of Science and Scopus

Table 1. *Cont.*

	Authors	*Source Title*	*Purpose*	*Database*
13	[41]	Journal of Knowledge Economy	This article presents a discussion regarding nuclear fusion energy through the lens of Industry 5.0 and Society 5.0.	Web of Science and Scopus
14	[47]	Journal of Industrial Integration and Management-Innovation and Entrepreneurship	This paper is a discussion about Industry 4.0 and Industry 5.0 and presents the main capabilities and elements needed to implement Industry 5.0 in the manufacturing industry.	Web of Science and Scopus
15	[42]	Applied Sciences-Basel	This paper covers the value-oriented and ethical technology engineering aspects of Industry 5.0, evidencing the findings through a survey of industry leaders from different companies.	Web of Science and Scopus
16	[46]	Kybernetes	This article discusses the relationship between Society 5.0, Industry 4.0, responsible economic development, and social problems solutions through the enhancement of corporate social responsibility (CSR) in organizations.	Web of Science and Scopus
17	[50]	Information	This research presents an innovation management framework—absolute innovation management (AIM)—as an innovation ecosystem for the Industry 5.0 context.	Web of Science and Scopus
18	[65]	International Review	This article provides a general view regarding actual development directions of the concepts of Industry 4.0 and Society 5.0, taking into consideration the context of sustainable development.	Web of Science
19	[66]	Intelligent Distributed Computing XIII	This article presents a conceptual model of an advanced digital platform for adaptive management of enterprises considering the context of Industry 5.0.	Web of Science and Scopus
20	[67]	Energy Conversion and Management: X	It considers aspects of the transition from Industry 4.0 to Industry 5.0 in the algae industry.	Scopus
21	[68]	Journal of Asian Finance, Economics and Business	The article is a discussion regarding cyberloafing effects through the lens of Industry 4.0 and Society 5.0.	Scopus
22	[69]	Journal of Physics: Conference Series	This work demonstrates a conceptual approach of a control system of multitasking between Society 5.0 and Industry 5.0.	Scopus
23	[70]	IOP Conference Series: Materials Science and Engineering	This paper presents the intelligent complex security management system for Industry 5.0 (FEC—fuel and energy complex), based on the Russian human–machine concept.	Scopus
24	[71]	IOP Conference Series: Materials Science and Engineering	This article provides an approach related to condition-based maintenance (CBM) and machine learning of artificial intelligence (MLAI) considering the context of Industry 4.0 and Society 5.0.	Scopus
25	[72]	AIP Conference Proceedings	This paper discusses the main technologies for the Industry 5.0 manufacturing systems design.	Scopus
26	[73]	Lecture Notes in Mechanical Engineering	This article proposes some areas that will need to be addressed with regard to the Industry 5.0 trend.	Scopus
27	[74]	CEUR Workshop Proceedings	The purpose of this study was to determine the level of readiness of municipalities in the Samara Oblast area to introduce Industry 5.0 technologies.	Scopus

Table 1. *Cont.*

	Authors	*Source Title*	*Purpose*	*Database*
28	[75]	European Journal of Molecular & Clinical Medicine	This article presents the main current technological developments of Industry 4.0 and future modifications for the Industry 5.0 context.	Scopus
29	[76]	Proceedings of the 5th North America International Conference on Industrial Engineering and Operations Management	This paper proposes a model of food product innovation for food manufacturing SMEs considering the trends of Industry 5.0 and Society 5.0.	Scopus
30	[51]	Sustainability	This paper introduces the concept of Industry 5.0 as well as presents key features and concerns related to Industry 5.0.	Web of Science and Scopus
31	[45]	International Scientific Conference Digital Transformation on Manufacturing, Infrastructure and Service	This paper presents the relationship between the objectives and goals of sustainable development and the concepts of Industry 4.0 and Society 5.0.	Web of Science and Scopus
32	[77]	4th Annual Applied Science and Engineering Conference	This research investigates the feasibilities and challenges of the implementation of fintech in small and medium industries in the Society 5.0 era.	Web of Science and Scopus
33	[78]	Next-Generation Spectroscopic Technologies XII	This paper explores the use of smartphone applications in Industry 4.0 or Society 5.0 applications.	Web of Science and Scopus
34	[79]	Proceedings of the 2019 IEEE International Conference of Quality Management, Transport and Information Security, Information Technologies	This article discusses the main technologies and approaches which will contribute to the transition from Industry 4.0 to Industry 5.0.	Scopus
35	[80]	Procedia Computer Science	This article presents a discussion related to Industry 5.0, especially linked to the human–robot co-working issues from an organizational and human relations perspective.	Scopus
36	[49]	International Journal of Recent Technology and Engineering	This study presents an innovative model to support the transition from Industry 4.0 to Industry 5.0.	Scopus
37	[81]	OMICS-A Journal of Integrative Biology	This paper presents a vision of Industry 5.0 based on big data, the internet of things, and artificial intelligence.	Web of Science and Scopus
38	[48]	Journal of Clinical Orthopedics and Trauma	This article discusses the main applications of Industry 5.0 and their benefits to the medical industry.	Scopus
39	[82]	Zigonghua Xuebao/Acta Automatica Sinica	This paper proposes a system architecture for the nuclear power industry considering the Industry 5.0 context.	Scopus
40	[83]	Engineering	This research investigates how Industry 5.0 may impact the development of bionics (synthetic biology)	Web of Science and Scopus
41	[84]	Zigonghua Xuebao/Acta Automatica Sinica	In this paper, a new framework called Energy 5.0 is proposed, taking into consideration interactions and trends of energy and industry development as well as other advances.	Scopus

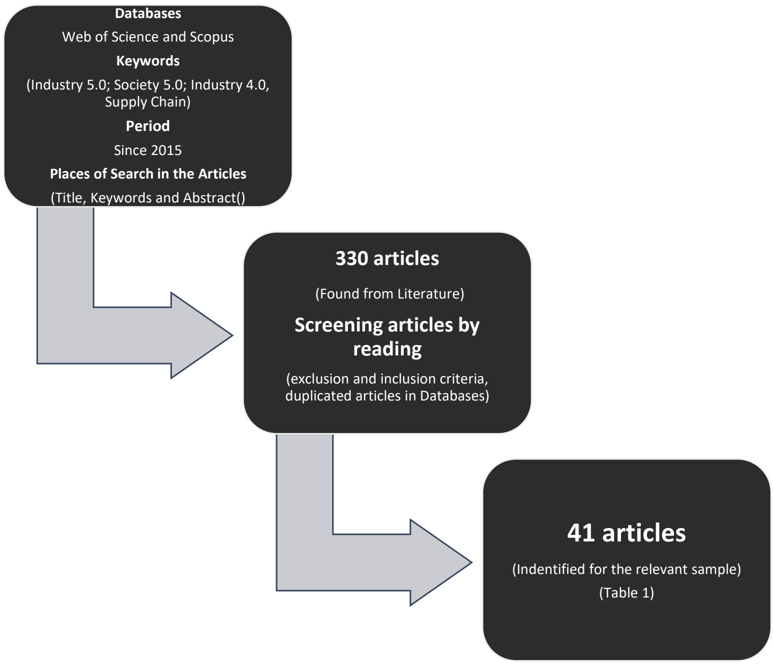

Figure 2. The systematic literature review process.

2.3. *Reporting the Literature Review*

After the conduction of the literature review, it was possible to analyze the forty-one (41) articles. Based on Table 1, it is possible to see how recent are publications related to Industry 5.0, the first publication being in 2015.

Figure 3 demonstrates the evolution of publications during the time since 2016. This shows why there are still few publications in the field. Considering that the year 2021 is still in the first quarter, the trend seems to be significantly high.

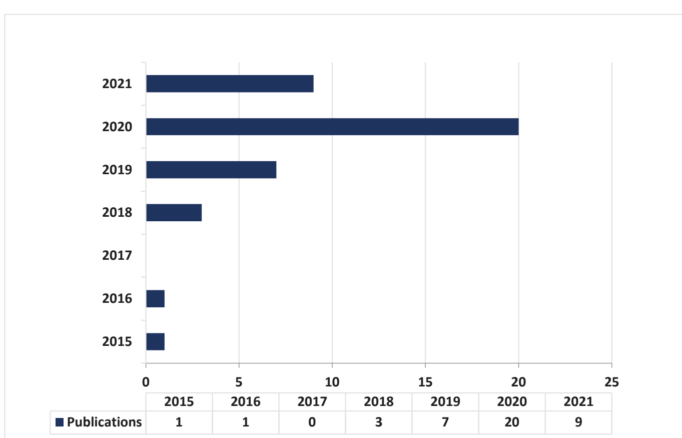

Figure 3. Quantity of publications since 2015 related to Industry 5.0.

Other evidence from Table 1 is regarding the journals where articles about Industry 5.0 have been published. The majority of publications are in journals on supply chain and operations management (which is the aim of this research), and in journals in the management field in general. This demonstrates how incipient the subject of Industry 5.0 is as well as the need for a broader discussion on this theme.

For the analysis of the articles sample, VOSviewer software was adopted. VOSviewer is an open software used to analyze literature content by providing a data network, indicators, and maps. This software was developed by [85] from Leiden University, and it has been largely used by researchers to support literature reviews.

With the aim to obtain reliable data from the VOSviewer software, the parameter of a minimum of five words co-occurring was set. Using this parameter, nineteen (19) words were identified as shown in Figure 4.

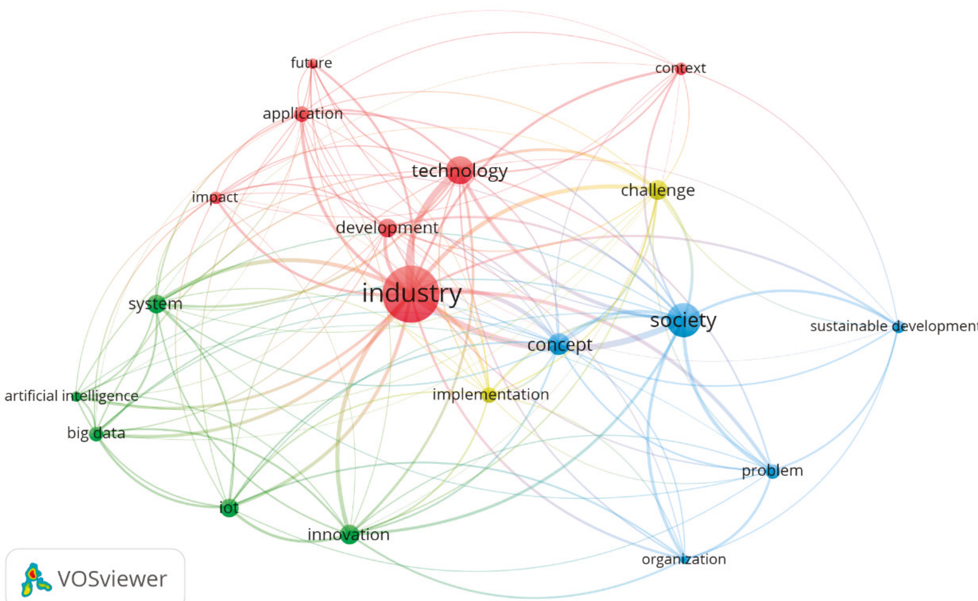

Figure 4. Graphic showing the links between keywords of articles sampled.

As can be noted in the density graphic (Figure 5) as well as in Table 2, four (4) clusters were formed. These clusters were the basis of the constructs that will be further presented in this article. They were formed based on Figure 5, which was generated by the VOSviewer software. These clusters were formed by the software based on the common relations between the words in the analyzed sample of articles. Another important piece of evidence is related to the words' links. A link represents a connection or a relation between two words. The link may be measured by a strength value. The higher this strength value, the stronger the link. The strength of a link may indicate the number of publications in which two terms occur together, in the case of co-occurring word links [86]. From Figure 4 and Table 2, we can see the links between the words which had more co-occurrences in the sample of forty-one (41) articles. Among these stand out industry, society, and technology. These were the words that have the highest weights regarding both occurrences and link strength. This makes sense, since these three words are core for the concept of Industry 5.0.

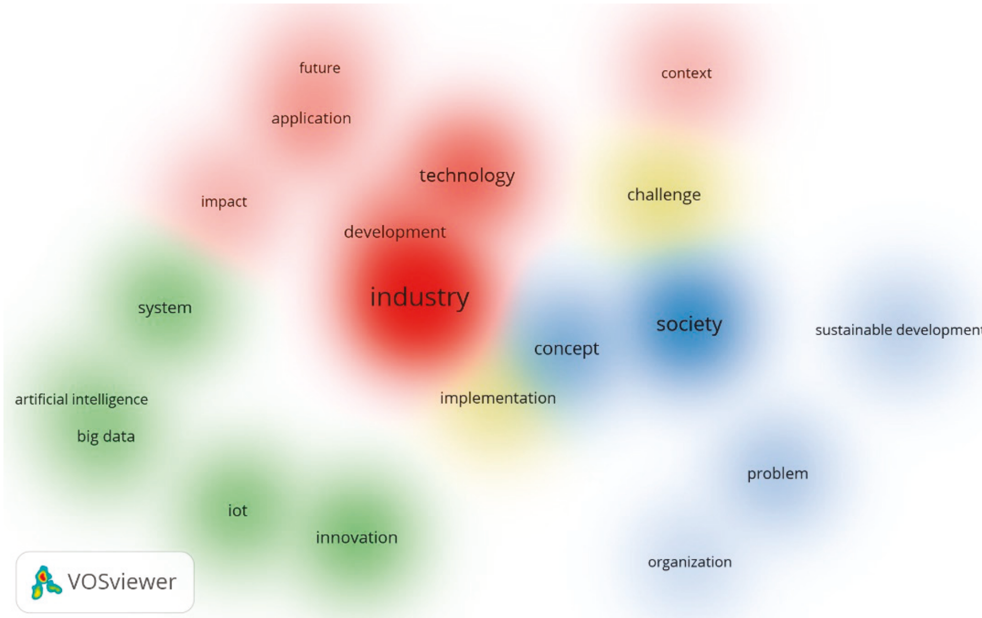

Figure 5. Density graphic of clustered words formed by VOSviewer from the articles sample.

Table 2. Main words clustered by VOSviewer software with regard to articles addressing the subjects of Industry 5.0, Society 5.0, and Industry 4.0.

Word	*Cluster*	*Weight <Occurrences>*	*Weight <Links>*	*Weight <Total Link Strength>*
Industry	1	74	18	955
Society	3	30	17	506
Technology	1	21	18	387
Concept	3	14	18	230
Innovation	2	12	15	227
Challenge	4	11	15	186
Development	1	10	15	141
IoT	2	10	13	164
System	2	10	16	167
Application	1	8	15	114
Implementation	4	8	14	137
Big data	2	7	12	132
Problem	3	7	13	184
Context	1	5	11	71
Impact	1	5	15	78
Sustainable Development	3	5	9	85
Artificial intelligence	2	4	12	79
Future	1	4	10	62
Organization	3	3	10	139

Regarding the cluster analysis, the evidence presented in Figure 5 as well as in Table 2 shows that cluster 1 was formed by articles that are related to issues concerning **Industry Strategy**. The seven (7) words in this cluster are: industry, technology, development, context, application, impact, and future. These are the words grouped in red color in Figure 5.

In respect to cluster 2, articles focused more on issues linked to **Innovation and Technologies**, and there were five (5) words clustered in that regard: innovation, IoT, system, big data, and artificial intelligence. These are the words grouped in green color in Figure 5. Cluster 3 was formed by five (5) words: society, concept, problem, sustainable development, and organization. As can be observed, articles from this cluster were concerned with **Society and Sustainability** issues. In Figure 5, this cluster is represented by the words grouped in blue color. Lastly, cluster 4 contains only two (2) words, challenge and implementation, which appear in articles addressing aspects of the **Transition Issues** arising from moving from Industry 4.0 to Industry 5.0. This cluster is formed by words grouped in yellow color in Figure 5. These results are supported by the author's concept-centric matrix (Table 3), as suggested by [55]. In that matrix, it is possible to verify from which of the forty-one (41) authors (articles) words and their formed clusters have originated. Using this literature review report, this article will consider the four (4) aforementioned evidenced elements as Industry 5.0's constructs: **Industry Strategy, Innovation and Technologies, Society and Sustainability, and Transition Issues**.

Table 3. Matrix-Industry 5.0's constructs and words versus authors.

	Industry Strategy (Cluster 1)							Innovation and Technologies (Cluster 2)					Social and Sustainability (Cluster 3)					Transition Issues (Cluster 4)	
Authors/Words	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
[56]	*	*		*	*	*	*	*	*				*		*	*	*	*	*
[43]	*	*	*		*	*	*	*	*	*	*	*			*	*	*	*	*
[44]								*	*	*	*	*	*	*	*	*	*	*	*
[57]	*		*		*		*						*			*	*	*	*
[58]	*	*			*		*						*	*					*
[59]	*	*	*		*	*			*	*	*	*	*	*	*	*		*	*
[40]	*	*	*		*		*		*	*	*	*						*	*
[60]	*	*	*	*	*	*	*									*	*	*	*
[61]	*	*			*								*	*			*		
[62]	*	*		*	*	*		*	*	*	*	*			*			*	*
[63]	*	*	*	*	*				*	*		*							*
[64]								*	*	*	*		*	*	*	*	*	*	*
[41]	*	*	*		*	*	*						*					*	*
[47]	*	*	*	*	*	*	*	*	*	*	*	*				*			
[42]	*	*			*	*	*		*	*	*	*	*			*	*	*	*
[46]	*	*	*		*			*	*	*	*	*	*	*	*	*	*		
[50]	*	*	*		*		*	*	*	*	*	*	*			*	*	*	*
[65]													*	*	*	*	*	*	*
[66]	*	*						*		*	*			*		*	*	*	*
[67]	*	*				*	*	*				*				*			
[68]	*								*			*					*		*
[69]	*	*			*	*	*		*	*	*	*	*	*					
[70]	*	*		*	*		*			*	*	*							*
[71]	*	*			*				*	*		*							
[72]	*	*		*	*	*	*		*	*	*	*						*	*
[73]	*	*	*		*	*	*						*				*	*	*
[74]	*	*	*	*	*		*		*	*	*	*							*
[75]	*	*	*		*			*	*	*	*	*	*			*		*	*
[76]	*	*	*		*		*	*	*	*	*	*				*			*
[51]	*	*	*	*	*	*	*		*	*	*	*						*	*
[45]	*	*	*		*			*			*		*	*	*	*	*	*	*
[77]									*				*				*	*	*
[78]	*	*		*	*				*	*	*		*					*	*
[79]	*	*			*	*	*	*				*	*		*	*	*	*	*
[80]	*	*	*	*	*	*	*		*	*	*	*	*		*	*	*	*	*
[49]	*	*			*	*	*	*	*			*	*	*		*	*	*	*
[81]	*	*	*	*	*		*	*	*	*	*	*	*	*					*
[48]	*	*	*	*	*	*	*	*	*	*	*	*						*	*
[82]	*	*	*		*		*	*	*	*		*	*			*			*
[83]	*	*	*	*	*	*	*	*				*							
[84]	*	*	*		*		*	*	*	*	*	*	*			*			*

1—industry, 2—technology, 3—development, 4—application, 5—context, 6—impact, 7—future, 8—innovation, 9—IoT, 10—system, 11—big data, 12—artificial intelligence, 13—society, 14—concept, 15—problem, 16—sustainable development, 17—organization, 18—challenge, 19—implementation.

3. Industry 5.0′s Constructs and the Supply Chain Context

3.1. Discussion about the Constructs for Industry 5.0

In Section 2.3, the four (4) identified constructs of Industry 5.0 from the analysis of the literature review were presented. This section will present the concept for each one of these constructs and their related words as demonstrated in Table 3. The answer to **RQ1** is the aim of this section.

3.1.1. Construct 1—Industry Strategy

As aforementioned, this construct was formed by seven (7) keywords: industry, technology, development, context, application, impact, and future. It is related to the Industry 5.0 strategy because articles have approached Industry 5.0 as a whole including this futuristic context, considering the possibilities of technologies' applications and their impacts on the future. This construct is related to the other constructs once the technologies' applications are deployed in Construct 2—*Innovation and Technologies*, which with the development of Industry 5.0′s strategy, directly impacts Construct 3—*Society and Sustainability*. However, the Industry 5.0 strategy faces challenges and implementation issues, mainly regarding the change from Industry 4.0′s paradigms. This is linked to Construct 4—*Transition Issues*.

For [48], Industry 5.0 allows increasing collaboration between humans and smart systems through advanced industrial automation, with the support of critical thinking skills. Ref. [72] affirm that Industry 5.0 is related to the efficient utilization of the workforce formed by machines and people in the manufacturing environment. This concept will redefine the manner in which skilled people are treated in the manufacturing scenario. According to [73], there is a relevant consensus that the era of robotics and automation in previous industrial revolutions brought about paradigm shifts in the manufacturing industry worldwide. For these authors, although Industry 5.0 has still to be materialized, the same will occur with this new revolution, mainly because the set of technologies established with the Industry 4.0 phenomenon is implicated in new paradigms.

In respect to Industry 5.0, some authors have emphasized the impact on personalization. According to [49], customer experience and organizational agility are sources of competitive advantage for Industry 5.0. For these authors, personalization and society collaboration, enabled by Industry 4.0 technologies, are key elements of Industry 5.0. Ref. [60] affirm that although there is a strong trend in highly focused technology applications, modern challenges of customization, personalization, and technology upgrading are only possible with human involvement. These modern challenges have led to Industry 5.0, which aims to align technology advancement with human empowerment. According to [75], some futurists have initiated discussion of Industry 5.0, considering this as the theme of adding a human touch or personalization through collaboration and co-working between humans and robots. Industry 5.0 aims to provide more customized products and services to the customer, characterized by the era of personalization [50]. Ref. [65] point out that the focus of Industry 5.0 is to get efficient use of machines and humans at the same time, creating a synergistic environment and allowing personalization to achieve a higher level in the Industry 5.0 context. For instance, in the medical industry, Ref. [48] affirm that Industry 5.0 provides the opportunity of mass personalization, being able to produce several types of implants according to the patient's requirements.

3.1.2. Construct 2—Innovation and Technologies

This second construct was formed by seven (5) keywords: innovation, IoT, system, big data, and artificial intelligence. Authors have mostly mentioned these technologies as the scaffolding for creating an Industry 5.0 environment, although they belong to the current age of Industry 4.0. Industry 4.0′s technologies are seen as the basis for implementing the Industry 5.0 approach [64]. However, some authors have mentioned new technology approaches integrated with those already applied in Industry 4.0 are required, and innovation plays a crucial role in this process.

For instance, Ref. [47] have identified seventeen (17) components of Industry 5.0. They are big data, collaborative robots (cobots), smart sensors, internet of things, artificial intelligence, multi-agent systems and technologies, digital ecosystems, digital manufacturing, complex adaptative systems, smart materials, 3D printing, 4D printing, 5D printing, 3D scanning, holography, and virtual reality. Ref. [42] argue that technologies that enhance cognitive capabilities do not only include those linked to artificial intelligence (e.g., cognitive computing, computer vision, knowledge representation, machine learning, recommendation systems and planning, scheduling, and optimization algorithms) but also include simulation for what-if scenario analysis, big data analytics, cloud computing, and virtual reality. Ref. [50] state that Industry 5.0 is characterized by a digital smart society, the integration of virtual and physical spaces, internet of things, robots, augmented reality, innovation ecosystem, brain–machine interface, and human centrality of technology. With regard to innovation, Ref. [50] emphasize that as Industry 5.0 is gaining relevance, the focus of innovation management becomes paramount. In that sense, Ref. [56] affirm that several scholars have emphasized the importance and role of modifying the innovation management framework with a focus on human/user-centeredness. Ref. [48] consider that the main components of Industry 5.0 are collaborative robots, internet of everything, multi-agent systems and technologies, complex adaptative systems, smart manufacturing, digital ecosystems, and emergent artificial intelligence. Ref. [79] affirm that there is a set of technologies and approaches which will give a format for Industry 5.0, such as distributed computers and distributed robotics, internet of things, multi-agent systems and technologies, complex adaptative systems, emergent intelligence, evergetics, and new enterprise architecture. For the implementation of Industry 5.0, some advanced technologies are required when compared with those traditional to Industry 4.0. Some of them are networked sensor data interoperability, digital twins, shopfloor trackers, virtual training, intelligent autonomous systems, and advances in sensing technologies and machine cognition [51].

3.1.3. Construct 3—Society and Sustainability

Society and Sustainability construct was formed by five (5) keywords: society, concept, problem, sustainable development, and organization. Some authors have considered social and sustainable aspects as the main elements impacted by the implementation of the Industry 5.0 approach.

According to [64], Industry 4.0′s technologies play a crucial role in the search for a Society 5.0. This is a society with sustainability at its core, supported by disruptive technologies. Particularly, information and data play an essential role in the achievement of Society 5.0's purpose. Ref. [45] consider that a Society 5.0 goes beyond the boundaries of technological and organizational transformation of the industrial system. It involves considering social and human aspects with the aim to achieve a sustainable environment in this technological context.

For [80], Industry 5.0 includes two visions: one is related to the interaction between humans and robots and the other is approaching issues related to the bioeconomy, which is pretty much related to the sustainability issues. For instance, Ref. [67] emphasize that Industry 5.0 may generate huge and positive impacts in terms of sustainability in production systems (e.g., algae production). Yet, Ref. [59] affirm that Society 5.0 becomes an obligatory practice to get stability in terms of sustainable economic due to the advent of Industry 4.0. The main idea of the concepts of Industry 5.0 and Society 5.0 is developing from digital manufacturing to digital society. Social orientation and technical innovations from Industry 4.0 were the basis for the concept of Industry 5.0, being focused on more sustainable development. Industry 5.0 and Society 5.0 have as their main aim digital technologies for the development of society [65].

3.1.4. Construct 4—Transition Issues

For this fourth construct, only two words were grouped: challenge and implementation. It is related to the challenges and implementation aspects that must be addressed for Industry 5.0 to become a reality. The transition from a fully technological to a balanced human-centric perspective is being considered as one of the main challenges and the Industry 4.0 paradigm to be overcome.

In that sense, Ref. [44] emphasize that it is challenging to create an Industry 5.0 by incorporating the disruptive technologies from Industry 4. 0. Ref. [80] state that although there are few visions about what Industry 5.0 means, some futurists are fostering this theme. One emerging theme is human–robot co-working and its implications from the organizational and human relations side. According to these authors, psychological, social, ethical, learning, legal, and regulatory issues will play some of the most important roles to properly guide and regulate the relations between humans and robots. In the same sense, Ref. [73] emphasize that some areas need to be addressed with regard to Industry 5.0 implementation, including education and skills, working environment, the relationship between productivity and wages, technologies and human redundancies, optimum products, sustainability, governance, and ethics. Ref. [56] argue that the implementation of strategies for Industry 5.0 often depends on a series of factors for which sharing is necessary, such as any territorial support in growth policies. Institutions, entrepreneurs, and managers should take into consideration these differences and plan interventions reflecting the real conditions of their contexts. Ref. [40] propose to consider four main elements in designing Industry 5.0′s strategy: organization, people, technology, and tasks. Ref. [73] emphasize that some areas that need to be addressed with regard to Industry 5.0 trend are education and skills, working environment, the relationship between productivity and wages, technologies versus human redundancies, optimum products, sustainability, governance, and ethics.

3.2. Alignment with the Supply Chain Context

In the current context, Supply Chain 4.0 has been reasonably discussed by the academic and practical audience. Some researchers have proposed some frameworks for the development of a Supply Chain 4.0 strategy. Among these stand out the models proposed by [24–31]. In their majority, these proposals consider similar aspects which have been extracted from the literature review about Industry 5.0 herein presented and discussed in Section 3.1. Supply Chain 4.0 also takes into consideration aspects such as its own strategy, a set of disruptive technologies, required capabilities and other criteria such as challenges to properly implement these disruptive technologies, and implications in terms of the performance of the supply chain processes.

In order to follow the structured rationale of this article, the alignment between Supply Chain 5.0 and Supply Chain 4.0 will be presented according to the four (4) constructs extracted from the systematic literature review, as presented and discussed in Section 3.1.

Concerning the construct **Industry Strategy**, while the literature considers the Supply Chain 4.0 concept as having a highly technological environment focus, Supply Chain 5.0 keeps this technological aspect, but also considers a balanced human–technological environment, mainly allowed by cobots (collaborative robots). Supply Chain 4.0 also aims to have a mass customization advantage besides enabling greater performance from the supply chain's processes in terms of transparency, responsiveness, flexibility, waste reductions, and efficiency. Supply Chain 5.0 seeks to keep those performance improvements, but also add more value by pursuing a mass personalization of products and services.

In respect to the construct **Innovation and Technologies**, Supply Chain 4.0 is formed by technologies such as IoT, big data analytics, 3D printing, cloud computing, robotics, blockchain, augmented reality, and artificial intelligence. These technologies remain in Supply Chain 5.0, and artificial intelligence is enhanced. Indeed, these Industry 4.0 technologies are the scaffolding for the implementation of Supply Chain 5.0; however, new technological advancements are added as well, including collaborative robots (cobots), multi-agent systems and technologies, digital ecosystems, complex adaptative systems, 4D printing, 5D printing, 3D scanning, holography, intelligent autonomous systems, evergetics, and machine cognition. Additionally, the approach of innovation ecosystems is going to play a crucial role in this upcoming technological transformation.

In the construct of **Society and Sustainability**, while in Supply Chain 4.0 the society is more passive, being smoothly impacted by Industry 4.0′s technologies, in the Supply Chain 5.0 approach society is an active and target element. In this new industrial revolution, one of the main aims is to create a super and digital smart society. In this new concept, the focus goes beyond the organization's thresholds and embraces the supply chain's linked society. Additionally, in Supply Chain 5.0, sustainable development becomes one of the main targets, much more than only being impacted by technologies, as it is being approached in the current context of Supply Chain 4.0. This interaction between Supply Chain 5.0′s technologies and approach and smart society must be designed to create a most advanced sustainable environment in both organizations and societies.

Regarding the **Transition Issues** construct, authors who have discussed Supply Chain 4.0 have in general considered as challenges and implementation issues aspects such as coordination and leadership support, digital infrastructure, strategic alignment, and people skills and training. In the Supply Chain 5.0 concept these issues remain; however, they become more complex and comprehensive, by including aspects such as psychological issues, workers' safety, social, ethical, learning, and legal and regulatory issues. Lastly, the main challenge is the paradigm transition which involves a change from a fully technological to a balanced human-centric perspective.

Based on the presented alignment, Figure 6 shows the framework with a vision of the Supply Chain 5.0 concept and structure.

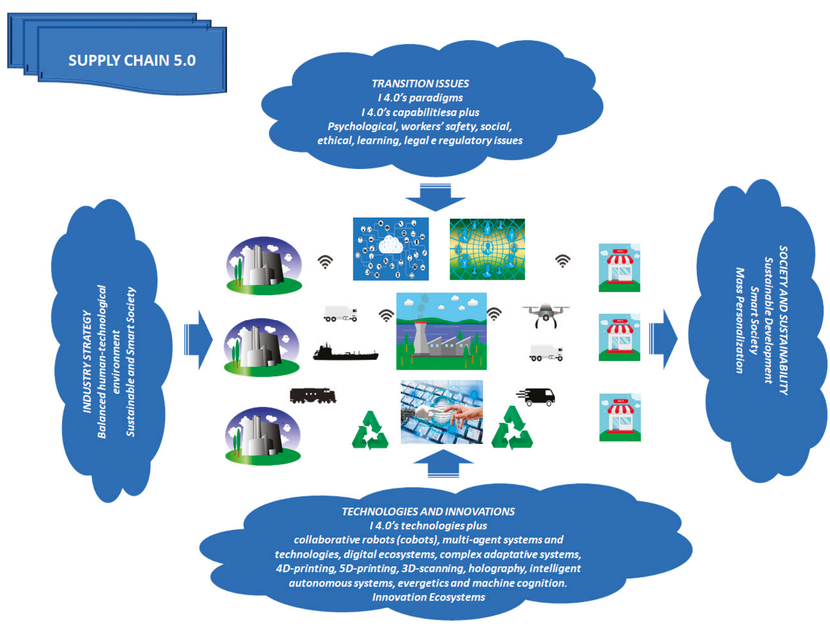

Figure 6. Supply Chain 5.0 framework and concept.

Therefore, based on Figure 6, Supply Chain 5.0 involves an industry strategy that pursues a balanced human–technological environment and a sustainable and smart society. This strategy is supported by technologies and innovation that include Industry 4.0′s technologies and other emergent technologies as well as an innovation ecosystem. A Supply Chain 5.0 strategy also has some transition issues related to Industry 4.0′s paradigms, Industry 4.0′s capabilities, and other issues such as psychological, workers' safety, social, ethical, legal, and regulatory. As the main purpose, in terms of social and sustainable aspects, Supply Chain 5.0 aims to allow a more sustainable, smart society. It also creates a mass personalization in terms of products and services of the supply chains.

4. Conclusions

Industry 5.0 is still a visionary concept which aims to include the human, social, and sustainability aspects amid the current and highly focused technological scope of Industry 4.0. Although the literature is still scarce, there is a growing trend towards Industry 5.0 discussions by the academic and practical audience. Aiming to contribute to these discussions, this paper has presented the relationship between Industry 5.0 and supply chains, having as its basis a systematic literature review.

In the systematic literature review, it was possible to identify forty-one (41) articles related to the subject herein proposed. By the analysis of these articles through VOSviewer software, nineteen (19) words were clustered forming the four (4) main constructs conceptualized and discussed: **Industry Strategy**, **Innovation and Technologies**, **Society and Sustainability**, and **Transition Issues**. This answered the **RQ1** of this research, as described in the Introduction of this article.

To answer **RQ2** of this research, an alignment between Industry 5.0′s constructs and the already available understanding of Supply Chain 4.0 was proposed. Although it is possible to identify some similarities between Supply Chain 4.0 and Supply Chain 5.0, the last adds more things in the four (4) constructs considered. Supply Chain 5.0 aims at mass personalization, adds revolutionary technologies, enables a super smart and sustainable society, and faces some transition challenges in its implementation, mainly linked to the paradigms established by the ongoing Industry 4.0 wave.

4.1. Practical and Theoretical Implications

The practical implications of this work are relevant since organizations' leadership, policymakers, and other practitioners involved in supply chains, and mainly those currently working with Industry 4.0 programs, can benefit from this research in having clear guidance regarding the dimensions needed to structurally design and implement Industry 5.0′s initiatives. Moreover, it can encourage practitioners to think about the benefits of Industry 5.0 in supply chains and their role with the aim to pursue a more sustainable and smart society. As identified in the literature review findings, Industry 5.0 may enhance strategic outcomes of supply chains by allowing mass personalization in products and services.

As theoretical implications, this article brings a novel contribution, being a starting point related to the relationship between Industry 5.0 and supply chains. This article also encourages further research in the area of supply chain and operations management in the context of this upcoming industrial revolution, by providing a clear set of constructs which form Supply Chain 5.0. The set of listed topics in Table 4 can also foster the development of new research programs linked to Industry 5.0 in supply chains. New theoretical and empirical studies may be deployed from the research. Surveys, case studies, and action research may support the validation of the constructs presented in this article as well as the addition of new ones. These new developments of research are crucial to a deeper understanding of the Industry 5.0 phenomenon in supply chains. Additionally, future reviews of the literature may also be of benefit to the subject of Supply Chain 5.0.

Table 4. Research agenda.

Industry 5.0′s Constructs	Research Questions—Industry 5.0 and Supply Chains
Industry Strategy	** How to deploy Supply Chain 5.0′s strategy amid the paradigms of Industry 4.0?* ** How mature should organizations be before the rollout of the Supply Chain 5.0 strategy?* ** How to get alignment with the supply chain's members to develop a Supply Chain 5.0 program?* ** What are the strategic impacts of implementing a Supply Chain 5.0 program (e.g., sustainability, mass personalization, digital society)?* ** How can stakeholders in the supply chain get competitive advantages by implementing joint initiatives regarding Supply Chain 5.0?"*
Innovation and Technologies	** What are the most beneficial technologies to create a Supply Chain 5.0 impact?* ** What are the key technologies of Industry 4.0 to create a proper scaffolding for the implementation of Industry 5.0′s technologies?* ** How can technologies of Industry 5.0 be interoperable across the supply chain and interplay with society?* ** How can innovation ecosystems foster the deployment of Industry 5.0 programs in supply chains?*
Society and Sustainability	** How can Supply Chain 5.0 interplay with society, to help the development of a super-smart society?* ** What are the benefits of the Supply Chain 5.0 approach for circular supply chains?* ** What are the benefits generated for individuals who interact with a Supply Chain 5.0?* ** How can Supply Chain 5.0 enhance the achievement of climate goals, helping to create a more sustainable environment?* *What is the role of the supply chain's members in the development of Society 5.0 and sustainable development?*
Transition Issues	** What are the main barriers to the transition from Supply Chain 4.0 to Supply Chain 5.0?* ** Which capabilities must be developed before the implementation of Supply Chain 5.0′s programs?* ** What are the triggers to implement a transition strategy from Supply Chain 4.0 to Supply Chain 5.0?* ** How can the stakeholders involved in supply chains impact a transition program?*

4.2. Limitations and Research Agenda

Although this paper presents relevant insights, further research is required to overcome the limitations related to the validation of the constructs herein proposed. As the literature is still scarce and incipient, more constructs may be added in the future as the understanding of Industry 5.0 evolves.

Therefore, there is a fruitful field of research to be explored in both empirical and theoretical sides about the future supply chains in the context of Industry 5.0. With the purpose to help in the guidance of these future studies, this article also proposes a research agenda which is not limited to some research questions based on the four (4) constructs identified in this study. This closes the article and answers **RQ3**, which was presented in the Introduction section.

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Evaluating the Status of SMEs in Jordan with Respect to Industry 4.0: A Pilot Study

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Abstract: *Background:* Industry 4.0 is a burgeoning research area that has been addressed by many research entities. However, the literature shows that the industrial sector lacks the awareness and knowledge needed to comply with Industry 4.0 implications, particularly in developing countries. *Methods:* This study evaluates the status of small and medium enterprises (SMEs) in Jordan concerning Industry 4.0. Four criteria are assessed, including Industry 4.0 readiness, maturity, drivers, and barriers. Samples of SME respondents and Industry 4.0 experts are surveyed using an online questionnaire. *Results:* The results show that SMEs in Jordan are not mature enough nor ready to apply Industry 4.0. For the readiness dimension, SME respondents and experts agreed that the Jordanian SMEs' status is between having initiatives in the pilot phase or implementing concepts to low degrees, except for autonomous workpiece and smart product aspects, in which Jordanian SMEs are behind due to financial and technological reasons. It was found that none of the Industry 4.0 investigated technologies have reached maturity levels. Customer requirements, cost reduction, competitors' practice, productivity improvement, and quality improvement are found to be the major influencing drivers for Industry 4.0, while a lack of awareness and knowledge is found to be the crucial barrier hampering Industry 4.0 implementation. *Conclusions:* Jordan needs country-scale initiatives for the implementation of groundbreaking Industry 4.0 development, incorporating government agencies, industrial parties, and experts, relying on Industry 4.0's readiness and practice status as a starting point, and considering the influential drivers and barriers to steer the development process.

Keywords: developing countries; digital transformation; Industry 4.0; drivers; barriers; readiness; maturity models; small and medium enterprises

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1. Introduction

Since the 1800s, humanity has experienced three industrial revolutions, each powered by new technology: the use of steam power and mechanization of production (Industry 1.0), the discovery of electricity and assembly line production (Industry 2.0), and partial automation using memory-programmable controls and computers (Industry 3.0). Recently, the concept of digital transformation of the industry (known as the fourth industrial revolution or Industry 4.0) has begun to change the world of manufacturing in parallel with its economic environment.

The term Industry 4.0 was invented in 2011 in Germany as an initiative of the German federal government to strengthen the competitiveness of the German manufacturing industry [1,2]. There are many definitions for Industry 4.0. For example, Kagermann et al. [3] defined it as the involvement of the technical integration of cyber–physical systems in manufacturing and logistics and the use of the internet of things and services in industrial processes. Trappey et al. [4] defined it as a general concept of manufacturing, enabling the elements of tactical intelligence using techniques and technologies such as the internet of things, cloud computing, and big data. Industry 4.0 technologies are applied to enable companies to have flexibility in manufacturing processes with real-time data analysis. This implies developing embedded systems and enhancing strategic and operational decision-making processes [5]. Nine technologies have been considered as Industry 4.0 application pillars: big data and analytics, autonomous robots, simulation, horizontal and vertical integration, the industrial internet of things (IIoT), cybersecurity, the cloud, additive manufacturing, and augmented reality [6]. Such technologies could improve information transmission throughout the system, which enables more control over operations and adaptability to stochastic environments [7].

Small and medium enterprises (SMEs) are engines of sustainable economic growth worldwide. Industry 4.0 application to SMEs is not only a new research field, but also it has a limited implementation even in developed countries due to a lack of awareness and knowledge [7–11]. This study aims to investigate the status of SMEs in Jordan concerning their Industry 4.0 readiness, maturity, drivers, and barriers. It aims to diagnose how ready the Jordanian industry is to absorb and apply Industry 4.0 concepts and technologies. Additionally, it aims to point out the weaknesses and improvement points that should be taken into consideration regarding applying Industry 4.0 technologies in Jordan.

The rest of this paper is organized as follows: Section 2 describes the industrial sector in Jordan. The literature review is presented in Section 3. The methodology is explained in Section 4. The key findings are demonstrated and discussed in Section 5. Finally, the conclusions, study implications, and suggestions for future research are outlined in Section 6.

2. Industrial Sector in Jordan

This section describes two aspects of the industrial sector in Jordan: the technological development process and the SMEs' status.

2.1. Technological Development

It is well known that the adoption of advanced technologies is more challenging in developing countries due to several reasons such as culture, level of education, limited resources, and political instability. Consequently, companies in developing countries are behind their counterparts in developed countries concerning technology adoption [5]. This technological gap is quantified by a measure called the "growth competitiveness index", which accounts for the competitiveness in several aspects such as institutional framework and infrastructure, health and education, the size of the market, the environment at the macroeconomic level, development of capital markets, availability of technology, and business development and creativity [12]. The first appearance of Jordan in this index, which is tabulated by the World Economic Forum, occurred in 1996 [13]. The annual survey of the World Economic Forum, in 2014, revealed that Jordan progressed forward by four degrees in indicators of competitiveness to be ranked 64th globally and eighth among Arab countries. The report also showed the relative improvement in the economic indicators of Jordan in terms of reducing the budget deficit and the development of the financial market and education sectors [13]. In general, it can be seen that Jordan is achieving progress according to several growth competitiveness index indicators, which makes it a promising environment for Industry 4.0 development. Jordan is also a good candidate for this study due to its vital geographical position and political stability. Moreover, the Jordanian government, in spite of its limited resources, is making tremendous efforts to support and facilitate SMEs' economic growth.

Several developed countries have formulated national strategies and programs for incentivizing Industry 4.0 technologies such as the "High-Tech Strategy 2020" program in Germany, the "Advanced Manufacturing Partnership" program in the USA, and the "Made in China 2025" program in China [3,14,15]. Jordan, as a developing economy, still does not have a roadmap for Industry 4.0 adoption and implementation; however, the government of Jordan has made a lot of effort to start up country-based initiatives to facilitate digitalization and technological development, including:

- The Higher Counsel of Science and Technology (HCST). This institute is responsible for coordinating and promoting science and technology in Jordan. It also sponsors projects championed by academics to support local industries [16];
- The Jordan Enterprise Development Corporation (JEDCO). This institute provides startups and SMEs with funds, technical assistance, and support to start their business in the local market [17];
- Several detached initiatives from different nonprofit organizations, universities, and private sectors have been launched to promote the implementation of Industry 4.0 technologies. Good examples of this category are the Deanship of Innovation, Technology Transfer and Entrepreneurship (DI-TECH) in the German Jordanian University and the Jordan Industry 4.0 Innovation Center (InJo4.0) [18].

2.2. SMEs' Status

Jordan is an upper-middle income country that depends almost completely on SMEs as the economy driver. For instance, in 2021, SMEs accounted for 95% of the business market in Jordan [19]. Moreover, SMEs represent roughly 95% of all registered companies, contribute 50 percent or more to GDP, and provide employment to an estimated 60 percent of the Jordanian workforce [20]. These are significant indicators of the importance of SMEs to the Jordanian economy and how crucial their involvement in any economic development plan is. In Europe, an SME is defined as a firm that has fewer than 250 employees with a total turnover that does not exceed EUR 50 million [21], while in Jordan the numbers are much smaller, where SMEs are defined as firms employing fewer than 100 employees with a total turnover that does not exceed JOD 3 million (JOD 1 JD equals USD 1.41) [17]. According to the Ministry of Industry (Trade and Supply Act No. 10 of 2005), a small enterprise in Jordan is defined as any individual company or enterprise with the primary purpose of industry, where its capital is less than JOD 30,000, and it has fewer than 10 employees registered in the Social Security Administration. Micro businesses comprise 89% of the total enterprises in Jordan, while 9% are small enterprises and the remaining 2% are medium and large enterprises [22]. Figure 1 depicts the sectoral distribution of SMEs in Jordan. It can be seen in Figure 1 that the largest share of SMEs in Jordan is in the commercial establishment category (35%), followed by the service provider category (23%), whereas a significant share is in industrial production (20%), and the rest is dedicated to tourism, construction, transport, and the finance sectors (9%, 8%, 4%, and 1%, respectively) [22].

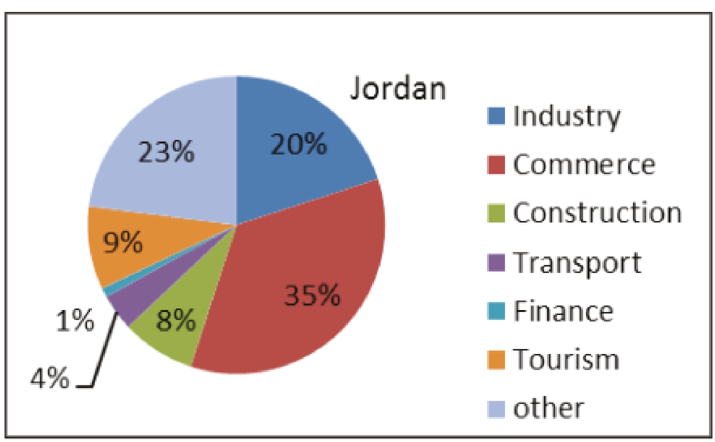


Figure 1. Sectoral distribution of SMEs in Jordan [22].

Jordan began promoting SMEs in the early 1970s through a five-year economic development plan (1976–1980), which enabled SMEs to provide alternatives for imported goods and products. After that, several corporations, societies, and socio-economic production programs were created, focusing on the development of SMEs [23]. SMEs have different characteristics to large enterprises that should be taken into consideration when investigating Industry 4.0 application; firstly, they have fewer resources and less experience in managing new technologies [24,25]. Secondly, they strongly involve top management in all the company's decisions. Thirdly, they are more operation-focused on the expense of strategic activities [26,27]. SMEs in Jordan are facing many challenges that could hinder their technological development, including financial, exports, fees and procedures, and decentralization challenges. Regarding the financial constraints, a lack of different forms of financial funding is a traditional constraint preventing SMEs from growth and expansion [28]. For instance, the share of credit allocated to SMEs in Jordan is small and shrinking too, declining from 11% to only 8.5% of total credit available to the private sector in 2016 [29]. Concerning exports, most SMEs are not export-oriented because they focus on the production of traditional, low-value-added products or services with modest quality [30]. Regarding fees and procedure limitations, the cost of conducting business is considered high for several SMEs in Jordan. The tax system in Jordan and the newly produced law, which forces companies with a capital of JOD 20,000 to appoint legal counsel, have both led to additional costs. Moreover, SMEs that create patents may not be able to protect their intellectual property due to the high cost of intellectual property registration in Jordan [31]. Decentralization is an obstacle facing SMEs in many countries, including Jordan. The companies and their commercial activities are agglomerated in the capital city, where a high-income population resides. Meanwhile, outside Amman, many cities suffer from underdevelopment, which implies high unemployment rates and poverty. SME establishment outside the capital needs encouragement via tax incentives and the facilitating of policies [31].

3. Literature Review

There is a scarcity of published research regarding the application of Industry 4.0 to SMEs [7]. One of the reasons could be the lack of awareness of how important it is to apply Industry 4.0 technologies, and how they could be harmonized with the companies' business processes [8]. According to several surveys, leaders of many enterprises have not heard about Industry 4.0. On the other hand, a large portion of them is aware of the Industry 4.0 basic concept, but they lack the knowledge related to introducing this new concept and how to be compliant with it [8]. It has also been found that many academic Industry 4.0 readiness models are not even known for the industrial sector [9]. For instance, a survey, conducted among 1000 medium-sized companies in Germany, revealed that in 25% of the surveyed companies, the topic of digitalization is not yet relevant [10]. In another recent survey, conducted by the consulting firm Deloitte in 19 countries, the results revealed that only 14% of chief executive officers were sure that their organizations are ready and capable to incorporate the changes accompanied by Industry 4.0 [11].

It is important to realize that the digital transformation process is an overall business strategy, with multi-components, which involves the management's commitment to adopt technological and organizational changes. Such a major strategic decision requires a prerequisite of enterprises' assessment of their status and readiness to apply Industry 4.0 technologies before investing resources [8,32]. Maturity models are one of the most used tools to evaluate the status of the company, concerning industrial revolutions, and assess its ability to apply Industry 4.0 technologies [32]. In the last few years, there has been a rapid increase in the number of Industry 4.0 readiness models [33]. However, a recent literature review revealed that there is a lack of empirical research on the application of Industry 4.0 technologies in SMEs [7]. Another study showed that larger companies are more ready to apply Industry 4.0 technologies than SMEs, which means that SMEs could face more barriers while trying to adopt and implement Industry 4.0 concepts, but this cannot be proved since little is currently known about implementing Industry 4.0 in this category [2,34,35].

Regarding maturity models, Mittal et al. [36] reviewed the commonly available models for Industry 4.0. Fifteen maturity models were presented and compared in terms of their methodology, focus, dimensions, and gaps. In terms of dimensions, the most used are strategy and organization, technology, IT, smart factory, smart products, data utilization, and employees. Other models included extra dimensions such as security policies [37] and customers [32].

IMPULS—Industrie 4.0 Readiness is one of the most well-known Industry 4.0 readiness models, which was developed by IW Consult (a subsidiary of the Cologne Institute for Economic Research) and the Institute for Industrial Management (FIR) at RWTH Aachen University [36]. The assessment process in this model relies on six pillars including strategy and organization, smart factory, smart operations, smart products, data-driven services, and employees. According to IMPULS, companies are classified into three categories, with six levels, based on their level of readiness to apply Industry 4.0. The first category is the newcomers, which includes two levels: the outsider and beginner levels. The learners' category is the second, which comprises the intermediate level. The third category is the leaders, which encompasses experienced, experts, and top performers [38]. Another well-known model is the connected enterprise maturity model in which Industry 4.0 is implemented in five stage processes; assessment, secure and upgraded networks and control, defined and organized working data capital, analytics, and collaboration [37]. A third important model for manufacturing enterprises' maturity is the one developed by Schumacher et al. [32]. In this model, nine dimensions are defined, and sixty-two items assigned to them. The dimensions are products, customers, operations, technology, strategy, leadership, governance, culture, and people.

Stentoft et al. [35] investigated the relationship between Industry 4.0 drivers and barriers to Industry 4.0 readiness and actual practice. They analyzed 308 Danish SMEs, from different manufacturing sectors, to examine how managers' perception of Industry 4.0 drivers and barriers could affect their companies' readiness and practice of Industry 4.0 technologies. They measured a relatively low degree of Industry 4.0 readiness and practice among the studied SMEs. They also found, through testing different hypotheses, that Industry 4.0 drivers have a positive impact on Industry 4.0 readiness and practice. Raj et al. [11] focused their study on the barriers to Industry 4.0 implementation, in the manufacturing sector, for both developed and developing economies. Among the 15 barriers they investigated, they found that the lack of a digital strategy alongside resource scarcity is the prominent barrier in both economies. They also found that improving standards and government regulation could enhance the adoption of Industry 4.0 technologies in developing countries, while in developed countries, technological infrastructure would be essential to promote Industry 4.0 adoption and implementation.

Several initiatives, in different countries, have tried to assess the readiness for Industry 4.0 technologies' application. One experience is from Hungarian industry where a hybrid model was used, relying on three different resources; the IMPULS—Industrie 4.0 Readiness model, the Hungarian Industry 4.0 National Technology Platform suggestions, and the authors' contribution based on in-depth expert interviews [39]. A study based on the Czech experience was simpler; it focused on four main aspects including Industry 4.0 awareness, barriers, drivers, and strategy [40]. Another country-based attempt to assess Industry 4.0 readiness was conducted in Malaysia and relied on seven key areas: market pressure, risk taking, knowledge, management support, competencies, motivation, and freedom [41]. A specific study for manufacturing companies was conducted in Serbia to evaluate the role of advanced digital technologies (e.g., ERP as a backbone of vertical integration) in the context of Industry 4.0 [42]. To the best of the researchers' knowledge, this study is the first to investigate the status of SMEs in Jordan concerning Industry 4.0.

4. Methodology

The current research surveys the awareness and application of Industry 4.0 concepts and technologies in Jordanian SMEs. The main research question in this survey is: What is the situation of Jordanian SMEs concerning Industry 4.0 readiness, maturity, drivers, and barriers? To answer this question, an online questionnaire was created. Questionnaires are the typical quantitative technique to adopt in such exploration studies [32,39,41,43]. The study explores the views of two different categories; the first one is the SME respondents, while the other category represents local experts in Industry 4.0, including industry consultants, legislation bodies, and academics. SMEs' responses reflect the real situation of Industry 4.0 on the ground, which is, in general, profit-oriented and focused on short-term deliverables. Conversely, the long-term vision, theoretical background, and enlightenments, revealed in experts' opinions, could be utilized in strategizing and planning schema for Industry 4.0 implementation at a country scale. Data collection was carried out by completing the online questionnaire. Overall, 90 companies and 35 Industry 4.0 experts were addressed and 24 of them fully answered the entire questionnaire, which made for a 19.2% response rate. These modest values are justified for such kinds of surveys due to the following practical and theoretical reasons; practically, purpose sampling technique was used as a pilot study to obtain representative responses. The questionnaire was only sent to respondents for whom Industry 4.0 concepts are relevant. Otherwise, the responses would have underestimated the status of Industry 4.0 due to misunderstanding and lack of knowledge. This technique is also used in other country-based initiatives to evaluate Industry 4.0 status [40,41]. Theoretically, the sample size was within the acceptable range for pilot studies mentioned in the literature. For instance, Saunders and Tosey [44] recommend a minimum of 10 respondents, Aaker and Keppel [45] recommend 15 to 25 respondents, Taylor et al. [46] recommend 15 to 30 respondents, Johanson and Brooks [47] recommend that 30 respondents' sample is a reasonable count for a pilot study. Respondents who answered the questions consisted mainly of practitioners from industry (37.5%) and experts (62.5%). According to Amman Chamber of Industry (ACI), the industrial companies in Jordan are categorized under one of the following ten categories: chemical and cosmetics; engineering, electrical, and IT; leather and garments; mining; printing, packaging, paper, cartoon, and stationeries; therapeutic and pharmaceutical; construction; food, supplies, agricultural, and livestock; wooden and furniture; and plastic and rubber [48]. In this study, the ACI classification is considered to group SMEs. Figure 2 depicts the breakdown of respondents by categories. As can be seen in Figure 2, most of the SME respondents (45%) were from engineering, electrical, and IT industries. The second largest category was from food, supplies, agricultural, and livestock industries (22%), followed by chemicals and cosmetics (11%). The category "others" included areas such as transport, tourism, and finance sectors. Industry 4.0 experts' sample consisted mainly of academics (73%). The "other" category includes Industry 4.0 consultants, legislation bodies, etc.

Table 1 depicts the four criteria surveyed in this study along with brief descriptions, number of related survey questions, questions' type, and associated literature. Those criteria are mainly based on the IMPULS model and partially on Stentoft et al.'s [35] study, with some modifications to make them compatible and applicable in a developing country such as Jordan. The first criterion is about how the SMEs in Jordan are able to exploit Industry 4.0 principles (Industry 4.0 readiness). It includes six items: strategy, plans, smart equipment, digital data collection, autonomous workpiece, and smart product. The second criterion is related to the degree the Jordanian SMEs apply the nine technologies of Industry 4.0. The third criterion measures the motivations behind Industry 4.0 application. Seven different drivers are investigated which are: customer requirements, competitors' practice of Industry 4.0, cost reduction, legal requirements, productivity improvement, quality improvement, and flexibility improvement. The last criterion measures the obstacles preventing the application of Industry 4.0 technologies. Seven different barriers are also investigated which are: lack of knowledge (know-how), lack of standards, lack of data protection, lack of qualified workforce, lack of awareness of the importance of Industry 4.0, lack of financial resources, and lack of governmental support. The first two criteria are measured using a 5-point rating scale to capture the intensity of respondents' opinions about the questionnaire items. The five scales used are: 1—Don't have, 2—Have only in the test and pilot phase, 3—Have to a low degree, 4—Have to a moderate degree, 5—Have to a high degree. The third and fourth criteria are measured using multi-response questions that allow the respondents to choose from none to all the drivers and barriers given in the designed questions.

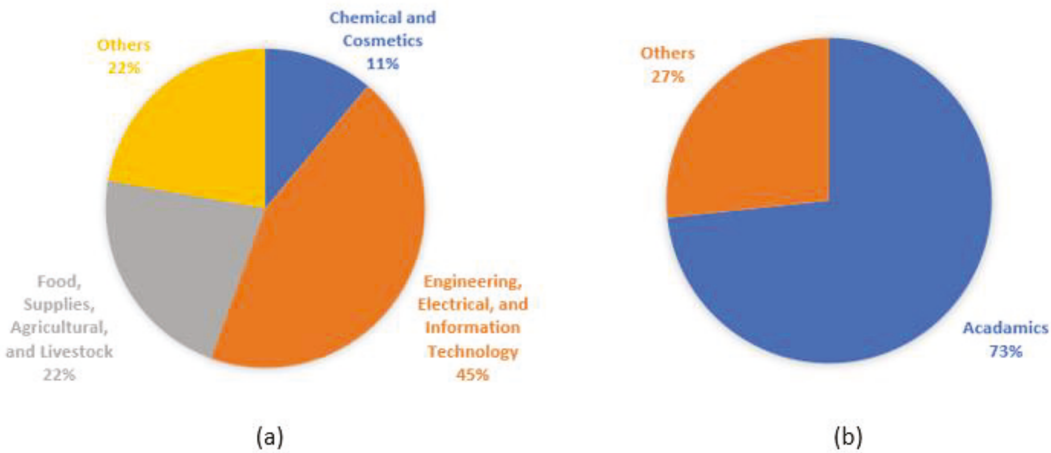


Figure 2. Responses' breakdown by categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.

Table 1. The four surveyed criteria in this study.

Criterion	Description	No. of Questions	Questions' Type	Reference
Readiness	It measures companies' ability to exploit Industry 4.0 technologies. It includes six items: strategy, plans, smart equipment, digital data collection, autonomous workpiece, and smart product.	6	5-point rating scale	Modified questions based on the IMPULS model [36].
Maturity	It measures the degree to which companies are applying Industry 4.0 technologies. Including nine items: big data and analytics, autonomous robots, simulation, horizontal and vertical integration, IIoT, cybersecurity, the cloud, additive manufacturing, and augmented reality.	9	5-point rating scale	Modified questions based on the IMPULS model [36].
Drivers	It measures the motivations behind Industry 4.0 application. It gives the respondent the freedom to choose from 0 to 7 different drivers which are: customer requirements, competitors practice of Industry 4.0, cost reduction, legal requirements, productivity improvement, quality improvement, and flexibility improvement.	1	Multiple response (from 0 to 7 responses)	A modified question based on Stentoft et al. [35] study.
Barriers	It measures the obstacles preventing the application of Industry 4.0 technologies. It gives the respondent the freedom to choose from 0 to 7 different barriers which are: lack of knowledge (know-how), lack of standards, lack of data protection, lack of qualified workforce, lack of awareness of the importance of Industry 4.0, lack of financial resources, and lack of governmental support.	1	Multiple response (from 0 to 7 responses)	A modified question based on Stentoft et al. [35] study.

The questionnaire used in this study was developed in a multi-stage process. Firstly, a more detailed and technical questionnaire was developed based on the IMPULS maturity model. Next, the developed questionnaire was evaluated by two Industry 4.0 experts to check if it would be applicable in the Jordanian market. The feedback received from the experts indicated that the first version of the questionnaire was too technical and advanced to be suitable for the modest initiatives of Industry 4.0 in Jordan. Finally, a simplified and generalized version of the questionnaire was constructed and used incorporating suggestions given by the two experts.

Regarding the theoretical contribution of this study, the new dimension, which is not addressed in the literature, is the alignment between the theoretical aspect, represented in the experts' opinions, and the practical aspect, which reflects the situation on the ground. Accordingly, the findings of this study add to the literature of Industry 4.0. As revealed in this study, Industry 4.0 experts in Jordan have a bird's eye view with accurate judgment for the status of Industry 4.0. This holistic view and experience should be exploited by the Jordanian government to steer the SMEs toward smart products and operations' transition, using the available resources and technologies. The other theoretical outcome of this study is the hybrid model, which was specifically built for the Jordanian case. In this modified model, Industry 4.0 major dimensions (readiness, maturity, drivers, and barriers) have been addressed but in a simplified schema to be compatible with the modest initiatives in Jordan. However, this model can be exported and applied in similar developing countries, especially in the Middle East region.

5. Results and Discussion

This section presents the findings of the Industry 4.0 criteria measures for SMEs in Jordan. Table 2 shows the mean of each measure for both respondents' categories (SME respondents and Industry 4.0 experts). The general trend in the results of both categories is that the Jordanian SMEs are not mature enough nor ready for Industry 4.0 implementation, with most mean values between two and three (mostly between a pilot level and a low level). This result is expected in a developing country with limited resources such as Jordan. In the absence of thorough governmental efforts to spread a digitalization culture among the industrial society, Industry 4.0 initiatives are launched by individuals who are not fully aware of the organizational and structural changes needed to embrace Industry 4.0 philosophy. Instead, they partially employ some Industry 4.0 technologies that are compatible with their business, need low investment, and acquire a naive technological infrastructure.

Going through the readiness six dimensions, the results, summarized in Table 2, show that the Industry 4.0 strategy is not clearly defined nor spread out among employees (SME respondents' mean: 2.56, experts' mean: 2.00), in the absence of indicators to orient the development process. The same is true for Industry 4.0 implementation plans over a five-year period (SME respondents' mean: 2.67, experts' mean: 2.80), with modest investments in this aspect. This proves the fact that SMEs are more operation-focused on the expense of strategic activities [26,27]. The smart equipment dimension is not found to be widely applied on the ground (SME respondents' mean: 2.56, experts' mean: 2.33). This could be simply due to financial and technological drawbacks incorporated in the smart equipment's utilization, which is not expected to witness a revolution under the current economic status of Jordan. As a prerequisite to smart factories, digital data collection systems should exist, including smart collection, storage, and processing of data to assure the efficient utilization of resources. The findings have revealed a shortage in real-time, enterprise-wide, and cross-enterprise collaboration between different entities (SME respondents' mean: 2.78, experts' mean: 2.40). This could be attributed to the point that the information technology culture in Jordan is not mature enough to support cyber–physical systems, interoperability, and IIoT, which are essential parts of the infrastructure for efficient digital data systems. The dimensions that show the lowest readiness levels are the autonomous workpiece (SME respondents' mean: 1.78, experts' mean: 1.60) and the smart product (SME respondents' mean: 1.44, experts' mean: 2.40). It is expected to have close findings for these dimensions because they are logically related. The smart product dimension implies equipping items with Information and Communications Technology (ICT) components (e.g., RFID, sensors, communications interface) to collect data related to their status and environment. Without having these features, the workpiece is not be able to interact with its environment and lead itself through the production process autonomously. Since these technologies require high investments in parallel with advanced technological levels, the Jordanian SMEs are behind in comparison to other Industry 4.0 readiness measures. It is worth mentioning that for the six readiness dimensions, there is no statistical difference (p-values are more than 0.05) between SME respondents' and experts' opinions, which reflects the experts' awareness of Industry 4.0's status in Jordan. This concurrence could lead to a consolidated onset of collaboration between theory and practice in order to set a schema for Industry 4.0 implementation at the country level.

Table 2. Summary of Industry 4.0 readiness and maturity measures' means.

Criterion	Item	SME Respondents' Mean	Industry 4.0 Experts' Mean	p-Value
Readiness	Strategy	2.56	2.00	0.397
	Plans	2.67	2.80	0.842
	Smart equipment	2.56	2.33	0.722
	Digital data collection	2.78	2.40	0.587
	Autonomous workpiece	1.78	1.60	0.901
	Smart product	1.44	2.40	0.176
Overall Mean		2.30	2.26	
Maturity	Big data and analytics	2.44	2.67	0.711
	Autonomous robots	1.11	2.53	0.050
	Simulation	1.89	2.67	0.153
	Horizontal and vertical integration	2.11	2.27	0.786
	Industrial internet of things	2.22	1.80	0.716
	Cybersecurity	2.22	2.80	0.368
	The cloud	2.67	3.00	0.602
	Additive manufacturing	1.00	2.00	0.028
	Augmented reality	1.11	1.87	0.041
Overall Mean		1.86	2.40	

Regarding Industry 4.0 technologies' implementation in Jordan, it is noticed in Table 2 that none of the surveyed technologies reached acceptable maturity levels (with almost all mean values below three). This is not a surprising outcome based on the modest readiness levels obtained in the previously investigated dimension. However, an interesting observation is that in three out of the nine surveyed technologies, experts overestimated the practice level (experts' mean values were higher than those for SME respondents. They statistically differed with p-values less than or equal to 0.05). The two respondents' categories differed in autonomous robots, additive manufacturing, and augmented reality aspects. Most experts who overestimated autonomous robots and augmented reality levels are academics, whose opinion, in these aspects, could be a bit biased toward technology, so we do think that the industries' findings are closer to reality for these items. Additive manufacturing is currently applied in different sectors in Jordan, especially the rubber and plastic industry. For instance, 3D printing, is currently used to produce prototypes and individual components. This feature could provide innovative solutions for supply chain implications, associated with manufacturing processes [49,50]. Experts' opinions reflected this fact. However, due to the SME samples' demography, taken from different sectors, a lower estimate for the status of this technology was obtained. To obtain more insight into each surveyed item within the four studied criteria, the responses of SME participants and experts are illustrated in Figures 3–19.

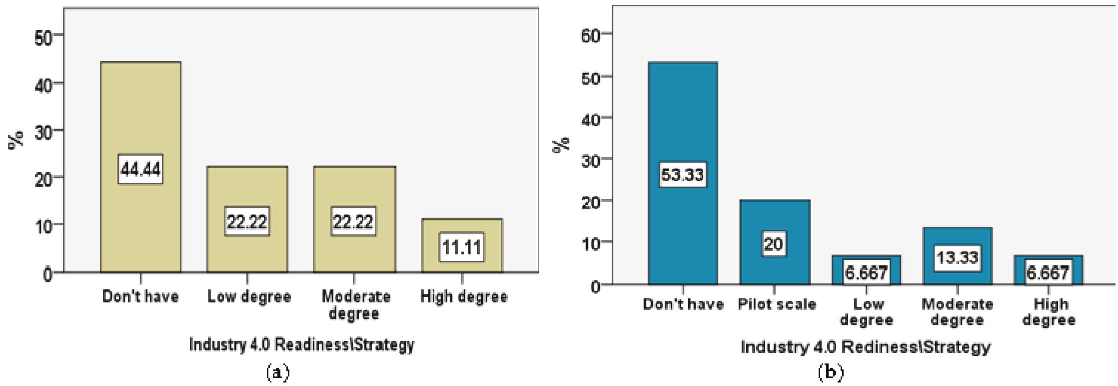


Figure 3. Response to Industry 4.0 Readiness\Strategy question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.

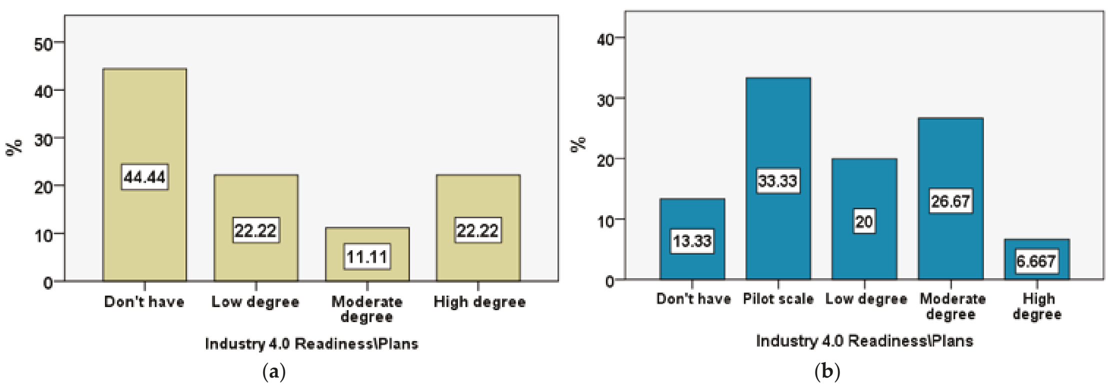


Figure 4. Response to Industry 4.0 Readiness\Plans question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.

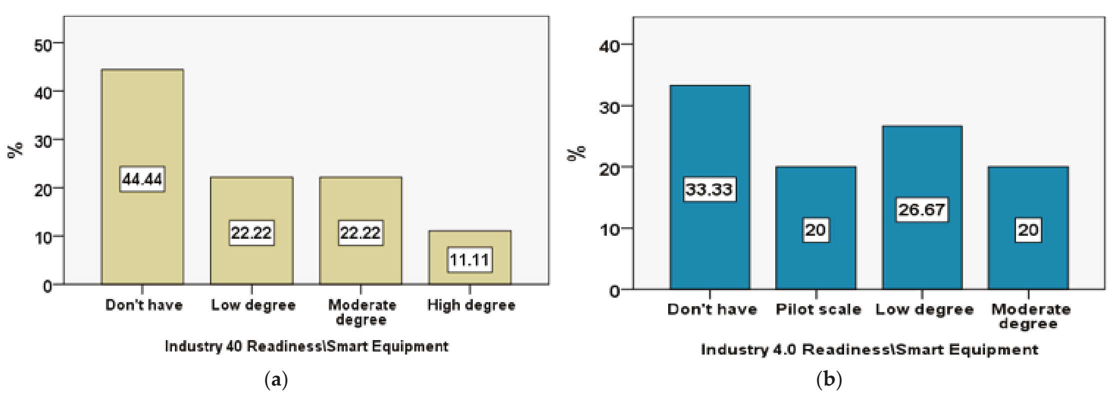
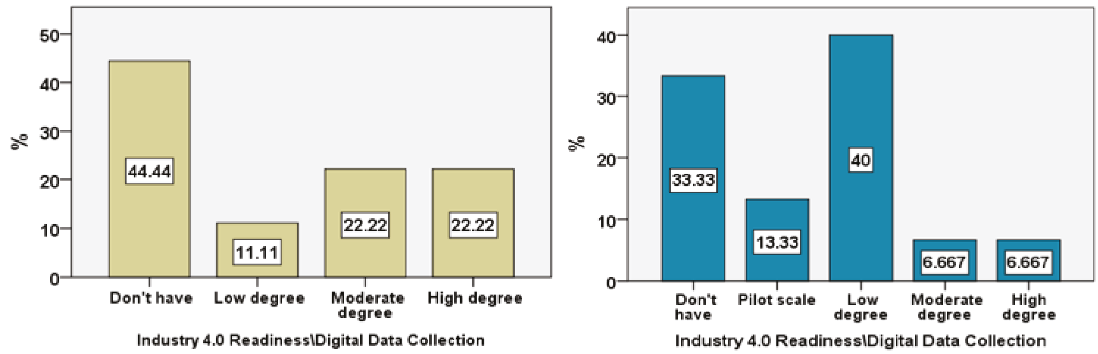
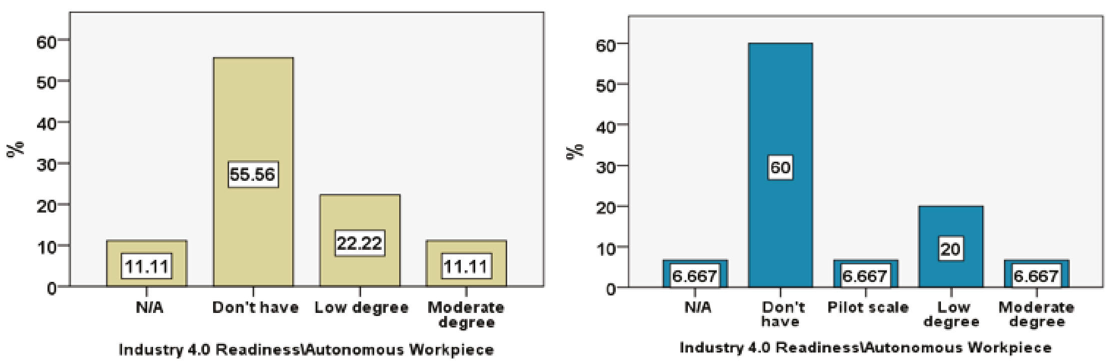


Figure 5. Response to Industry 4.0 Readiness\Smart Equipment question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.



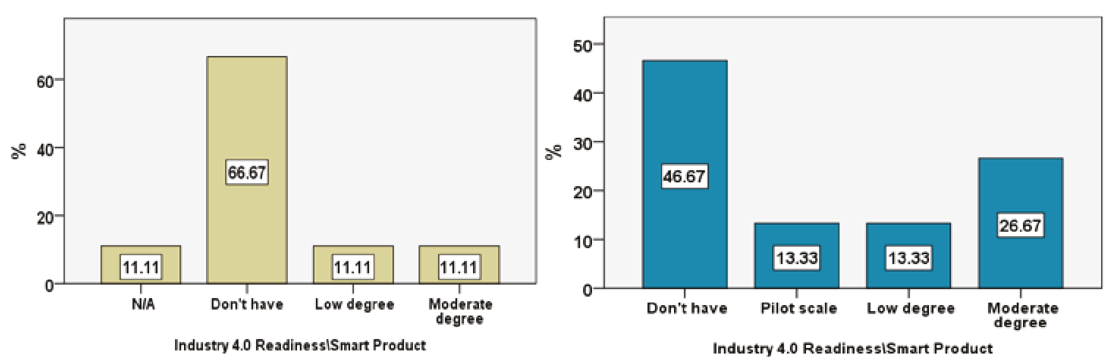
(a) (b)

Figure 6. Response to Industry 4.0 Readiness\Digital Data Collection question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.



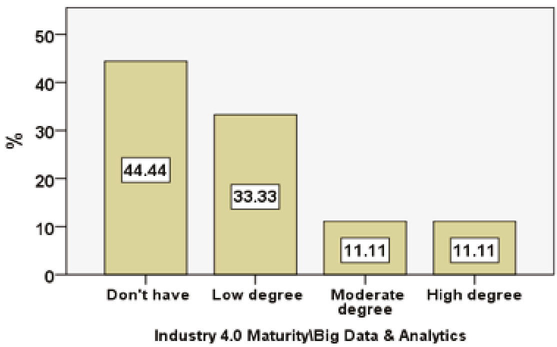
(a) (b)

Figure 7. Response to Industry 4.0 Readiness\Autonomous Workpiece question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.



(a) (b)

Figure 8. Response to Industry 4.0 Readiness\Smart Product question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.



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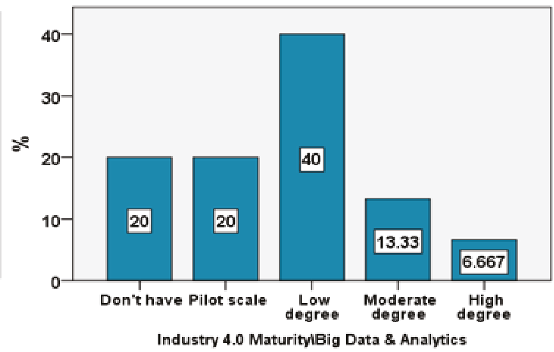
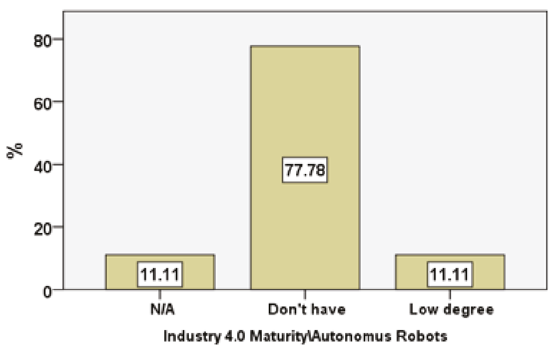


(**b**)

Figure 9. Response to Industry 4.0 Maturity\Big Data and Analytics question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.



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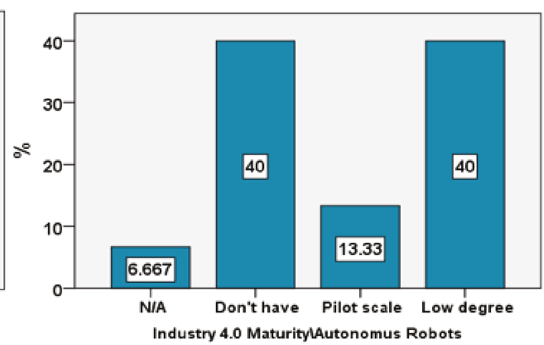
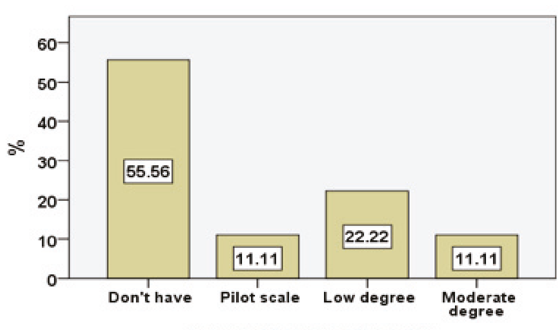


(**b**)

Figure 10. Response to Industry 4.0 Maturity\Autonomous Robots question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.



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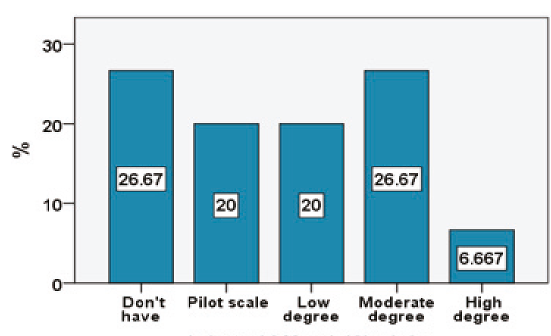

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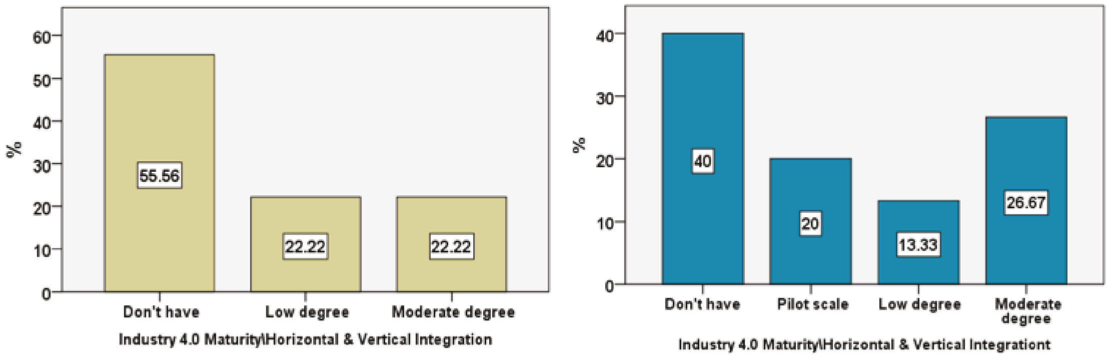
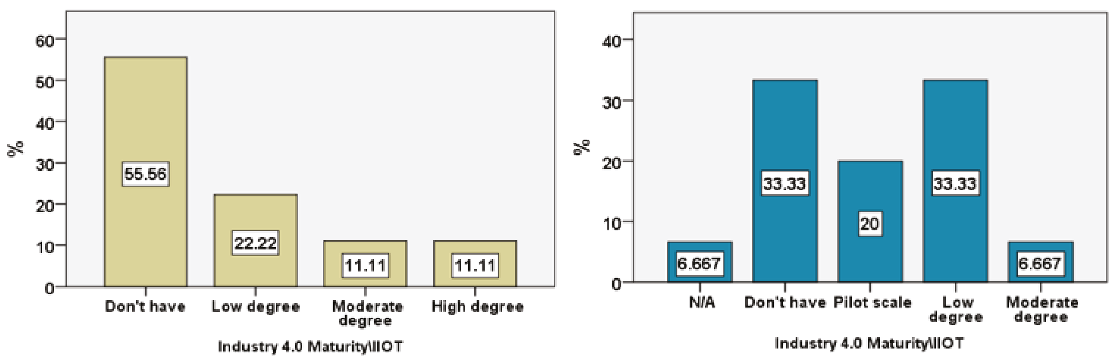
Figure 11. Response to Industry 4.0 Maturity\Simulation question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.



(**a**) (**b**)

Figure 12. Response to Industry 4.0 Maturity\Horizontal and Vertical Integration question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.



(**a**) (**b**)

Figure 13. Response to Industry 4.0 Maturity\IIoT question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.

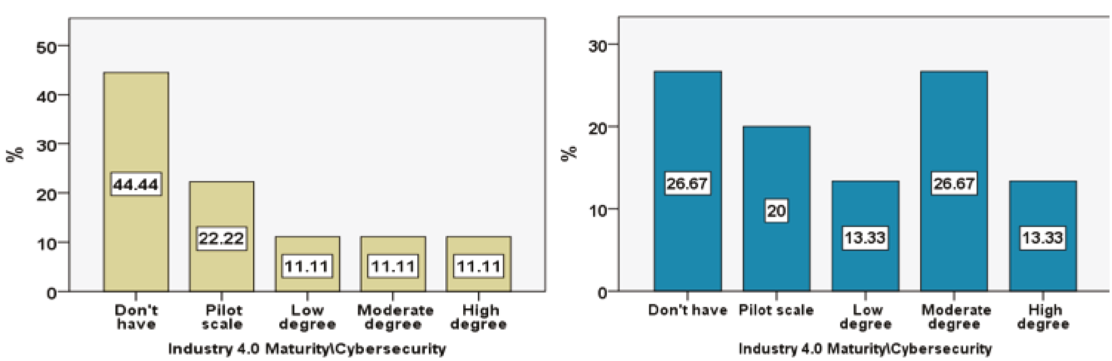


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Figure 14. Response to Industry 4.0 Maturity\Cybersecurity question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.

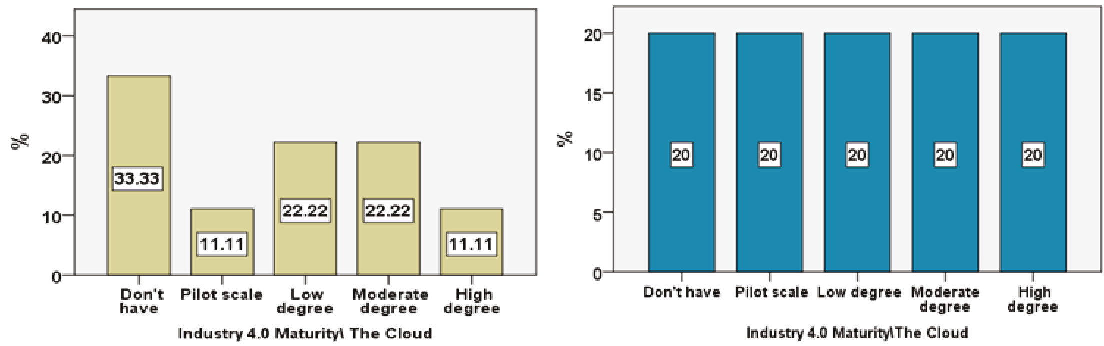

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Figure 15. Response to Industry 4.0 Maturity\The Cloud question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.

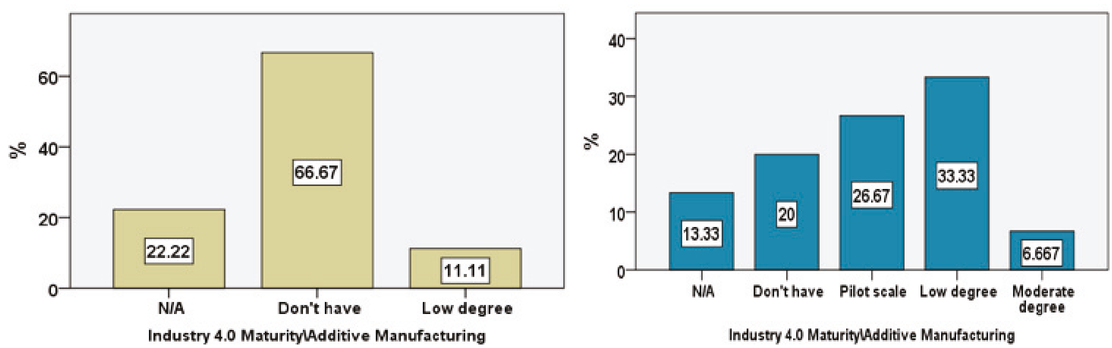

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Figure 16. Response to Industry 4.0 Maturity\Additive Manufacturing question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.

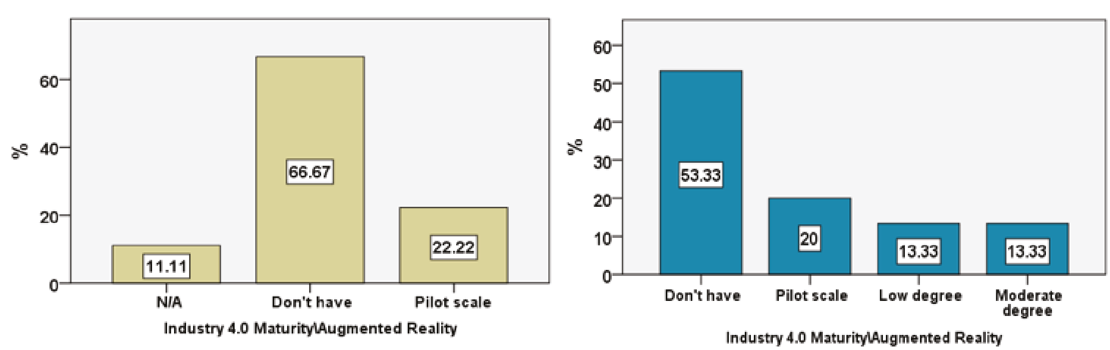

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Figure 17. Response to Industry 4.0\Augmented Reality question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.

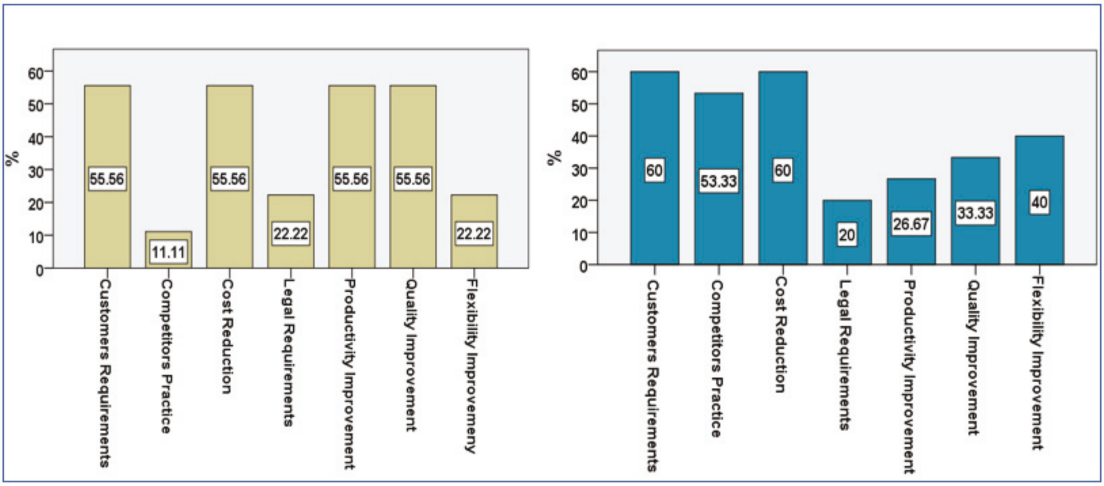

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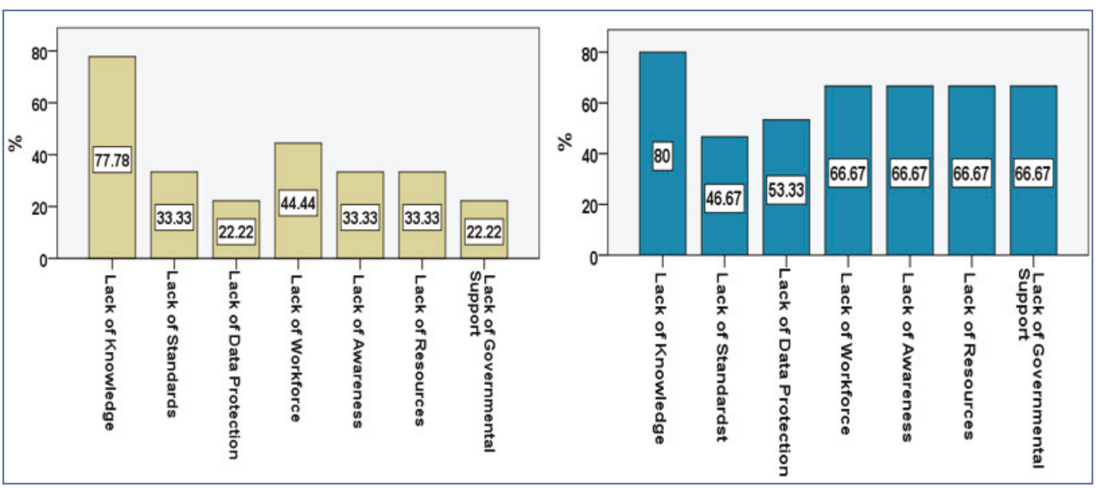
Figure 18. Response to Industry 4.0 Drivers multi-response question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.



(**a**) (**b**)

Figure 19. Response to Industry 4.0 Barriers multi-response question from two categories: (**a**) SME respondents; (**b**) Industry 4.0 experts.

To make it easier for the reader to analyze the data in the following figures, Figure 3 is described in detail, while in the other figures, only the major findings are summarized. As depicted in Figure 3, around 44% of the surveyed SMEs do not have a specific strategy for Industry 4.0 implementation, while around 22% of them have a strategy at low or medium levels. Only around 11% of the investigated companies have an Industry 4.0 strategy with a high level. Industry 4.0 experts have a slightly different opinion regarding this item; around 53% of Industry 4.0 experts, in the surveyed sample, see that SMEs in Jordan do not have a specific strategy for Industry 4.0, while 20% see that the SME sector has Industry 4.0 strategy initiatives in the pilot phase. The same percentage of the experts (around 6.7%) see that the companies have a strategy to apply Industry 4.0 to low or high levels. The rest of the investigated sample (around 13.3%) see that Industry 4.0 strategy is applied to a moderate level. As mentioned earlier in this section, the results obtained for this aspect coincide with the literature, stating that SMEs do not focus on long-term strategies and they are operations-oriented [8,27]. These findings highlight the exigency for country-scale initiatives to strategize Industry 4.0, incorporating government agencies, industry chambers, and experts.

In Figure 4, the major finding is that the highest percentage (around 44%) of the SMEs in the surveyed sample do not have plans to implement Industry 4.0 in the next five years. However, the experts' highest percentage (around 33%) shows that the companies have initiated plans in the pilot phase. Regarding having smart equipment infrastructure (e.g., machines and systems controlled through IT, machine-to-machine communication), the highest percentage of the companies in the sample (around 44%) do not have such infrastructure. The same trend is obvious in the experts' sample; around 33% agree that SMEs in Jordan do not have smart equipment infrastructure (Figure 5). SMEs' preference for the human workforce, at the expense of smart equipment, could be due to financial considerations. In developing countries such as Jordan, labor cost is relatively low and customer quality requirements are not excessive; hence, investing in smart equipment is not feasible. As can be seen in Figure 6, the highest percentage of the surveyed companies (around 44%) lack the availability of digital systems to collect machines and process data during production. Conversely, the experts' highest percentage (40%) supported the idea that SMEs in Jordan have digital data collection systems, which are used at low levels. This could be attributed to the nature of SMEs. The organizational structure of SMEs is simpler than large enterprises, with a lower number of organizational levels. This would decrease the need for traditional or digital data collection systems. Regarding the autonomous workpiece dimension, most of the investigated companies (around 56%) do not have this feature, which is compatible with most of the experts' opinions (60%) (Figure 7). The same is true for smart products, equipped with smart add-on functionalities (e.g., product memory, automatic identification, self-reporting). Most SMEs in the sample stated that they do not have these functionalities. This also complies with the judgment given by around 47% of Industry 4.0 experts (Figure 8). The outcomes obtained in the last two aspects are expected to dominate in Jordan. Autonomous workpieces and smart products are considered advanced Industry 4.0 technologies and having them within SMEs in developing countries is unlikely.

The first aspect of Industry 4.0 practice and maturity is big data and analytics. As can be seen in Figure 9, the highest percentage of the SMEs (around 44%) do not use big data and analytics, while 40% of Industry 4.0 experts think that this technology is applied in Jordan to a low degree. The reason for this difference could be the holistic view of Industry 4.0 experts, which is missing within narrow industrial horizons. Experts' opinion is based on their solid academic background in addition to their broad experience in Industry 4.0 implications. An interesting finding about the use of autonomous robots in production processes can be noticed in Figure 10. In total, 80% of the experts are divided into two equal groups, the first group (40% of the sample) think that SMEs in Jordan are not using autonomous robots, while the other group supports the idea that this technology is used in Jordan with low levels. Practically, most of the industry sample (around 78%) stated that they do not utilize autonomous robots. As stated earlier in this section, industry responses, in this aspect, are more realistic and objective than experts' opinions, which could be biased toward technology due to their academic background. The same pattern is noticed for the Industry 4.0 maturity\simulation aspect. Around 27% of the experts believe that this technology is not used in the Jordanian industry. The same percentage thinks that simulation is employed to a moderate level, while most SMEs (around 56%) depicted that they do not employ simulation in their industrial processes (Figure 11). For the horizontal and vertical integration measure, around 56% of the sample admitted that they are not users of this technology. At the same time, 40% of the experts expected this result (Figure 12). These results agree with the results of a study regarding the use of supply chain management information systems within the Jordanian manufacturing sector [44]. As can be seen in Figures 13–15 and 17, the pattern is the same for IIoT, cybersecurity, the cloud, and augmented reality technologies; the highest percentage of SMEs stated that they do not have this technology (around 56%, 44%, 33%, and 67%, respectively) which coincides with the statements given by the highest percentage of Industry 4.0 experts (around 33%, 27%, 20%, and 54%, respectively). For additive manufacturing technology, although 57% of SMEs stated that they do not use this aspect, the highest percentage of the experts (around 33%) agreed that additive manufacturing is utilized to a low degree in Jordan (Figure 16). This is because additive manufacturing does not require high investments and could be feasibly implemented in Jordanian SMEs, particularly in sectors such as engineering and plastic and rubber.

The third and fourth criteria investigated in this study are Industry 4.0 drivers and barriers (Figures 18 and 19, respectively). As mentioned earlier in this study, these criteria were measured using multi-response questions in which the respondent chose from none to all of the given drivers and barriers. For comparison purposes, any driver or barrier that is chosen by more than 50% of the samples, is considered an influential factor in Industry 4.0 adoption and implementation. As can be seen in Figure 18, there are many commonalities in the Industry 4.0 drivers chosen by industry respondents and Industry 4.0 experts. For the SME sample, the respondents chose four influential drivers which were: customer requirements, cost reduction, productivity improvement, and quality improvement. However, the experts selected customer requirements, cost reduction, and competitors' practice as influential drivers. As satisfying the customer requirements is crucial for all companies and is a key quality principle, it was expected to be the most important driver. Similarly, cost reduction is crucial in driving the adoption of any new technological revolution. For Industry 4.0 barriers, the two samples had different attitudes in selecting influential barriers. For SME respondents, only one barrier, which was lack of knowledge, was chosen by more than 50% of the sample, while for the Industry 4.0 experts, six out of the seven barriers were selected by more than 50% of the sample; these influential barriers were lack of knowledge, lack of data protection, lack of qualified workforce, lack of awareness of the importance of Industry 4.0, lack of financial resources, and lack of governmental support. This can be explained by the fact that the Industry 4.0 experts have a bird eye view toward not only the short-term barriers but also the long-term barriers that companies could face during all stages of Industry 4.0 application. This holistic view, in general, will not be clear for industry practitioners who do not have previous experience in implementing Industry 4.0 technologies in their companies.

Some of the findings in this paper are aligned with other research findings. For instance, it was found that many SMEs in Jordan do not have a specific strategy for Industry 4.0, and they do not assign employees to handle Industry 4.0 implications. The same result is true for the Czech case [40]. It was found that a lack of knowledge and lack of resources are major influencing factors that hamper Industry 4.0 penetration for both the SME respondents and Industry 4.0 experts in Jordan. The same barriers were also found in the Czech companies [40]; however, Raj et al. [11] stated that the most important influencing factor in the developed economy is the lack of maturity in technology. Regarding the other measures investigated in this research, the authors did not find in the literature a previous experience of evaluating Industry 4.0 status in a developing country such as Jordan to compare with.

6. Conclusions, Implications, and Future Work

This paper surveys the status of the Jordanian SMEs concerning Industry 4.0 readiness, maturity, drivers, and barriers. Two samples are selected from different parties: SME respondents and Industry 4.0 experts. The general outcome of both the respondents' samples is that SMEs in Jordan are not mature enough or ready to initiate the implementation of Industry 4.0 technologies.

For the six investigated aspects in Industry 4.0 readiness, SME respondents and experts agreed that, on average, the Jordanian SMEs' status is between having initiatives in the pilot phase or implementing concepts to low degrees. It is also noticed that the autonomous workpiece and smart product aspects are the least applicable in Jordan due to their considerable financial and technological requirements. Regarding Industry 4.0's maturity level, it is concluded that none of the Industry 4.0 investigated technologies have reached appropriate maturity levels. However, experts coincide with industry respondents in six out of the nine investigated technologies. The overestimation from the experts' side for the remaining three technologies (autonomous robots, additive manufacturing, and augmented reality) could be attributed to experts' possible bias toward technology.

It is concluded, from the empirical findings of this study, that customer requirements, cost reduction, competitors practice, productivity improvement, and quality improvement are essential motives to be considered when designing milestones of Industry 4.0 involvement. It is also found that the major obstacle preventing Industry 4.0 from advancing in SMEs in Jordan is the lack of awareness of the benefits and importance of applying Industry 4.0 technologies, in parallel with a deficiency in technical knowledge crucial to applying Industry 4.0 concepts.

The findings obtained in this study could be significant for current and future SME leaders to draw a roadmap for assessing their companies' status concerning Industry 4.0, measuring the gap between what exists and what is required based on their drivers for Industry 4.0 implementation, and then deploying an Industry 4.0 philosophy within their work environments. The results can also be used pragmatically by managers to identify strengths and weaknesses in the rollout of their Industry 4.0 projects. Helping SMEs to create strategies for Industry 4.0 adoption can lead to positive social changes by improving economies and creating jobs.

The government of Jordan might also use the findings of this study to diagnose how ready the Jordanian market is for Industry 4.0 implementation, providing improvement spaces for policy making on Industry 4.0. For instance, if such studies are performed on a regular time basis, they would be a reference for the government to measure the progress the companies achieve regarding technological advancement. Accordingly, they can target the government's financial and technical support for specific aspects that are promising and influential in the Industry 4.0 transition process. The outcomes of such studies could also help the government to formulate its key performance indicators that are tailored to the Jordanian experiment. The findings can be employed in country-scale initiatives for groundbreaking Industry 4.0 development, incorporating government agencies, industrial parties, and experts, relying on Industry 4.0's readiness and practice status as a starting point, and considering the influential drivers and barriers in steering the development process.

One of the major limitations of this study is the low size of the questionnaire responses. In the absence of Industry 4.0 philosophy in Jordan, it is challenging to find a representative sample from SMEs for which Industry 4.0 concepts are relevant. One recommendation is to increase the sample size and to have a variety of sectors involved. It is expected for a developing country with limited resources such as Jordan to have many struggles while trying to adopt the major changes needed to implement Industry 4.0 technologies. Some of the hampering factors found in this study that should be further investigated are the lack of data protection, lack of a qualified workforce, lack of financial resources, and lack of governmental support. There is a scarcity of country-based studies that investigate the status of Industry 4.0 in general and in developing countries specifically. For future research, these findings from Jordan can be compared with other counties, especially in the Middle East. Another recommendation is to have similar studies, in Jordan, for large enterprises to find out how sensitive the process of Industry 4.0 application is to business size. A good point is to have customized surveys for specific industrial or service sectors and compare the results of the same sector in different countries, investigating how geography and demography can affect Industry 4.0 implementation. Finally, there will be added value if more studies are conducted on specific industrial sectors in Jordan that are more advanced and more able to absorb Industry 4.0 concepts such as the pharmaceutical and mining industries.

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Article

Quantifying the Benefits of Digital Supply Chain Twins—A Simulation Study in Organic Food Supply Chains

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Abstract: *Background*: Digital supply chain twins (DSCT) are gaining increased attention in academia and practice and their positive impact on logistics and supply chain management (LSCM) performance is often highlighted. Still, LSCM executives are hesitant regarding DSCT implementation. One reason is the difficulty of making a reasonable cost–benefit comparison, because the benefits of using a DSCT are rarely quantified. Moreover, there seems to be no method of quantifying these benefits as of today. *Methods*: This article builds upon an extensive simulation study of a constructed organic food supply chain (FSC), containing as many as 40 simulation experiments. In this simulation study, three volatility scenarios in the FSC were simulated and their effects on LSCM performance were measured. Subsequently, dynamic simulation experiments were run to emulate DSCT use. The benefits of using a DSCT were then quantified using a newly developed approach. *Results*: A conclusive method for quantifying the benefits of using a DSCT is presented and validated. Moreover, the performance evaluation of using a DSCT for the multi-echelon inventory management of an organic FSC is given. *Conclusions*: The study leads towards a method for quantifying the use of DSCTs that is of importance for research and practice alike. For managers, it additionally provides an exemplary application of said method in the context of organic FSCs.

Keywords: digital supply chain twins; logistics and supply chain management; digital twin; logistics; supply chain management; organic food supply chains; agent-based simulation; discrete event simulation

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1. Introduction

Supply chains (SC) today are facing a variety of challenges. Globally distributed production sites, a growing world population, natural disasters and even crises such as the COVID-19 pandemic or global financial crises are placing a strain on companies worldwide. SC volatility often leads to consequences such as supply bottlenecks and lost sales. In addition, the topic of sustainability is becoming increasingly important in LSCM. The demand for sustainable SCs requires companies to come up with new ways of managing LSCM activities. To overcome these challenges, digitization offers new, innovative approaches [1]. While it presents companies with difficulties, digitization also offers a lot of problem-solving potential. Processes and business models are changing, and the appropriate implementation of innovative digital concepts provide LSCM companies with the opportunity to increase efficiency [2].

Furthermore, the COVID-19 pandemic has increased the issue of SC resilience in the face of SC volatilities. SCs have been put under pressure and customers often could not be supplied on time. In addition, there was a sharp increase in demand for individual product categories. For example, there was a shortage of various products in supermarkets and shelves remained empty [3]. Another example of vulnerable SCs was the Suez Canal obstruction in 2021, which disrupted international SCs, resulting in various products being delivered several weeks late. This revealed the problem of SCs featuring dependencies on individual, globally distributed suppliers [4]. In order to prevent fulfillment delays, companies must rely on resilient SCs in order to ensure customer satisfaction. In this regard, supplier selection plays a critical role in order to be able to respond to volatile customer demand [5].

Meanwhile, Digital Twins (DT) are receiving more and more attention in research and in practice. It is considered an innovation that is seen as an opportunity across industries and sectors to improve the planning and control of all kinds of systems. Since only a few concepts have been implemented in science and in companies and most of these concepts are in the development phase, there is a need for research in this area [1]. The technology has great potential for growth. Estimates predict an annual market growth for DTs of 38 percent by 2025 [6]. Even less researched and implemented in practice is the concept of the digital supply chain twin or digital logistics twin (DSCT), which represents the application of the DT concept in the domain of LSCM. It promises, for example, greater SC transparency, increased network resilience, and lower inventory levels [2]. LSCM is a suitable application area for DTs because of the ever-increasing amounts of data and the interdependencies in decision making [6]. DSCTs can find applications in a variety of industries, such as pharmaceuticals, organic food, and precision agriculture [7]. All in all, the DSCT is discussed as a promising innovative solution to overcome the aforementioned challenges in LSCM.

One industry where volatility and resilience are especially significant is the organic food industry. Issues such as visibility and traceability play a major role here to ensure product quality and customer satisfaction. Optimizing logistics processes for companies in the food sector is particularly important, as logistics costs in the food sector account for 6–10% of total sales [8]. Annual sales in the organic food industry have been growing steadily since 1999, rising from €96.7 billion to €106.4 billion between 2018 and 2019. This trend is expected to continue to strengthen due to the change in customers' environmental awareness [9]. Still, the industry is characterized by SC inefficiencies. More than one third of food is lost from farm to fork [10]. In order to reduce food waste, better planning and control of the relevant logistics system is required. Through greater transparency and the use of technological advancements food loss can be reduced and additional costs can be saved [8]. Therefore, the organic food sector presents itself as a promising application domain for DSCT development [7].

Several studies discuss the benefits of using the simulation capabilities of a DSCT in order to better be able to react to SC volatility. However, as of today, a small number of implemented DSCTs exist, both in practice and in research. Although some publications describe the benefits of using a DSCT qualitatively, few are shown to quantify the benefits [2]. In particular, the benefits of a DSCT in the organic food industry have not yet been investigated, although there are great potentials, such as an increase in product quality. As the costs and benefits are not easily estimated, it is difficult to determine the overall value of a DSCT [7]. This makes it all the more difficult for practitioners to generate a reasonable cost–benefit comparison, which presents a major barrier for the implementation of DSCTs.

Considering these developments and recent shortcomings of the current literature in this field, this study seeks to contribute to a much-needed method for quantifying the benefits of using a DSCT in terms of LSCM performance improvement, using the example of an organic FSC. More specifically, this study aims at the following research objectives (RO):

RO1: Develop a method for quantifying the effects of using a DSCT in terms of LSCM performance.
RO2: Evaluate the effect of using a DSCT in multi-echelon inventory management of an organic FSC in terms of LSCM performance.

For this purpose, an extensive simulation study was conducted. Subject of investigation is a case study featuring a constructed organic FSC, which was depicted in a simulation model. Different volatility scenarios regarding both customers and suppliers were then simulated and their effects on LSCM performance were measured. Subsequently, the simulation model was used to emulate the use of a DSCT, altering the system's inventory, procurement, and order strategies. The benefits of a DSCT were then measured using a newly developed quantification method. Thereby, this study provides a first attempt of a quantitative analysis of a DSCT application, thus filling a considerable gap in DSCT research.

In order to contribute to RO1, Section 2 first provides a detailed description of a DSCT in organic FSC. The specific use case of multi-echelon inventory management is then described, as well as the processual and analytical improvements the DSCT provides. Moreover, the case study is defined, introducing the structure of the organic FSC in question, as well as the existing challenges with regard to volatility. Finally, a new method for quantifying the benefits of using a DSCT is derived and described in Section 2.3. In accordance with RO2, a simulation study containing 40 simulation experiments is presented in Section 3, with the ultimate goal of quantifying the effect of using a DSCT in multi-echelon inventory management of an organic FSC in terms of LSCM performance. In Section 4, an analysis of the experiment results is shown, demonstrating the DSCT's effect on different dimensions of LSCM performance. This does not only demonstrate and verify the usability of the quantification method presented in Section 2, but also gives a good overview of what benefits to expect when using a DSCT in this specific use case. Afterwards, the results are discussed in Section 5. Finally, Section 6 provides a conclusion.

2. A Digital Supply Chain Twin in Organic Food Supply Chains

2.1. A DSCT for Multi-Echelon Inventory Management

Today, many definitions and understandings of the DSCT concept exist in the scientific literature. According to Ivanov et al. [5], a DSCT serves as a decision-making aid for the physical value network through data support. Accordingly, the DSCT reflects the SC in real-time with existing stocks, demands, transport routes and other logistical parameters. Niaki and Shafaghat [11] criticize that this understanding reflects common practices of SC planning and modelling, but does not describe the properties of a DSCT. They define the DSCT as a detailed simulation model of the SC, which can be analyzed in order to better understand, learn, and reason in regard to the real-world system. To provide a conceptual clarification, Gerlach et al. [2] conducted an extensive literature review, where they came up with the following definition, which serves as a basis for this study. Figure 1 acts as a visual representation of the concept.

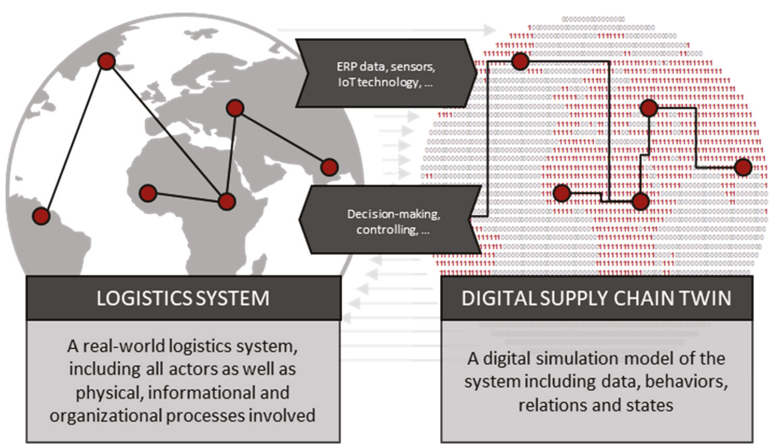

Figure 1. The digital supply chain twin (DSCT) concept Reprinted with permission from Ref. [2]. Copyright 2021, copyright Benno Gerlach.

*A **digital logistics twin** or **digital supply chain twin (DSCT)** is a digital dynamic simulation model of a real-world logistics system, which features a long-term, bidirectional and timely data-link to that system. The logistics system in question may take the form of a whole value network or a subsystem thereof.*

Through observing the digital model, it is possible to acquire information about the real logistics system to draw conclusions, make decisions, and carry out actions in the real world. The DSCT enables the use of diagnostic, predictive and prescriptive methods with the ultimate goal of holistically improving the logistics performance along the whole customer order process [2].

Among other aspects, the authors underline the importance of dynamic simulation capabilities in a DSCT, which in turn enable the user to run what-if scenarios. It is also made clear, that not all attributes of a DSCT are predefined when talking about the general concept. While some DSCTs are updated in real-time, for example, for others a lower updating frequency is sufficient. These attributes are determined by the specific use case, in which the DSCT creates benefits.

In the study at hand, a DSCT on the network-level is analyzed. It is applied in the area of network management, more exactly multi-echelon inventory management. In multi-echelon inventory management, the DSCT represents a SC from suppliers to customers. This model is then used to test inventory and procurement strategies and evaluate their SC performance [2]. In this sense, the DSCT might also be used to improve a company's ability to react to SC disruptions and other risks in order to improve SC resilience [12]. In order to do so, the DSCT is updated in a timely manner. Real-time updating seems to be unnecessary, because relevant changes in the system do not occur within seconds or minutes. SC disruptions may be addressed in day-to-day operations, where the user is still able to respond efficiently. Therefore, a daily frequency seems to be sufficient. A DSCT might be used both reactively and proactively. Some SC disruptions, such as demand spikes, can be anticipated before they occur. In this case, scenarios can be proactively simulated in the DSCT in order to test the best possible response [13]. In other cases, risks are not predictable. The DSCT then helps to make reactive decisions immediately after the incident occurs. In this study, only reactive use is examined.

Several researchers have addressed the use of a DSCT in the food industry. Defraeye et al. [14] describe the optimization of a fruit SC by modeling the temperature of a transcontinental value network. DSCTs are considered a useful addition in the perishable food sector to minimize food losses due to improper storage. Burgos and Ivanov [15] develop a model of a DSCT in risk management using the COVID-19 pandemic as a motivation, as it can help value networks recover after a breakdown. AnyLogistix (ALX) is used as a simulation tool. However, their approach notably lacks the feedback of the DSCT into company processes and therefore does not differ significantly from a basic SC simulation model. Nikitina et al. [12] develop a DSCT of a food network with the help of a mathematical simulation model. The complex properties of the food products play a decisive role in their calculations.

In recent years, FSCs have been subject to numerous simulation studies, observing their ability to react to SC disruptions. Lohmer et al. [16] analyzed different resilience strategies with an emphasis on blockchain technology. Singh et al. [17] as well as Zhu and Krikke [18] examined the effects of COVID-19 related disruptions on FSCs. All these studies underline the importance of resilience enhancing technologies to ensure SC performance even in the face of SC disruptions. Accordingly, Yuan et al. [19] stress the importance of horizontal logistics collaboration. This study builds on this area of research by examining the use of DSCTs to improve decision making in FSCs in the face of SC disruptions.

The results of this study will tie in with various studies in DSCT research. First, the organic food industry is identified as a relevant industry for the use of a DSCT by Srai et al. [7], as it promises higher transparency. Moreover, a continuation of some aspects of the publication by Burgos and Ivanov [15] is given, in which the authors perform scenario analyses using a simulation model of an FSC. This study further developed their approach by extending the quantification method to integrate a feedback loop into the real logistics system. Finally, Gerlach et al. [2] identified a research gap in quantifying DSCT use. Accordingly, through the investigation of a DSCT in the organic food industry conducted in this study, insights can be derived that have not yet been addressed in academia.

This study seeks to further investigate the use of DSCTs in the organic food industry. Therefore, a case study featuring an organic FSC was constructed, which will be described in detail in the next section.

2.2. A Case Study in Organic Food Supply Chains

In this study, subject of investigation is a SC in the organic food industry. Organic food products are usually available in conventional retail supermarkets as well as in organic supermarkets, in which up to 10,000 different organic food articles can be found. Often, the procurement is carried out regionally in small-scale and decentralized transports [8]. The FSC is one of the most complex and fragmented value networks, with production mostly worldwide. The wide range of products and the large number of individual product categories lead to a variety of logistical challenges. Products such as dairy products, fresh meat, fish, fruit and vegetables or frozen foods must be temperature-controlled [20]. This complexity is a further argument for the use of a DSCT. Figure 2 shows the individual actors and functional areas of an FSC.

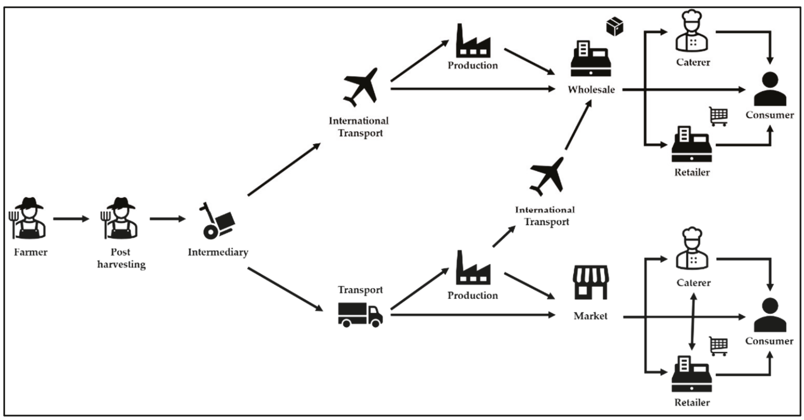

Figure 2. Functional areas and actors in international food value chains. Reprinted with permission from Ref. [21]. Copyright 2020, copyright Julia Kleineidam.

In 2021, Patidar et al. [22] conducted a structured review of the literature published on FSC management in the past 15 years to give an overview of the research field and identify research gaps. Among other implications, the authors found that even though a large number of articles discussed and highlighted the problems, challenges, and issues in the FSC, few studies presented strategies to overcome them. Especially the prevention of food loss through LSCM efficiency as well as the proper utilization of emerging technologies are identified as possible research gaps. This work aims at filling these gaps by examining the DSCT as a potential technological solution in the context of a domain-specific case study.

The case study examined in this work features a European FSC, with an emphasis on the German sales market. It includes a value network from suppliers to supermarkets (retail stores). Even though production takes place worldwide, the immediate suppliers of finished products are located in Europe, predominantly in Germany. There are twelve European suppliers, who receive their products from global producers. These suppliers supply a central distribution center (DC) in Germany, which in turn supplies five wholesalers, that are spread across Germany. These sites act as hubs, storing goods and distributing them to the retail stores all across the country. The retail stores are characterized as organic food supermarkets and act as the final customer for the FSC in question. Hence, the system in question is a four-stage value network. Only four product categories are considered. Figure 3 shows a simplified representation of the FSC.

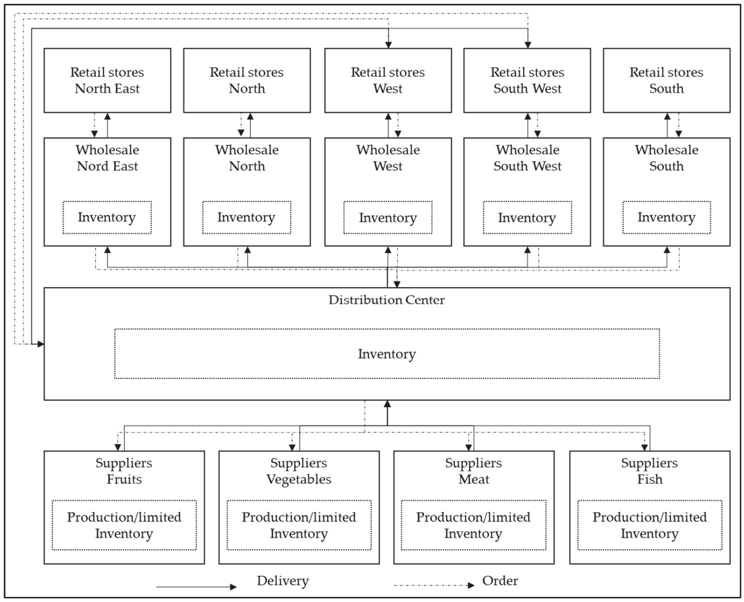

Figure 3. Food supply chain of the case study.

The case study company sells organic food produce at German retail stores. It is based on one of the three largest retailers in Germany, which sources about 6000 organic products worldwide [23]. In order to achieve greater visibility and transparency along the FSC, the company decides to use a DSCT. It hopes to be able to better manage its network-wide inventory as well as react to SC risks operationally and strategically.

The user of the DSCT is the SC manager in Germany, who coordinates and optimizes the company's network-wide product supply. She is responsible for the procurement of products, up to the delivery of the products to the supermarkets. His tasks include developing procurement, inventory and order strategies, drawing up contingency plans and evaluating suppliers. The SC manager sits at the DC but is in close contact with dispatchers in the respective hubs, in order to optimize inventory levels across different SC echelons. One of the user's goals is to ensure efficient hub utilization, enabling timely product deliveries to the retail stores, even under changing SC conditions. The scope of the SC manager in this case study thus includes both operational and strategic tasks. Accordingly, she is responsible for procurement logistics, determining the ordering policies as well as defining inventory policies. Thus, a holistic approach to LSCM tasks is given [24].

The user in question has access to a network-wide DSCT, representing the SC from the suppliers to the retail stores. In the event of changing SC conditions, he can run "what-if" scenarios in order to develop a suitable strategy. For this purpose, it is assumed that the user feeds the knowledge gained back into the real logistics system by adopting different strategies. The DSCT evaluates these strategies across different dimensions of SC performance. For this purpose, several performance measurement systems exist in theory and practice, which include financial as well as non-financial measures [25,26].

2.3. *A Quantification Method for DSCT Benefits*

Ironically enough, most DSCT studies do not feature a real-world DSCT. They mostly use a basic simulation model, which is not connected to any real-world system and therefore does not qualify as a DSCT. Still, it is carried out so in a variety of studies: A SC disruption is first being simulated, after which the level of SC performance drops. Subsequently, the features of the simulation model are being used to improve SC performance due to strategies, that better fit the new situation. The level of improvement is then presented as the expected benefit of the DSCT.

However, this approach neglects the fact, that in a real use case a user would have to use the DSCT during ongoing operations. There has to be a feedback loop returning the simulation results into company processes. This process needs to be emulated in order to obtain a better understanding of the effect a DSCT use has on SC performance. Even if this feedback loop is not executed using real-world company data, it can be emulated using a fitting simulation model. For this purpose, an adequate method should be developed in order to be able to adequately quantify the benefits of using a DSCT, as a basic simulation model is not sufficient. Therefore, in accordance with RO1, the following approach is presented as a possible solution:

1. Use Case Definition
    a. Logistics System Description
    b. Input Parameters
    c. Output Parameters
2. Scenario Selection
    a. Baseline Scenario
    b. Modified Scenarios
3. Process Emulation
    a. Objectives
    b. Resources
4. System Simulation
    a. Initial Baseline Scenario
    b. Modified Baseline Scenarios
    c. Optimized Modified Scenarios

Use case definition: First, the DSCT use case is to be defined in detail. This begins with a description of the logistics system in question. Furthermore, the input and output parameters have to be set. The input parameters consist of the decisions and actions that the user in question inputs into the real system. The output parameters are certain LSCM performance measures. The user's performance is evaluated on the basis of these. The measures used should always form a holistic performance evaluation of the logistics system in question, as is appropriate in LSCM.

Scenario selection: Next, scenarios to be investigated are to be selected. The scenarios chosen should reflect possible applications of the DSCT in the use case described prior. The first scenario should always be an initial baseline scenario. On the one hand, this initial baseline is used as a validation. The output parameters should be compared with real-world measures to ensure model accuracy. On the other hand, the initial baseline serves as a means of comparison. Afterwards, the modified scenarios have to be selected. These scenarios should represent alternative situations the DSCT user can find himself in during ongoing operation. For this purpose, domain experts should be consulted. The scenarios should be both probable and relevant in terms of the use case in question. For an application in risk management, for example, these modified scenarios might be the occurrence of various SC risks.

Process emulation: The first level of simulation is the emulation of the user process. This should be a replication of all the steps a user would perform in the real-world optimization process. During this phase, the simulation model acts as a tool for reacting to the modified scenarios defined in the prior step when trying to optimize the output parameters. For this purpose, objectives have to be defined. They may take the form of measures and respective target values the user tries to achieve with her actions. As the user would not have unlimited time in a real-world application, money and other resources, these resources also have to be defined beforehand. This may be carried out by setting a fixed maximum number of iterations for the optimization process.

System simulation: Ultimately, the different final scenarios have to be fed into the model to simulate the system's behavior over time, thus forming the second level of simulation. During this phase, the simulation model acts as a tool to reflect the system's behavior over time. For this purpose, the results of the prior process emulation step are taken. These results represent the user's decisions that were made using the DSCT as a decision support tool. These decisions are then input into the simulation model in the form of altered input parameters. In order to be able to put the results into perspective, the initial baseline scenario should first be simulated. Subsequently, further baseline scenarios should follow—one for each modified scenario to be investigated. The results of these experiments reflect the system's behavior when the modified scenarios occur, but no DSCT is used. Lastly, the optimized modified scenarios should be simulated. The results of these experiments reflect the system's behavior when the modified scenarios occur and a DSCT is used to optimize the system. The input parameters for these experiments are taken from the process emulation step. The reaction time of a user should also be considered in this step.

Following these steps should give a realistic overview of the expected benefits of using a DSCT in a given use case. A comparison between the initial baseline scenario and the modified baseline scenarios gives an estimate of the expected outcomes of the SC modifications on SC performance. In the example of risk management, this may form a means of risk assessment. A comparison between the modified baseline scenarios and the optimized modified scenarios gives an estimate of the effect DSCT use has on LSCM performance regarding the use case in question. In the following, the method was applied to the use case of this study:

Use case definition: The use case in question is multi-echelon inventory management of an FSC. A detailed use case description is presented in Section 2.2. The input parameters are the inventory, procurement, and order strategies of the DC and the hubs as described in the case study. In order to evaluate the DSCT's effect on SC performance, a fitting performance measurement system was derived from theory. The performance measurement system is divided into the five categories of efficiency, flexibility, responsiveness, food quality and sustainability [25–27]. Each category is measured by key performance indicators (KPI) that are presented in Table 1:

Table 1. Supply Chain Performance Measurement System of the Case Study.

Category	KPI
Efficiency	Total costs Purchasing costs Inventory carrying costs Transport costs Profit
Flexibility	Dropped orders
Responsiveness	Order fill rate Lead time
Quality	Average daily available inventory Service level per product On time delivery (OTD) of orders OTD of products
Sustainability	Total CO_2 emissions

Scenario selection: As the use case in question deals with multi-echelon inventory management of volatile SC, the scenarios to be examined are different volatility scenarios. Three scenarios including two different kinds of SC disruptions were examined. First, an increase in demand. Second, the breakdown of a supplier. Third, both a demand increase and a supplier breakdown.

Process emulation: The user utilized a simulation model in order to test different strategies in response to SC disruptions. Therefore, he ran experiments for different what-if-scenarios with the DSCT and made quantitatively justified decisions on suitable solutions based on the experiment results. His ultimate goal was the optimization of the logistics system in the face of the given SC disruption. For reasons of simplicity, only one objective was defined for this study: Achieving a service level of at least 98% per product for all locations within the scope. Still, all SC performance measures were evaluated in the end. For resource constraints, a minimum of 5 iterations and a maximum of 15 iterations were selected. The what-if scenarios were carried out using a consistent procedure, which will be further described in Section 3.3. This process led to a final set of strategies for each of the three volatility scenarios, determined by the user in order to best handle the given SC disruptions.

System simulation: In this step, the system's behavior over time was simulated for each volatility scenario. For this purpose, the initial baseline, the modified baseline, and the optimized modified scenario were compared. Thus, the use of a DSCT in the given use case could be evaluated. A visual representation of the applied method is shown in Figure 4.

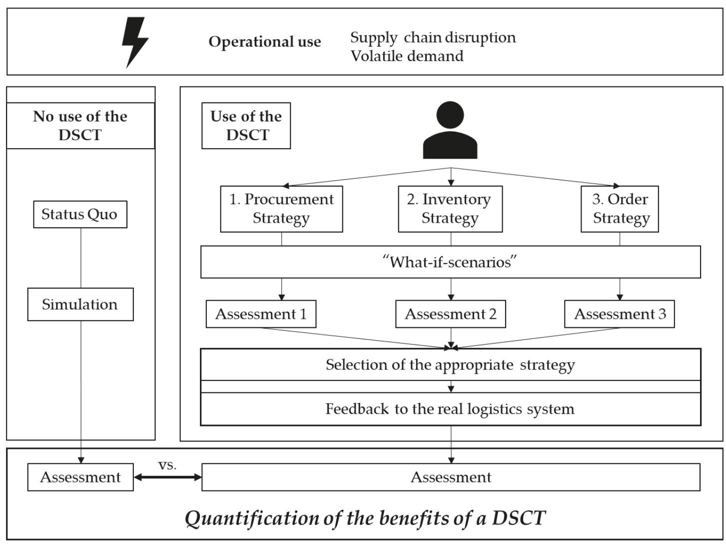

Figure 4. Quantification method for DSCT benefits of the case study.

3. Research Design

In order to apply and test the developed method and its application to the given use case, a simulation study was conducted. ALX was used as a simulation tool. Furthermore, a well-proven process model for conducting simulation studies by Rabe et al. [28] was used as a methodological guideline. The sub-processes of said model were slightly adapted and are described in the following part. Similar approaches have been utilized in the recent scientific literature, where simulation studies were chosen as a methodology in order to examine the effects on organizational or technological measures on FSC performance [16–19,29].

3.1. Objectives and Tasks

Objective description: The objective of the simulation study is quantifying the effects of using a DSCT for managing inventory and procurement in an organic FSC. Simulation is used as it constitutes a major component of the DSCT. Thus, this simulation study directly targets RO2.

Task description: The objective is met through conducting what-if scenarios, emulating the use of a DSCT in the face of different volatility scenarios. The selection of the volatility scenarios is further described in Section 3.3. The effects of different strategies on certain LSCM measures are then evaluated in order for them to be comparable. Therefore, the user performs an optimization for each volatility scenario in order to deal with the DC disruption she is facing. By means of dynamic factor design, a step-by-step attempt is made to improve LSCM performance.

3.2. System Analysis and Model Formalization

The system in question is the FSC described in Section 2.2, with focus on four product categories: fruits, vegetables, meat, and fish. For reasons of simplicity and feasibility, a consideration of sub-categories or single products was refrained from. To gain insights into the system, several data sources were used. Some of the data used were freely available on the Internet, while other data were obtained from publications. These are either statistical calculations, real data, or estimates. All data sources are provided in the following paragraph.

The location data regarding the retail stores in Germany were taken from a publicly available database [30]. The demand values of the individual product categories are based on a calculation using the per capita consumption per year with the respective market share of the given retail chain. This was then multiplied by the share of organic food in the total food market in Germany. Therefore, the demand per day per inhabitant in Germany was determined. Finally, the demand of all retail stores was automatically generated in ALX, using the number of inhabitants of the different locations [23]. The sales prices were determined by the average prices of the given food categories in the year 2022 [9].

For reasons of simplicity, shipping costs were included in the purchase price. Initial stock levels as well as costs for stock refilling were also reflected in the purchase price. [15] To measure CO_2 emissions, truck emission factors based on load weight and distance travelled were derived using the publicly available EcoTransit calculation tool, which is recognized in research. In order to take energy consumption for truck loading activities into consideration, an additional coefficient was added per delivery [31]. Furthermore, a distance- and weight-based calculation of travel costs was selected.

Since only some product categories are included, the key figure of truck utilization is not decisive. Accordingly, trucks could drive at less-than-truck-load (LTL) between locations. Two types of trucks were considered. Between the suppliers, the DC and the hubs, trucks with larger capacity (26 t) were used. The last-mile delivery to the supermarkets was executed using trucks with smaller capacity (7.5 t), as they have to drive to city centers.

Inventory policies of the DC and the hubs were set to be identical: make-to-stock (MTS). By selecting a Min-max policy (s, S), excessively high and low inventories can be avoided. For this purpose, a replenishment point (s) and a target stock (S) were defined. A new order is placed whenever the inventory level falls below the replenishment point (s). The ordered quantity is the delta between S and the current inventory level. The target stock (S) at the DC was set to be larger than the daily demand in Germany as a whole. The replenishment point (s) at which reordering takes place is usually half of the value of S. At the hubs, inventory levels are lower. The target stock was set to be equal to the daily local demand per product. Inventory levels are checked twice a day, so that orders are placed a maximum of twice a day.

To calculate the system's inventory cost, the storage costs at the DC and the hubs were calculated. The storage costs for the suppliers were not considered. All suppliers had the same capacity and could order from the producer as often as they wanted. The expected lead time of the retail stores was set to be two. An overview of the case characterization is presented in Table 2, while Figure 5 shows the model SC implemented in ALX.

Table 2. Case study characteristics.

Characteristic	Amount	Attributes
Product categories	4	Fruits, vegetables, meat, fish
Supermarkets/customers (blue icons)	139	Spread country-wide
Wholesalers/hubs (dark green)	5	Northeast, north, west, southwest, south
DC (red)	1	Lorsch, Germany

Table 2. *Cont.*

Characteristic	Amount	Attributes
Suppliers (orange/fruits, green/vegetables, brown/meat, blue/fish)	12	3 per product category
Vehicle types	2	Small truck (7.5 t), heavy truck (26 t)
Inventory policy of wholesalers	1	Min-max policy
Inventory policy of DC	1	Min-max policy
Supplier restrictions	2	Production capacity, order capacity

Figure 5. Food supply chain of the case study implemented in the simulation tool.

3.3. Experiment Plan and Analysis

Four different kinds of scenarios were tested in order to simulate the system's behavior in the face of different forms of SC volatility. There is one initial baseline scenario and three volatility scenarios. In the initial baseline scenario, the status quo of the FSC was simulated. In this scenario, the FSC was set up so that all suppliers are available and deliver to the DC in Lorsch. The SC performance measurement system presented in Section 2.3 was used to evaluate LSCM performance. It should be noted that some of the KPIs have different names when implemented in ALX. The dropped orders, for example, were derived from the product backlog measured in the simulation tool, as both measures represent the lack of order fulfillment to the customer.

Scenario 1 examines the occurrence of a customer risk. One reason for this could be a worldwide pandemic, for example, which causes a strong and spontaneous increase in demand. It was assumed that demand increased by 100% during a defined period. The duration of the demand increase was set between 15 and 120 days. In a sensitivity analysis, the influence of the duration of the demand increase was determined first.

In scenario 2, there are supplier disruptions. The suppliers of meat products in Germany close their sites and can no longer supply the DC. The company needs to react quickly and use the DSCT to develop a strategy to still be able to supply the retail stores. The breakdown duration was set between 15 and 90 days. Again, a sensitivity analysis was performed to evaluate the effect of different durations of supplier downtime on the LSCM performance.

In scenario 3, it is assumed that both effects mentioned above occur simultaneously. Possible reasons for this are global pandemics causing unexpected demand spikes and factory closures. The duration of both the demand increase and the supplier breakdown was assumed to be 60 days. The magnitude of the demand increase was set between 50% and 200%. Again, a sensitivity analysis of different magnitudes of demand increase was performed.

An overview of the different scenarios and the respective experiments is presented in Table 3.

Table 3. Volatility Scenarios analyzed in the Case Study.

Scenario	Demand Increase	Time (Days)
Scenario 0: Initial baseline	/	/
Scenario 1: Demand increase	100%	15–120
Scenario 2: Supplier breakdown	/	15–90
Scenario 3: Demand increase + supplier breakdown	50–200%	60

For each scenario, the SC performance measurement system presented in Section 2.3 was used to evaluate different inventory and procurement strategies. The system was implemented in ALX in the form of a dashboard, which is a good representation of an actual DSCT being deployed in a real-world use case. For reasons of readability, not all parts of the dashboard can be shown in all steps.

For each scenario, the user then performed an optimization in order to deal with the DC disruption she is facing. By means of dynamic factor design, a step-by-step attempt was made to improve LSCM performance. A maximum of 15 iterations were conducted per scenario, with the goal of achieving a service level of at least 98%.

4. Results

In this section, the experiment results are presented. The section is structured in accordance with the different volatility scenarios presented in the previous section. For each volatility scenario, an overview of the LSCM performance is given. Additionally, a description of the disruption effects on the FSC is given in scenarios 1–3. Subsequently, the effects of the DSCT use are described. This is done not only in terms of LSCM performance measures, but also in terms of the system's behavior over time.

4.1. Scenario 0: Initial Baseline Scenario

First, the initial baseline scenario was examined. For this purpose, one simulation experiment was conducted. The KPIs measured present the status quo of the FSC without any SC disruptions.

The lead time for each order is less than 0.54 days, the service level for each product is 100% at all times, and the available inventory in the hubs and the central DC is constant. Furthermore, there are no delayed or dropped orders. This overview reflects a functioning and efficient logistics system. Figure 6 shows an overview of some important KPIs in the form of a dashboard. This dashboard represents the simulation tool, which is available to the real-world user for decision-making support.

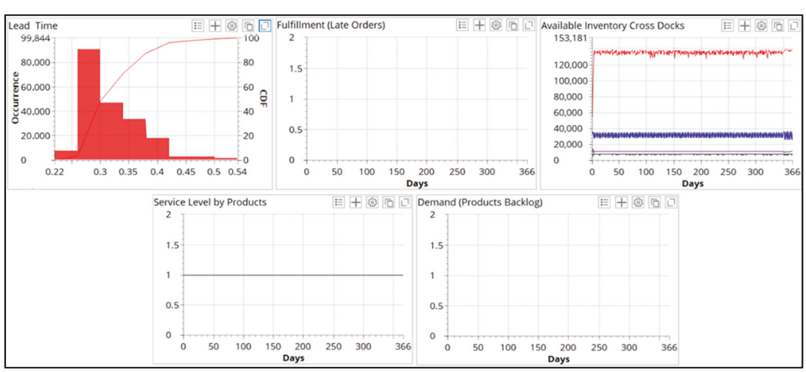

Figure 6. Initial baseline scenario: Dashboard.

The complete performance evaluation of scenario 0 is presented in Table 4.

In the efficiency category, the total costs are about €309 million. Of this, 86% is attributable to purchasing costs, while 13% is attributable to inventory carrying costs and less than 1% to transport costs. This leaves an overall profit of €42.16 million, which accounts for approximately 13% of total revenue. The purchasing costs of 86% are rather high. However, this corresponds to the common share in the organic food industry, since the products are not being produced, but rather procured. In addition, other cost components are included in this amount, as described in the model assumptions in Section 3.2.

Table 4. Performance evaluation of scenario 0.

Category	KPI	Scenario 0
Efficiency	Total costs [million €]	308.85
	Purchasing costs [million €]	265.65
	Inventory carrying costs [million €]	40.23
	Transport costs [million €]	2.42
	Profit [million €]	42.16
Flexibility	Dropped orders	0
Responsiveness	Order fill rate	1
	Lead time [days]	0.318
Quality	Average daily available inventory	281,159
	Service level per product	1
	OTD of orders	1
	OTD of products	1
Sustainability	Total CO_2 emissions [t]	4440

It is observed that all orders can be delivered on time and that there are no dropped orders at any time. The fill rate is 100% and the average lead time is 0.32 days. Therefore, the logistics system can meet the retail stores' lead time requirement of less than two days at all times. The service level per location and per product category is 100%. The average stock level per day is 281,159 kg. Accordingly, the DC and hubs are always ready to meet the customer demand. The total CO2 emissions from transport and storage are 4856 t CO_2.

This evaluation acts a mean of comparison for the scenarios to come.

4.2. Scenario 1: Demand Increase

Disruption effects: After a demand increase occurs, some orders can no longer be fulfilled. Moreover, some orders cannot be fulfilled on time. This is reflected in the occurrence of dropped orders, as well as in the OTD and service level drop. As demand at the retail stores increases, demand at the hubs and at the DC in Lorsch also increases during this period. As a result, inventory levels in the hubs drop sharply, while the inventory level in the DC increases. The DC is supplied by several suppliers who normally do not use their maximum delivery capacity. The bullwhip effect is evident here, as the inventory fluctuation, that begins at the retail stores, is highest at the supplier level. After inventory levels in the hubs plummet, it takes a while for service levels to recover.

Figure 7 provides an overview of the disruption effects on the KPIs over time for different durations of demand increase. It shows a visualization of four important KPIs for two consecutive iterations. A sensitivity analysis shows that the longer the demand increase, the longer the average lead times. Furthermore, a linear relationship is observed between the duration of the demand increase and the effects described above. The longer an increase lasts, the longer the logistics system takes to recover. This figure compares an increase of 30 and 60 days. More iterations have been made subsequently, up to a duration of 120 days, thus ending the sensitivity analysis. As the analysis shows a linear relationship between the disruption duration and the effect, the duration can be chosen freely within the given range without affecting the interpretability of further results.

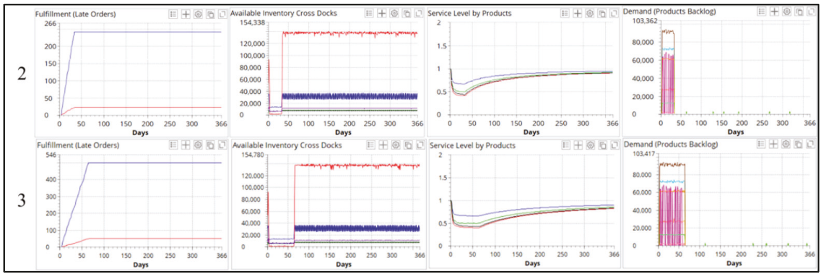

Figure 7. Scenario 1: Sensitivity analysis (iteration 2 = 30 days, iteration 3 = 60 days).

Iterative Optimization: After the sensitivity analysis, a duration of 60 days was selected as a modified baseline. In the event of a 60-day demand increase, the user tries to improve the LSCM performance through various adjustments. Figure 8 contains the dashboard with the relevant KPIs, on the basis of which various measures are taken. By means of dynamic factor design, a step-by-step approach is made to improve LSCM performance. Three steps are selected representatively to show the iterative improvement. By adjusting the order frequency, the number of delayed orders can be significantly reduced (iteration 8). Next, the availability of new suppliers leads to an improvement in service levels and fewer orders are delivered late (iteration 10). Finally, an increase in inventory leads to less dropped orders and thus to a stabilization of service levels (iteration 13).

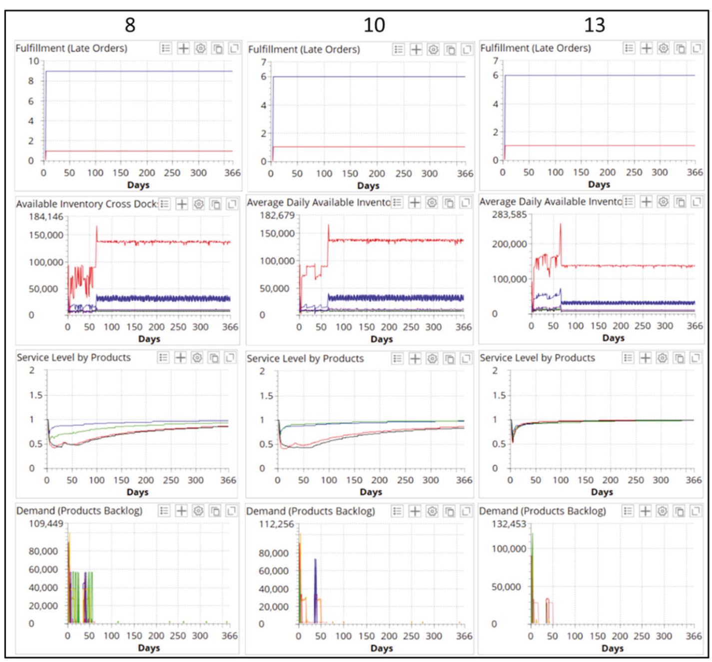

Figure 8. Scenario 1: Iterative optimization (iteration 8 = adjusted order strategy, iteration 10 = adjusted procurement strategy, iteration 13 = adjusted inventory strategy).

Performance evaluation: In the final iteration 13, order strategies as well as procurement and inventory strategies have been adjusted in order to better adapt the logistics system to the SC disruptions. Table 5 gives an overview of the LSCM performance of scenario 1 with the use of a DSCT (optimized) and without (baseline). However, the user can only react to the increase in demand in a reactive way. Therefore, a delay is simulated between the occurrence of the SC disruption and the point at which the changes are implemented in the logistics system. This leads to delayed orders and a slightly higher lead time.

Table 5. Performance evaluation of scenario 1: Demand increase.

Category	KPI	Scenario 0 Baseline	Scenario 1 Baseline	Scenario 1 Optimized
Efficiency	Total costs [million €]	308.85	298.64	352.53
	Purchasing costs [million €]	265.65	261.67	306.08
	Inventory carrying costs [million €]	40.23	33.49	42.93
	Transport costs [million €]	2.42	2.83	2.83
	Profit [million €]	42.16	39.97	51.41
Flexibility	Dropped orders	0	548	0
Responsiveness	Order fill rate	1	0.99	1
	Lead time [days]	0.318	0.35	0.3194
Quality	Average daily available inventory	281,159	288,048	275,547
	Service level per product	1	0.84	0.99
	OTD of orders	1	0.99	1
	OTD of products	1	0.98	1
Sustainability	Total CO_2 emissions [t]	4440	4902	5043

When comparing the scenario 1 baseline with the optimized final iteration, an overall increase in costs is observed. Still, there is an increase in profit of around €11.5 million. This is because after the demand increase, there are 548 dropped orders, which in turn lead to lost sales and therefore less revenue. With the use of a DSCT this can be prevented. The service level of 0.99 is also notably better than without DSCT use (0.84).

4.3. Scenario 2: Supplier Risk

Disruption effects: After a supplier breakdown occurs for one product category (meat), it is observed that the lead time for meat products grows significantly for the duration of the breakdown. Meat orders from the retail stores arrive constantly and they cannot be serviced. Therefore, dropped orders are observed, which lead to lost sales. Inventory levels in the DC and the hubs are lower and the service level for meat products decreases. Figure 9 visualizes the effects described above. A sensitivity analysis analogue to scenario 1 is carried out. Iteration 2 (30-day supplier downtime) and iteration 3 (60-day supplier downtime) are displayed in the figure.

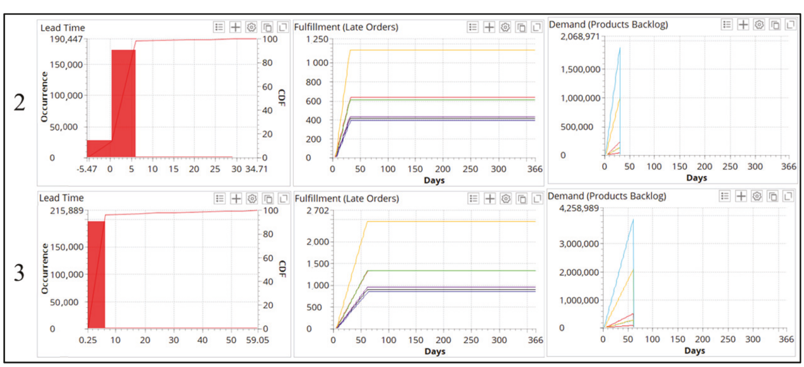

Figure 9. Scenario 2: Sensitivity analysis (iteration 2 = 30 days, iteration 3 = 60 days).

Iterative Optimization: After the sensitivity analysis, a duration of 60 days was selected as a modified baseline. The user has different strategies to follow in the event of a supplier breakdown. Since no suppliers are available in Germany, an attempt is made to involve suppliers from abroad. Adding a supplier from Poland has the effect that no more orders are delivered late. The inventory levels in the DC and the hubs can also be increased slightly. As a result, the service level improves (iteration 5). Adjusting the order frequency for meat products in the hubs and distribution center results in the supplier not being able to re-deliver quickly enough because they have limited capacity and their location is further away from the DC (iteration 7). Finally, establishing and selecting a supplier relationship in the Netherlands with the same capacity but with a shorter distance leads to a significant improvement in service level and other relevant KPIs as compared to prior iterations (iteration 9). In addition, the DSCT helps to determine that the supplier from the Netherlands is sufficient. The costs for establishing new supplier relationships are neglected. The effects of adjusting the strategies iteratively are shown in Figure 10.

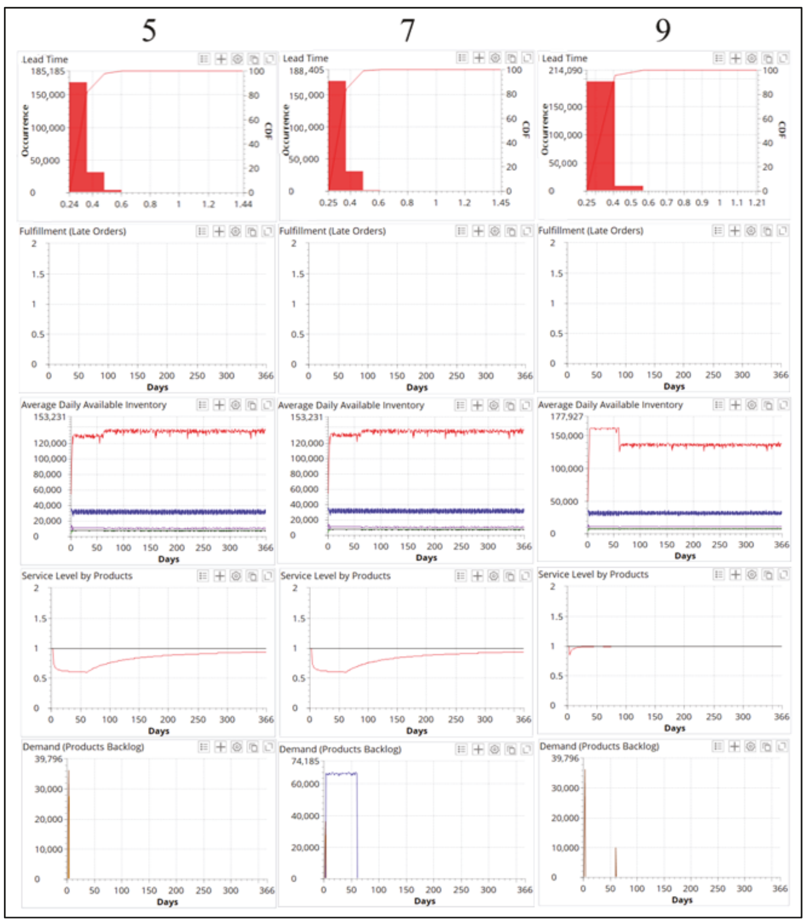

Figure 10. Scenario 2: Iterative optimization (iteration 5 = adjusted procurement and inventory strategies, iteration 7 = adjusted order strategy, iteration 9 = adjusted procurement strategy).

Performance evaluation: In scenario 2, the effects are similar to scenario 1. In the final iteration 9, order strategies as well as procurement and inventory strategies have been adjusted in order to better adapt the logistics system to the SC disruptions. Table 6 gives an overview of the LSCM performance of scenario 2 with the use of a DSCT (optimized) and without (baseline). Again, the user can only react to the supplier breakdown in a reactive way. Therefore, a delay is simulated between the occurrence of the SC disruption and the point at which the changes are implemented in the logistics system. This again leads to a slightly higher lead time.

Table 6. Performance evaluation of scenario 2: Supplier breakdown.

Category	KPI	Scenario 0 Baseline	Scenario 2 Baseline	Scenario 2 Optimized
Efficiency	Total costs [million €]	308.85	308.12	307.81
	Purchasing costs [million €]	265.65	242.00	264.20
	Inventory carrying costs [million €]	40.23	37.11	40.58
	Transport costs [million €]	2.42	2.42	2.40
	Profit [million €]	42.16	33.45	41.35
Flexibility	Dropped orders	0	7789	0
Responsiveness	Order fill rate	1	0.99	0.99
	Lead time [days]	0.318	1.46	0.32
Quality	Average daily available inventory	281,159	285,272	279,087
	Service level per product	1	0.951	1.000
	OTD of orders	1	0.96	1
	OTD of products	1	0.953	1
Sustainability	Total CO_2 emissions [t]	4440	4399	4436

The profit increases by €8 million when using a DSCT relative to the scenario 2 baseline. This occurs due to higher revenue, although total costs increase by 9%. The increase in revenue is due to the prevention of almost 7800 dropped orders. The main drivers for the higher total costs are the higher inventory costs of 28% and the higher purchasing costs of 9%. The lead time is also significantly lower after optimization (0.32) as compared to the scenario 2 baseline (1.46).

4.4. Scenario 3: Customer and Supplier Risk

Disruption effects: In this scenario, both a demand increase and a supplier breakdown happened simultaneously for a duration of 60 days. Effects from both scenario 1 and scenario 2 can be observed. As the demand in some retail stores cannot be satisfied, dropped orders occur. The performance measures related to the product category affected by the supplier breakdown (meat) suffer particularly in this scenario. The service level drops, as well as inventory levels at the hubs. The effects on the KPIs are significantly higher than in the prior two scenarios, as the logistics system has to deal with two disruptions at the same time. Figure 11 gives an overview of the observed effects.

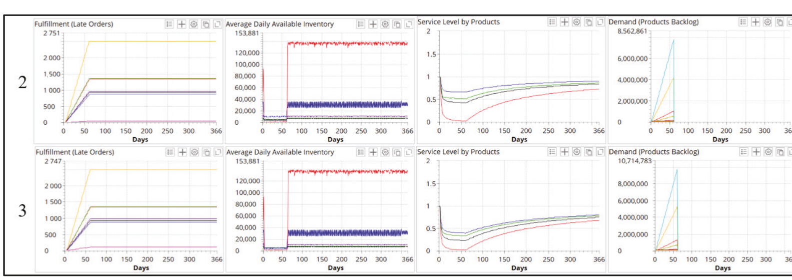

Figure 11. Scenario 3: Sensitivity analysis (iteration 2 = 50% demand increase, iteration 3 = 100% demand increase days).

Iterative optimization: After the sensitivity analysis, a demand increase of 100% was selected as a modified baseline. The user then again tries to handle the SC disruptions properly. The supplier breakdown is prioritized, as its impact is more severe when compared to the demand increase. Figure 12 shows another exemplary excerpt of the user dashboard, where the inventory levels of the DC for different strategies are shown. In the first two visualizations, stock outs can be observed. In the last one the supplier selection seems to be appropriate, as no stock outs occur. This way the demand can be met.

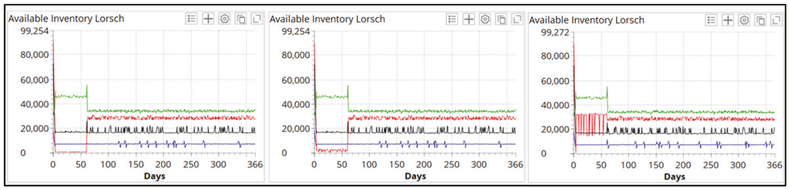

Figure 12. Scenario 3: Inventory levels of the DC for different procurement strategies.

Figure 13 shows some significant iterations in the optimization process. The addition of two suppliers stabilizes inventory levels in the DC. It also improves service levels and reduces the number of dropped orders (iteration 7). Increasing order frequency leads to higher inventory levels at the hubs as well as an improved service level (iteration 8). Finally, an adjusted inventory strategy leads to the required service level (iteration 14).

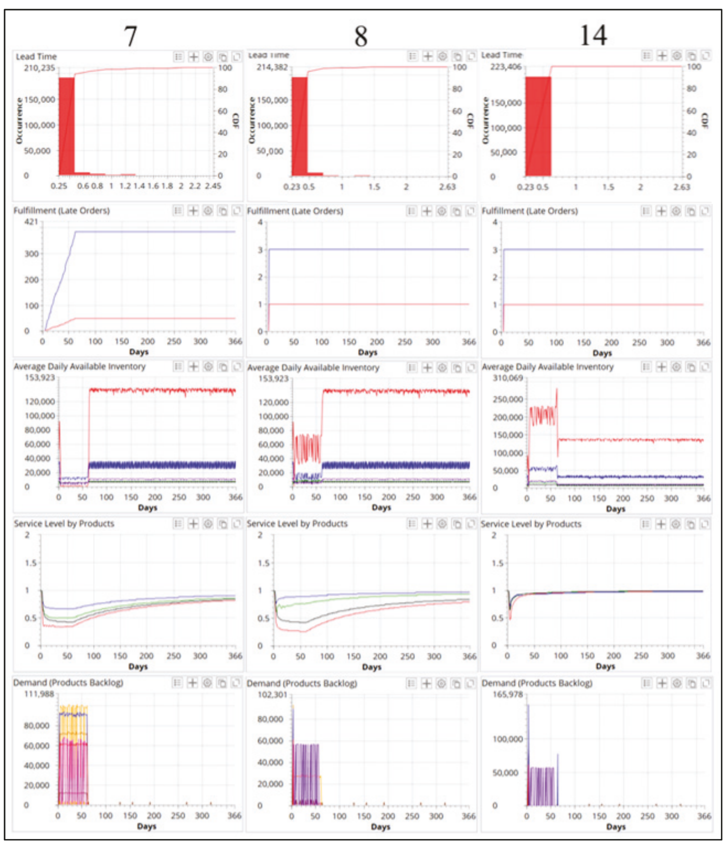

Figure 13. Scenario 3: Iterative optimization (iteration 7 = adjusted procurement strategy, iteration 8 = adjusted order strategy, iteration 14 = adjusted inventory strategy).

Performance evaluation: In scenario 3, it took the user 14 iterations to teach the final result. Order strategies as well as procurement and inventory strategies have been adjusted in order to better adapt the logistics system to the SC disruptions. Table 7 gives an overview of the LSCM performance of scenario 3 with the use of a DSCT (optimized) and without (baseline). Again, the user can only react to the SC disruptions in a reactive way. Therefore, a delay is simulated between the occurrence of the SC disruptions and the point at which the changes are implemented in the logistics system. This leads to delayed orders and a slightly higher lead time and a reduced service level.

Table 7. Performance evaluation of scenario 3: Customer and Supplier Risk.

Category	KPI	Scenario 0 Baseline	Scenario 3 Baseline	Scenario 3 Optimized
Efficiency	Total costs [million €]	308.85	370.03	358.12
	Purchasing costs [million €]	265.65	261.44	308.72
	Inventory carrying costs [million €]	40.23	30.95	45.65
	Transport costs [million €]	2.42	3.00	2.81
	Profit [million €]	42.16	39.20	49.47
Flexibility	Dropped orders	0	8066	0
Responsiveness	Order fill rate	1	0.99	0.99
	Lead time [days]	0.318	1.532	0.319
Quality	Average daily available inventory	281,159	284,494	284,699
	Service level per product	1	0.741	0.993
	OTD of orders	1	0.96	1
	OTD of products	1	0.9013	1.0000
Sustainability	Total CO_2 emissions [t]	4440	5094	5106

After optimization, the profit increases by €10 million. Even though the total costs increase by 21% due to the build-up of a higher inventory, the company is more profitable, since more than 8000 dropped orders can be prevented. The service level after the optimization (0.993) is significantly higher than without DSCT use (0.741).

5. Implications

This study shows how a DSCT can be used in multi-echelon inventory management of an organic FSC. A method for adequately measuring SC performance was developed and tested. When using this method as a guideline, one is able to not only make an estimation of the effects a DSCT in a certain use case has on LSCM performance, but also obtain a better idea of the user process during ongoing operations. Additionally, an analysis of the conducted case study gives a good overview of what benefits are to be expected when implementing a DSCT in a comparable use case in the food industry. This study is therefore of great use for researchers and practitioners alike who are concerned with DSCT.

The quantification method presented in Section 2.3 generates multiple added values for DSCT research. First, it is a structured approach, which helps to generate reproducible and verifiable results when trying to measure DSCT benefits. Second, it displays some major advantages of using merely a simulation model for this purpose, which is still common practice as of today. By emulating and documenting the user process, a realistic application is ensured. Both the user's objectives and the user's resources are determined beforehand. Insights into the utility and usability of the DSCT can be obtained. Furthermore, a feedback loop of the optimization results into the logistics system is given. The user's reactiveness is being simulated as well, thus creating a realistic overview of the system's behavior in case of a real-world application. Lastly, the quantification method presents different levels of comparableness. Depending on what baseline is used, different conclusions can be drawn.

All in all, the quantification method is an improvement of the methods being used commonly in DSCT research. Therefore, when using this method as a guideline, researchers may be able to achieve more realistic and comprehensible results when trying to evaluate DSCT benefits. Practitioners may benefit from the method as well, as they may use it as an assessment tool when deciding on implementing a DSCT in their company. However, one has to keep in mind, that this study completely neglects the cost of DSCT implementation. In order to carry out a cost–benefit comparison, reasonable cost assumptions would have to be made beforehand.

The extensive simulation study conducted, which is described in Sections 3 and 4, showed a realistic application of said method in a case study featuring an organic FSC. Thus, a first verification of the method is given. The organic food industry seems to be a plausible application domain. The volatility scenarios analyzed, namely demand increase and supplier breakdown, appear to be realistic scenarios, as they have been observed during the COVID-19 pandemic. For both scenarios, the DSCT presents itself as a feasible solution with promising effects on LSCM performance. An evaluation of the experiment results gives an estimate of the quantified benefits.

In case of a demand increase, a company's profit goes down. This is because the logistics system is not able to fulfill the customers' needs with the current order, inventory, and procurement strategies. Fill rate, service level, and OTD drop, while the lead time goes up. When a DSCT is used, these effects can be prevented for the most part. Notably, the logistics costs of the FSC go up, but since the revenue rises even more, an overall profit increase can be achieved, while otherwise quasi maintaining the LSCM performance level of the status quo. Interestingly enough, a comparison between the optimized scenario and the initial baseline shows, that a SC disruption in the form of a demand spike acts as both a risk and an opportunity, due to the potential profit gain for the company.

In case of a supplier breakdown, similar effects can be observed. It goes to show that if not properly dealt with, the missing supplier has devastating effects on the LSCM performance. Customer needs cannot be fulfilled and dropped orders go up, which in turn leads to a decrease in revenue. Other LSCM KPIs also deteriorate. When using a DSCT, a proper alternative for the missing supplier can be found, as is shown in the simulation experiments. Again, dropped orders can be prevented, resulting in higher revenue and therefore greater profit, while again maintaining the LSCM performance level of the status quo. Unlike in the event of a demand increase, the supplier breakdown leads to an overall profit loss when compared to the initial baseline. Still, the DSCT can help mitigating negative impacts, therefore potentially preventing major disasters.

These findings should present a first attempt of a realistic quantification method for DSCT benefits and make it easier for researchers and practitioners in LSCM to evaluate DSCT applications in practice. Combined with an adequate simulation study design, an assessment tool for DSCT implementation is formed.

6. Conclusions and Final Remarks

In conclusion, the aim of this paper was to develop a quantification method for evaluating DSCT benefits (RO1) and evaluate the effect of using a DSCT in multi-echelon inventory management of an organic FSC in terms of LSCM performance (RO2). All ROs have been met sufficiently by the authors. Section 2.3 provides a conclusive method for benefit quantification of DSCT use. Meanwhile Sections 3 and 4 describe the application of said method to a case study in the organic food sector, providing an evaluation of this very use case. Finally, Section 5 derives implications for researchers and practitioners.

The quantification method presented in Section 2.3 provides a conclusive process model for measuring DSCT benefits. This is of great value for practitioners with an interest in implementing a DSCT and DSCT researchers alike, since it paves the way for a reasonable cost–benefit comparison of DSCTs. As pointed out in Section 5, the method features significant advantages over other methods commonly used in the field, most notably simple simulation models. This allows for more realistic DSCT studies, making the research field overall more tangible.

Furthermore, the results of the simulation study offer a first point of reference in terms of what benefits to expect when using a DSCT to improve decision making in an FSC. The use case in question featured decisions in regards to order, procurement, and inventory strategies in a multi-echelon logistics network when facing SC disruptions, namely demand spikes and supplier breakdowns. When utilizing the DSCT, the case study user was able to prevent the devastating effects the disruption would have had on LSCM performance. Through the application of better strategies, lost sales were prevented, resulting in higher company revenue. Even though these strategies sometimes led to increased costs, overall profit went up. Non-financial KPIs were also improved, leading to a better OTD rate, increased service levels, and overall shorter lead times. Nevertheless, these results have to be interpreted with caution, since validity and generalizability of the quantified magnitude of said effects heavily depend on the case study data quality. Since the case study at hand was constructed, the authors would like to refrain from deriving far-reaching implications for the food industry. However, the study results reveal insights into the underlying mechanisms at work in FSCs and how the application of a DSCT in this domain might look like.

Still, this study is not without limitations, which shall be addressed in the following paragraph. First of all, the simulation model used in this study does not classify as a DSCT, since it does not feature a data link to any real-world logistics system. So even though a real-world application process is being emulated, the level of accuracy of a DSCT cannot be matched. Therefore, some assumptions have been made while creating the case study and the respective simulation model. For one, truck utilization has mostly been neglected during evaluation, since only LTL transports have been used. This also led to higher CO_2 emissions in the optimized scenarios. Since awareness for sustainability has been rising over the past years in LSCM, this factor should be subject of more detailed investigation in the future. Some costs and efforts have also been neglected during the modelling phase, for example the ones related to building supplier relationships and applying certain order strategies. Additionally, storage capacities were neglected for the DC and the hubs. Still, it was implicitly given through inventory costs. Lastly, it was assumed that the user does not take any actions in the modified baseline scenarios, that is, after the SC disruption occurs, but no DSCT is used. Given proper SC transparency, this seems rather unlikely. However, on the one hand, SC transparency might actually not be given, which would render the assumption somewhat realistic. On the other hand, the magnitude of the positive effects brought by the DSCT use are not crucial for the core findings of this paper. Therefore, even though the study results have to be put into perspective in this regard, the authors are nonetheless confident in the generalizability of this study's results.

This work also lays the foundation for a variety of future research. Firstly, researchers may use the presented quantification method to more accurately evaluate DSCT benefits in their works. Secondly, as pointed out earlier, some dimensions of a LSCM performance have not been focus of this study. Especially the sustainability aspect of DSCT use should be looked into further. Thirdly, the application domain of the presented use case was the organic food industry. Similar studies should be conducted in other domains as well. Lastly, this study focusses solely on the benefits of a DSCT while ignoring the implementation costs for the most part. However, to properly conduct a cost–benefit evaluation, these implementation costs have to be estimated as well. Therefore, it seems crucial for researchers in the DSCT area to look into methods of evaluating DSCT implementation costs.

All in all, while benefits of using DSCT are widely being discussed in academia and practice, they are rarely quantified. As DSCT are a promising solution for handling complex tasks in LSCM, such as inventory and risk management, a detailed quantification of their effects on different LSCM performance measures is an essential instrument for making the concept's discourse more comprehensive. The authors of this paper hope to have underlined the importance of this topic and also to provide guidance for researchers and managers who have an interest in the subject of DSCT.

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Article

A Soft Computing View for the Scientific Categorization of Vegetable Supply Chain Issues

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Abstract: Over the most recent couple of years, the Internet of Things and other empowering innovations have been logically utilized for digitizing the vegetable supply chain (VSC). *Background*: The unpredictable examples and complexity inserted in enormous data dimensions present a test for an orderly human master examination. Hence in an information-driven setting, soft computing (SC) has accomplished critical energy to investigate, mine, and concentrate confidential information data, or tackle complex improvement issues, finding some harmony between good productivity and maintainability of vegetable supply frameworks. *Methods*: This paper presents a new and diverse scientific classification of VSC issues from the SC methodology. It characterizes VSC issues and sorts them in light of how they be demonstrated according to the SC perspective. Moreover, we examine the SC methodologies commonly utilized in each phase of the VSC and their related classes of issues. Accordingly, there is an issue in distinguishing and characterizing VSC issues according to a more extensive point of view, enveloping the different SC strategies that can apply in various phases (from creation to retailing), and recognizing the issues that emerge in these phases according to the SC viewpoint. *Results*: We likewise acquaint some rules with the assistance of VSC analysts and specialists to settle on appropriate strategies while resolving specific issues they could experience. Even though a few latest examinations have arranged the SC writing in this field, they are situated towards a solitary group of SC strategies (a gathering of techniques that share standard qualities) and survey their application in VSC phases. *Conclusions*: We have suggested a novel approach and complete scientific classification of vegetable supply chain concerns about soft computing. We present a view of three delegate supply chains: cruciferous vegetables, dark green leafy vegetables, and tomatoes. We assembled the scientific type in light of different parts to arrange vegetable supply chain issues as per how they can be demonstrated utilizing soft computing methodologies.

Keywords: vegetable supply chain; soft computing; neural networks; machine learning; deep learning

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1. Introduction

As of now, one comprehensive test is how to ensure worldwide vegetable needs economically for a developing populace that is estimated to reach 9–10 billion by 2050 [1]. In this regard, upgrading the creation and the executives of the ongoing vegetable supply chains (VSCs) is a critical element that adds to achieving such a point. These days, new ICTs (information and communication technologies) (e.g., the Internet of Things) assume an active part in the digitization of VSCs [2]. Thus, enormous volumes of information are being created in all VSC phases, from creation to retail. Investigating such information would empower VSC entertainers to extract relevant data or enhance explicit cycles. It permits improvement of the VSC scientific categorization, efficiency, and supportability.

The high volumes of accessible information and examples raise critical difficulties while investigating and separating values. In this unique circumstance, soft computing (SC) is an adequate worldview to assemble wise frameworks that are ready to use this high accessibility of information. SC is the capacity of an advanced framework or calculation to perform assignments generally connected with intelligent creatures [3]. Inside such commitments, we can find discussions on acknowledgment, visual sensitivity, independent direction, forecast, and interpretation, among others [4]. The number of academic distributions considering SC applied to VSC has expanded [5–7] quickly. Inside the most delegated SC techniques used for VSCs, we track down neural networks, fuzzy logic, swarm intelligence, and deterministic reasoning.

The analytical writing indicates various examinations that expect to survey and request the utilization of SC strategies in different VSC phases. The assortment of SC techniques has prompted the development of examination papers (distributed somewhere in the range of 2012 and 2020), which select a specific group of SC methods and examine their application in VSC phases [2,6–12]. These papers center around only a couple of groups of SC strategies and do not cover all VSC phases in the more significant part of cases. Along these lines, there is an absence of extensive concentration in that survey using the main groups of SC techniques in all VSC phases (from creation to retail). This study has suggested a novel approach and complete scientific classification of VSC concerns about SC. We present a view of three delegate supply chains: cruciferous vegetable, dark green leafy vegetable, and tomatoes. We assembled the scientific type in light of different parts to arrange VSC issues as per how they can be demonstrated utilizing SC methodologies. These parts are centered around recognizing the chain phase (creation, handling, dissemination, and retail) and the particular VSC issue to be tended to (e.g., vehicle steering issues in the appropriation phase).

In light of the previously mentioned thoughts, we propose an original scientific categorization of VSC issues according to the SC point of view. In particular, we center around the production network of cruciferous vegetables, dark green leafy vegetables, and tomatoes. The last option is advocated in light of the way that these stock chains give the more significant part of the vegetables eaten by the inhabitants on the planet [13]. Subsequently, they are the most considered and investigated VSCs in analytical and scholarly writing. The principle commitments of this article are:

- A scientific classification that gives a far-reaching perspective on various VSC issues situated in the chain organizes commonly concentrated in the analytical writing (creation, handling, dispersion, and retail). This scientific classification addresses a new and more extensive proposition to distinguish and characterize VSC issues closer to involving SC in the four previously mentioned phases. Furthermore, although some exploration articles have portrayed various VSC issues, their definitions are not brought together and differ from one paper to the next. Along these lines, this scientific categorization additionally addresses a work to bring together and combine meanings of the VSC issues accessible in writing, which addresses a significant origin of data for VSC scientists and specialists working in this area;
- To group the VSC issues according to the SC point of view. This grouping permits VSC issues to be planned into normal classes of issues in the SC area. Hence, we give a system that helps show the likenesses and contrasts among VSC issues, relying upon how they can be displayed according to the SC point of view. According to our observation, in such manner, no order has recently been offered in this manner;
- To lay out many rules for utilizing SC in the VSC domain. These rules intend to assist VSC analysts and proffesionals in recognizing that VSC issues could be tended to by utilizing SC and the most proper groups of strategies to address them. In this manner, these rules address the principle endeavor to characterize an overall structure to help the model choice issue where the fields of VSC and SC studies;

- To recognize and talk about difficulties and explore open doors in the VSC space, which are coordinated towards more hearty, reasonable, incompatible, and precise SC arrangements that help VSC the board and activity.

Listed below is the content of the rest of this article. Section 2 of this paper surveys the related work. Section 3 discusses the scientific categorization of SC-based issues in the vegetable supply chain. Section 4 describes the use of SC strategies in vegetable chain supply. Finally, Section 5 concludes this advanced research.

2. Related Work

This section provides the background relate to supply chain management. A tremendous amount of work has been done in supply chain management. We will discuss the work and describe how our approach is different from the previous work. We wrote some past supply chain work: The "First Pass" Test to Identify Market Power Exertion along Food Supply Chains, Asymmetric Price Transmission (APT) Analyses, and Structural Models.

The "First Pass" Test to Detect Market Power Exertion along Food Supply Chains: The two combinations of models (APT and NEIO) share, somehow or another, a similar goal to test or market power effort. Regardless of whether the aftereffects of APT models are decisive, be that as it may, they work at various parts, utilize multiple sorts of information, and give unique discoveries. An attempt to implement the location of market power effort in vegetable frameworks that are extra powerful for competition strategy aims is attracting similar methodologies [14]. As recently expressed, these goals require a procedure that brings together the benefits.

Furthermore, attempts to address the restrictions of the APT and NEIO models test the effort of market power and the whole vegetable production network. A goal for this philosophy should start with the principle model, which expressly portrays working in an upward direction-related store network [15], in any event, expecting an ideal contest in the intermediate phase. McCorriston et al. [15,16] adjusted the model, taking into consideration market power effort inside the advertising chain, variable versatility of replacement, and non-constant returns to scale to infer the flexibility of cost transmitting under various circumstances. Lloyd et al. [17,18] used this structure and created (and utilized) a hypothetical model prepared to recognize market power effort along with the pecking order.

Such commitments are not interesting; without a doubt, Holloway [19] adjusted the Gardner model, loosening up the presumption of the completely aggressive way of behaving to test its impact on the extended homestead retail value (and afterward examine the market power effort). The two methodologies use lead boundaries to consider not perfect competition and the natural pecking order, even if just the last option considers the entry of new firms. Even the technique utilized by Holloway [19] is more requesting regarding information for the same use-case, with the demands of time-series information at costs and amounts (of unrefined horticultural items). However, the "primary pass" trial of Lloyd et al. requires a time series of costs (or cost lists) enhanced by other effectively accessible information (intermediaries of advertising expenses, requests, and supply shifters). According to the viewpoint of information requirements, the last approach is ideal when information on item amounts are not promptly accessible. This technique has been utilized in numerous nations [20–27]. As of late, Kinnucan and Tadjon [28] promoted a system that can verify great competition, guaranteeing its benefits over those of Lloyd et al. (2009) [17]. Sadly, A certain method needs outright homestead and retail costs, and frequently, only file costs are accessible in numerous nations.

Asymmetric Price Transmission (APT) Analyses: These approaches investigate the speed, timescale, and the degree to which costs are sent these two temporally (among business sectors of a similar item) and in an upward direction, from contribution to the retail market [29]. Concentrating on upward-related markets (particularly vegetable supply chains), the inadequate transmission of cost changes from the homestead to the purchaser phase is generally credited to defective contests [29]. From a clear perspective, APT examinations utilize time series of the maker (discount) and retail costs, in part or as records, by testing their deviated developments utilizing different time series econometrics apparatuses. Provided the accessibility of information needed, APT examinations are very well known in writing on vegetable markets. The clarifications of the reasons for APT are different and differentiating [30], regardless of whether market power in at least one phase of the store network is identified as one of the reasons. Different APT examinations are being conducted in the dairy industry at this time [31–37]. The weak spots of APT investigations are their absence of hypothetical establishments and, thus, their failure to illustrate a reasonable causal connection between defective competition and cost deviations along with the established pecking orders [14,38,39]. The nexus betwixt flawed competition and APT has been explored broadly. Peltzman [40] inspected cost transmission in a wide scope of upward direction equivalent markets, placing the outcomes in examination with an intermediary of market power for every market. A major flaw of investigation is utilizing a market fixation record as an intermediary for the activity of market power. This methodology (like each of those given the Structure-Conduct-Performance worldview) experiences the internal market design and synchronization inclination [41–43]. Along a similar line, Bakucs et al. [44] completed a meta-examination on the connection betwixt the construction of rural business sectors and cost transmission. They suspected the potential for market power effort was not a genuine competition of hard conduct. Furthermore, for this situation, they already addressed the causal nexus betwixt the blemished contest and ATP.

Covering the hypothetical sector, Gardner [45] promoted a farm retail store network harmony dislodging model, accepting ideal competition in the intermediate phase and consistently getting back to an extent. The result demonstrates a more significant impact on vegetable request shifters' thoughts about encouraging supply shifters on the advertising edge. Following the Gardner structure, McCorriston et al. [15,16] have demonstrated that market power can minimize cost transmitting versatility. However, various circumstances in the flexibility of replacement and getting back to an extent may offset or enhance the impact of market power. Research shows that, indeed, in marketplaces where competition is only partially intense, such as the handling and retail industries, as well as specific innovation and expense circumstances (rise flexibility of replacement and expansion gets back to an extent), could make up for the market power impact, resulting in symmetric cost transmission onward the showcasing chain. For this situation, the existence of APT would not be a suitable device for recognizing the effort of market power along with established orders of things.

The past reactions and writing gives different reasons for ATP that are not quite the same as market power, for example, strategy negotiation in farm costs [32], expansion [46], stock expenses [47], and menu-repricing costs [48,49].

Structural Models: The current sub-section makes use of the commitments of Perloff et al. [50], and Perekho-zhuk et al. [51]; this should be referred to in order to have a more in-depth conversation.

The general classification of underlying approaches, otherwise called New Empirical Industrial Organization (NEIO) models, were destined to conquer the limits of the design lead execution worldview [43]. In their less complex forms, NEIO models usually are focused on determining the existence of market power effort or assessing its degree in the market part and within the whole pecking order. A particularly striking case and advancement is addressed by multi-phase market power models, examined afterward. NEIO models vary as per the side of the market investigated item supply or variable interest, estimating, individually, authority or leadership power, the sort of item inspected (homogeneous versus separated), the assessment procedure embraced (parametric versus non-parametric model), and the reiteration of the connections among financial specialists (static versus dynamic models).

Along with complex variants, NEIO methods dissect the degree of authority and leadership power in additional phases of the advertising chain [52,53]. They assess market power for each phase of the production network, yet apparently at the expense of expanding requests for information and econometric complexity. There are different commitments to utilizing NEIO methods to assess market power in the dairy markets, for example, those of Grau a Hockmann [54]; Zavelberg et al. [55], Sckokai et al. [56], Salhofer et al. [57], Hockmann and Voneki [58], De Mello and Brandao [59], and Perekhozhuk et al. [60].

As NEIO models are established in financial hypotheses, discoveries on the degree of market power effort found from their utilization are much more definitive and solid as compared with APT studies [14]. Regardless, there are a few reactions concerning their precision [61,62]; be that as it may, their requirements concerning the amount and nature of information and econometric attempts increment with model complexity (single-phase versus multi-phase).

The above mentioned is different from our work as we are describing a soft computing view for the scientific categorization of vegetable supply chain issues.

3. The Scientific Categorization of the SC-Based Issues in the Vegetable Supply Chain

This segment presents similarities to the scientific classification proposed. To begin with, Section 3.1 demonstrates that the methodology adheres to planning the scientific category. Section 3.2 describes the organized overview of issues. At last, Section 3.3 shows the scientific categorization's construction and presents its features.

3.1. Methodology Followed to Plan the Scientific Classification

This part describes the technique followed by fabricating the scientific categorization proposed. In the first place, we note that this exploration paper does not plan to do orderly writing or study. Our extension relevance is looking at and exploring the literature to suggest a scientific classification that portrays and arranges VSC issues and how they are settled from the SC-based point of view. Accordingly, the scientific categorization proposed does not look to recognize all similarities related to the VSC issues to keep up with its understandability. According to the SC point of view, it is planned by center qualities that might modify the complexity and displaying of VSC issues.

Considering these thoughts, Figure 1 shows the system followed to assemble the scientific categorization presented in this examination paper. This philosophy follows a design-based writing survey that incorporates the means portrayed in Figure 1. The initial step is named the range and exploration question, which plans to restrict the subject matters to be counseled; that is, where VSC and SC merge. For this progression, the exploration questions that directed our pursuit were: "What are the most widely recognized VSC issues announced in writing?", "What are the SC techniques normally used to move toward these issues?", "How might VSC be classified according to the SC viewpoint?", and "Is there any scientific categorization to classify VSC issues thinking about the SC methodology?".

The accompanying advance characterized the inquiry setup. We represent the time frames, online assets, and standards to look at and examine the analytical writing. The sayings considered were: vegetable supply chain(s), agri-vegetable, cruciferous vegetable growth, agri-business, tomatoes, creation, handling, dissemination, strategies, retail, deep learning, computational knowledge machine learning, meta-heuristics, fluffy frameworks, and deterministic methods. The time was somewhere between 2012 and 2020, and the bibliographic assets looked at were the Web of Science, Scopus, and Google Scholar. Finally, the most important criteria for selecting and examining the writing were that they were exploratory or study papers, among other considerations. The last alternative may be considered depending on how well this article provides a general and integrated summary of the SC-based VSC difficulties shown in writing. Additionally, these papers permitted us to be aware, assuming that any scientific categorization was recently proposed to arrange the VSC issues.

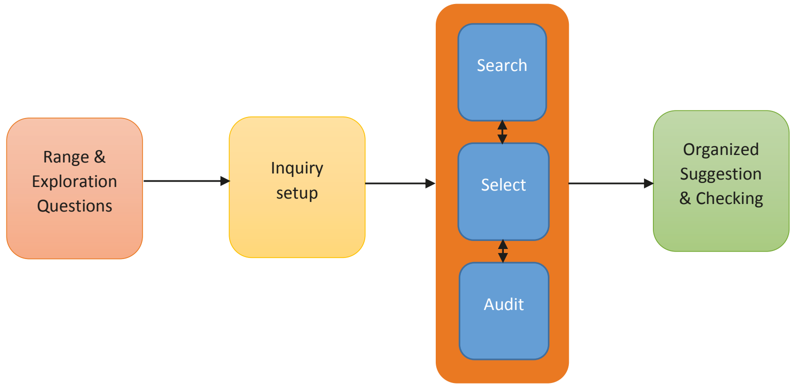

Figure 1. Steps followed to fabricate the proposed scientific categorization.

The following phase in Figure 1 is search, select, and examine. Using the inquiry setup described above, we could discriminate between the overview and survey studies given in Section 2. Then, we looked at the VSC issues raised in these papers and the VSC phases where that discovered the problems, and the groups of SC techniques are generally considered to move toward these VSC issues.

Because of the discoveries referenced above, we moved to the last advance of the approach displayed in Figure 1. The goal was to plan another scientific categorization that embraces the complete VSC and the five groups of SC techniques most typically utilized in the VSC phases. This scientific categorization likewise intends to extend the past grouping attempts by adding a new arrangement property, showing the sort of VSC issue tended to from the SC viewpoint. Hence, we described how the VSC issues distinguished in the past step can be displayed according to the SC viewpoint. To do so, we thought about the typologies of issues in the SC area (critical thinking, questionable information and thinking information disclosure and capacity estimate, and correspondence and sensitivity) that qualified the groups of SC techniques considered in the investigations explored.

We have constructed the scientific classification and examined its strength and capacity to separate papers that drew nearer unique VSC issues. We extracted applicable references referred to by the inspection and study papers, found recently distinguished new writing, and placed them into the proposed scientific categorization. Following that, the scientific classification is offered, and its characterization power is approved, and this is displayed in the following section.

3.2. The Organized Overview of Issues

The scientific categorization initially points to broadening the past grouping attempts on VSC issues to encompass all phases of vegetable supply chains; furthermore, to also include another degree of arrangement that permits typologies of VSC issues to be planned typologies the SC issues. We can see the construction of the proposed scientific classification in Figure 2. As may be obvious, in part one, the scientific categorization incorporates the four fundamental phases of the VSC that were presented in Segment 3.3; that is, creation, handling, dissemination, and retail. Then, at that point, part two contains the various classifications of VSC issues that we can explore in every phase. It is essential to explain that, although these VSC issues have been accounted for already in related studies [2,6–12], as far as we could know, this is when their definitions first are brought together and united in one scientific categorization. In part three, the scientific categorization presents the typologies of issues according to the SC viewpoint. In particular, this part tries to characterize the VSC issues by relying on how they can be displayed and settled by SC techniques.

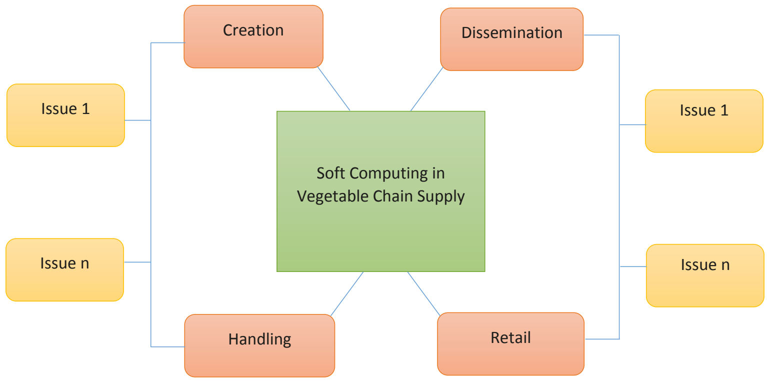

Figure 2. A soft computing view for the scientific categorization in the VSC.

We have introduced the construction of the scientific categorization that distinguished the accompanying similarities of the VSC issues for the creation, handling, appropriation, and retail arrangements in Section 3.3. Those issues address the second part of scientific categorization. They are officially characterized from a VSC point of view, and we express the critical target of every issue inside the specific chain phase where it is distinguished.

3.3. Pointing out of Vegetable Supply Chain Issues

In this segment, we suggest the VSC issues recognized for each of the VSC phases displayed in Figure 2, compared to the second part of our scientific classification. These problems are formally described in further depth further down in this article.

3.3.1. Creation Issues

The VSC creation phase can be separated into three principle creation frameworks: cruciferous vegetable growth, farming, and store arrangement. These three creation frameworks and their related issues can be seen in Figure 3, and they are characterized underneath.

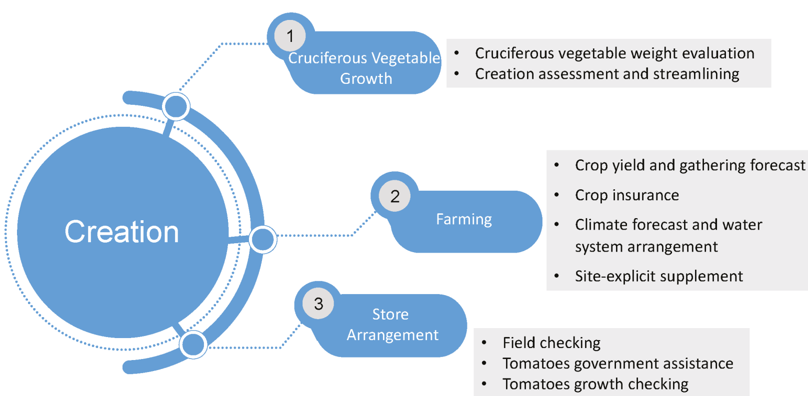

Figure 3. VSC issues in the creation phase.

Cruciferous vegetable growth is the creation framework concerned with cruciferous vegetables' up and down conditions, like fertilized soil or covered fields, for human utilization. These days almost 50% of the cruciferous vegetable consumed in the world are brought up in average conditions [63]. Cruciferous vegetable growth creation has a severe part of complexity as it includes interrelated physical (e.g., water and supplement supply), compound (e.g., pH, oxygen), and ecological (e.g., loss produced) components. This way, the administration of this interaction requires progressed detecting, control, and correspondence advancements and master information to make proficient and maintainable choices and increase efficiency. Inside this unique circumstance, the most average SC-based processes revealed in writing are cruciferous vegetable weight assessment [64], creation assessment, and enhancement [65]. Their definitions are introduced beneath.

- **Cruciferous vegetable weight evaluation:** This interaction measures cruciferous vegetable weight considering morphological highlights (e.g., length, width, and mass).
- **Creation assessment and streamlining:** This interaction is focused on the advancement of cruciferous vegetable creation and estimating occasional interest to change the creation. To achieve such points, the creation enhancement is done by checking vital components of cruciferous vegetables, supplements, and vegetable supply, which impact the development of cruciferous vegetables. In the interim, documented records of occasional interest are put away and constantly investigated to decide the most appropriate degrees of creation, relying upon the year and season.

The accompanying creation framework considered in this study is agri-business, explicitly farming. Farming is the nursery business committed to developing and handling various yields for vegetable and business utilization (e.g., blossoms, leafy vegetables, vegetables, and spices). The main challenges of these development frameworks are to improve plant development, yields, excellence, nutritious advantage, and protection from pests, illnesses, and environmental pressure.

In order to accomplish these upgrades, various cycles are figured out to attempt and keep harmony between proficiency, efficiency, and maintainability, such as observing, controlling indoor-open air environment conditions, cropping the board, and creating measures. They are normally drawn nearer in the specific writing [6,9,66] in open-field agribusiness and concentrated preparation. Inside the few agent procedures, we observe the collecting yield and gathering forecast [66–68], crop insurance [69,70], climate forecast and water arrangements [71,72], and site-explicit supplement the board [73,74]. The following are the characteristics of these cycles, as seen in Figure 3, which are discuses below.

- **Crop yield and gathering forecast:** This issue is centered around yield assessment to coordinate collecting supply with request and on crop the executives to increment efficiency.
- **Crop insurance:** This depends on the recognizable proof and analysis of biotics (pervasions, illnesses, and weeds) and abiotics (supplements, water). That is why stress factors influence crop efficiency.
- **Climate forecast and water system arrangement:** This issue is mostly concerned with weather conditions estimating the ideal utilization of water, which empowers the plan and organization of yield water system booking and arranging.
- **Site-explicit supplement arrangement:** This depends on the administration of soil quality to figure out which supplements should be provided to keep up with the compound attributes expected for the yield.

Finally, the third creation framework considered for the creation phase is tomatoes. This creation framework is devoted to developing homegrown creatures brought up in rural settings to create vegetables. This can bring domesticated tomatoes likewise to broad or serious frameworks. Broad frameworks include creatures wandering meadows (ordinarily under the oversight of a herder). Differently, serious tomatoes are situated in shut foundations and are outfitted with ICT innovation, which empowers creatures to be observed continuously. Inside these creation frameworks, the most run-of-the-mill issues we run over are meadow observing [75], creature government assistance [76], creature conduct following [77], and tomato creation forecast and enhancement [78,79], as displayed in Figure 3. According to a VSC point of view, the formal meanings of these issues are recorded beneath.

- **Field checking:** This issue is connected with the exact recognizable proof of meadow inventories to separate between the most reasonable sorts for tomatoes purposes.
- **Tomato government assistance:** This is centered around the example arrangement of the dehydration way of behaving in brushing creatures for investigations of creature nourishment, development, and well-being.
- **Tomato growth checking:** This depends on the utilization of conduct investigations to recognize early indications of medical problems and advance early negotiation.

3.3.2. Handling Issues

When the unrefined components of vegetable foods are produced, they are sent to the "handling" step of the VSC. Various modern cycles (for instance, laundering, sanitizing, packing) are completed in this phase to change the unrefined result of creation into a consumable vegetable. That can follow dependent upon the creation framework that is feasible and the vegetable acquired from them, various modern cycles to get the products that continue toward the dissemination phase.

Even regardless of such creation particularities, we have distinguished many usual issues that could happen in the three creation frameworks introduced in the segment above. These issues are displayed in Figure 4; they are request expectations [80], creation-making arrangements for dissemination [81], forecast post-reap losses [82], and fabricating industry processes, such as cooking, additional dishes, and others [83].

- **Request expectation:** This issue is concerned with the interest expectation of vegetable necessities to abstain from overloading, overproduction, and over-use of assets. The key thought is to assess the number of vegetables offered to characterize how many unrefined substances should be handled.
- **Creation anticipating conveyance:** This is focused on creation wanting to match dissemination necessities. This issue is not predetermined by the revenue growth that is expected to be generated by a certain vegetable product.
- **The expectation of post-gather losses:** This is centered around composition assessments of vegetable deprivation related to the handling techniques completed after collecting unrefined materials coming from the creation phase.
- **Vegetable growth industry:** This is related to the improvement of the handling innovations expected to change unrefined vegetable varieties into eatable vegetables (e.g., warm, drying, contact cooking, microwave warming, and so on.). These cycles are performed utilizing modern apparatuses.

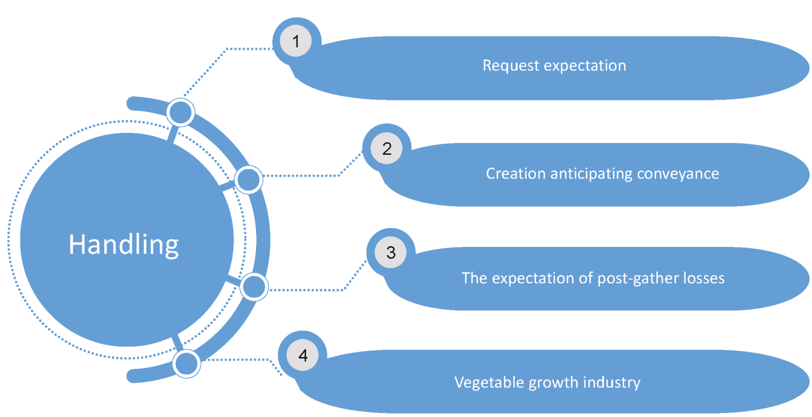

Figure 4. VSC in the handling phase.

3.3.3. Dissemination Issues

In the third step of the vegetable store network, vegetables prepared for human utilization are received from the handling phase to be conveyed to end-shoppers. In particular, completed items show up at distribution centers, and from that point, the shipment division is accountable for characterizing the most reasonable methodology to convey things to end-buyers. The fundamental object is to disseminate vegetables on schedule by the date indicated in the retail phase.

For this specific phase of the VSC, the most widely recognized issues revealed in the particular writing are displayed in Figure 5 and characterized underneath. These issues incorporate vehicle steering and the executives [84,85], capacity area task [86,87], expectation of production network dangers and interruptions [88,89], the the timeframe of realistic usability expectation and development [90–92], request anticipating [93], and last-mile conveyance [94].

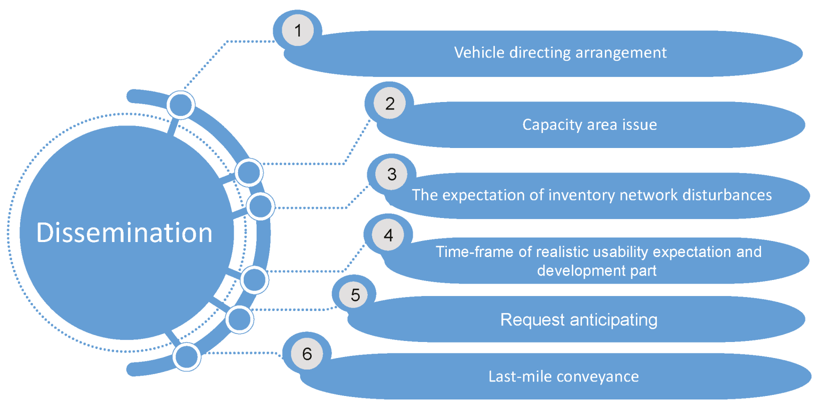

Figure 5. VSC issues in the dissemination phase.

- **Vehicle directing arrangement:** This is centered around deciding the ideal course for the conveyance of vegetables under various situation limitations (e.g., fuel accessibility, and so forth).
- **Capacity area issue:** This issue is concerned with choosing the most reasonable method for putting away vegetables in distribution centers to adapt to everyday interest activities.
- **The expectation of inventory network disturbances:** This is concerned with the measuring of possible disturbances in the operations of vegetable and their related vegetable losses.
- **Timeframe of realistic usability expectation and development:** This issue is connected with the estimating of the timeframe of realistic usability in light of information detected during the conveyance interaction.
- **Request anticipating:** This comprises understanding ways of behaving and estimating client requests created from the retail phase. In this way, it is feasible to improve the conveyance courses and stockroom areas utilized during the dispersion phase.
- **Last-mile conveyance:** This issue is devoted to the conveyance of vegetables utilizing the nearby street transport organization (last mile) in urban areas.

3.3.4. Retail Issues

The retail phase is presented in the final section of the VSC. Now, vegetables are received through the dissemination channels and prepared to be purchased. This phase envelops the idea of an "end-purchaser", which could be grocery stores or clients that go to these spots to purchase vegetables. The most widely recognized issues distinguished in writing for this phase of the inventory network are characterized underneath and are additionally summed up in Figure 6.

Finally, we described the retail phase (Figure 2). Retail-related issues that normally relate to SC, in this connection of the VSC, are diet and sustenance applications [95,96], vegetable utilization and vegetable loss [97,98], purchaser interest, insight and purchasing conduct [99,100], dynamic limiting in view of the sell-by date [101], and day interest expectation and stock administration [80].

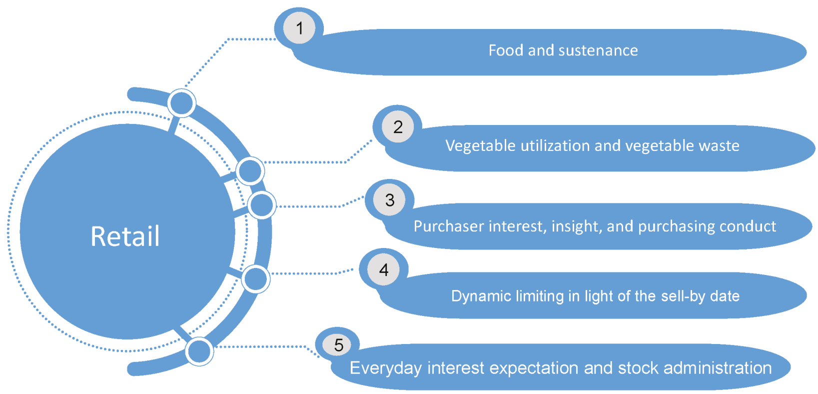

Figure 6. VSC issues in the retail phase.

- **Food and sustenance:** This depends on assessing supplement values utilizing the arrangement of vegetable dishes and nutritive evaluation.
- **Vegetable utilization and vegetable waste:** This issue is related to the distinguishing proof and the forecast of vegetable losses given end clients' purchasing and store conduct.
- **Purchaser interest, insight, and purchasing conduct:** This issue is centered around deciding buyer profiles to foresee purchasing ways of behaving and support the board of shop counters.
- **Dynamic limiting in light of the sell-by date:** The focus here is on automated cost changes in general retailers due to the sell-by date. The idea is to set higher restrictions for things that can be used for the shortest possible time.
- **Everyday interest expectation and stock administration:** This issue comprises anticipating everyday interest to more readily oversee item stocks at stores.

4. Use of SC Strategy in Vegetable Chain Supply

Having introduced and approved the scientific categorization of VSC issues, this segment provides many rules for scientists and specialists in VSC to utilize SC inside this space (Figure 7). Solidly, we attempt to direct the clients to (1) select the typology of SC issue that they are tending to; (2) recognize what groups of SC techniques could be more reasonable for the front and center concern. The last option does not intend that in all cases, the group of techniques recommended is the most fitting, as this might rely upon the issue being tended to by particular qualities.

The rules portrayed in Figure 7 begin with an essential inquiry presented to the client: "What is the reason and displaying attributes of the main issue?" (it very well may be correspondence and insight, questionable information, and thinking information revelation; furthermore, it may be work estimate and critical thinking). Assuming the design is the programmed investigation, and extraction of data from advanced pictures to settle on the move to be made concerning the executives of vegetable supply frameworks (correspondence and sensitivity), the appropriate group of techniques would be deep neural networks (e.g., convolutional neural networks). This group of SC techniques empowers the production of PC sight frameworks, and it makes it possible to observe the climate of item properties graphically. Because of this visual examination, these frameworks impart or suggest activities that accomplish wanted conditions or meet predetermined criteria (for example, differentiate the nature of potatoes to determine the quantities that have been harmed or consumed).

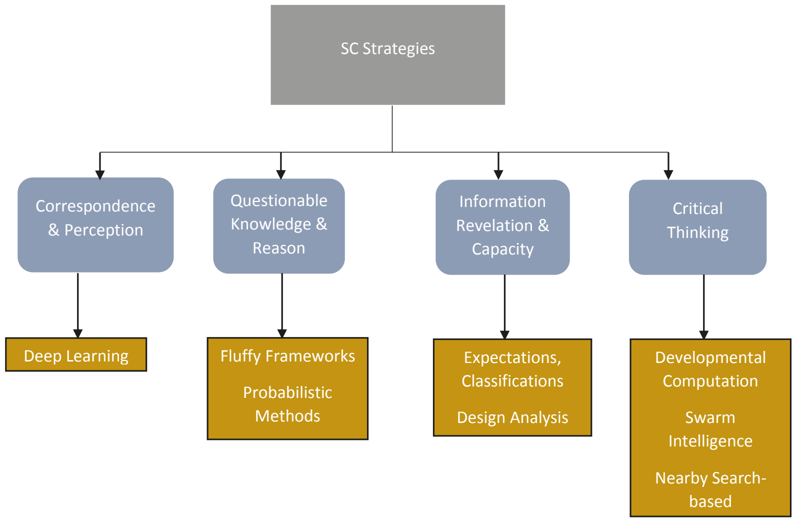

Figure 7. Guidelines for the strategy in the vegetable supply chain issues: creation, handling, dissemination, and retail.

Assuming the client's goal is to deal with issues portrayed by, to some degree, noticeable, non-deterministic, or loose information (unsure information and thinking), fluffy frameworks or then again deterministic techniques are suggested. It is significant for the previous SC methodology to feature that it should match a soft framework with equipment (e.g., PID regulators) to deal appropriately with vegetable applications. That is because equipment parts permit choices made by fluffy frameworks to be converted into activities (e.g., the executives of supplements and water system supply inside a nursery framework relying upon conditions related to temperature). Deterministic techniques are reasonable for making assessments of relevant factors (e.g., arranging creation as per occasional interest) in situations with, to some degree, perceptible information.

When the clients' point is to make forecasts from recorded information, make orders that separate between information classes, or track down secret examples in communication, information disclosure and capacity guess are the best to demonstrate how to deal with the use. First and foremost, the client should decide the information for expectations and arrangements. The data can then be organized (e.g., accurate information, basic information) or unorganized (e.g., clip, pictures). Earlier, and depending on the quantity of the data, administered learning algorithms included SC methodologies to use when dealing with small, moderate, and large data sets of little more than 40–50 gigabytes. Directed DL, be that as it may, is the suggested approach for massive datasets.

Regarding making forecasts and arrangements while utilizing unstructured information, regulated DL has been a much more reasonable learning method; hence unaided ML or solo DL is the suggested SC methodologies for design examination. At last, as we can find in Figure 7, a different class of issues that clients could confront is critical thinking. The client's point is to improve specific qualities to accomplish an ideal degree of execution for this situation. The above-proposed approaches are, in this way, all meta-heuristics (e.g., EC, SI, and nearby search-based procedures).

Even if the examinations are introduced, the base piece of Figure 7 likewise portrays which VSC phases the four SC demonstrating methods (and having related techniques) are usually used. Fluffy frameworks and deterministic methodologies are typically known for control programs in the creation, handling, and retail organization. Interestingly, advancements with meta-heuristics and forecast grouping design investigation with ML and DL display points of view are accepted in the whole VSC procedure. This will ordinarily concentrate on the commitments of correspondence and insight methods that utilize DL techniques to create retail arrangements.

5. Conclusions

This study has suggested a novel approach and complete scientific classification of VSC concerns about SC views for three delegate supply chains: cruciferous vegetables, dark green leafy vegetables, and tomatoes. We assembled the scientific type in light of different parts to arrange VSC issues as per how they can be demonstrated utilizing SC methodologies. These parts are centered around recognizing the chain phase (creation, handling, dissemination, and retail) and the particular VSC issue to be tended to (e.g., vehicle steering issues in the appropriation phase).

To check the strength of the scientific categorization, we classified VSC issues with SC techniques, particularly in the creation, handling, dispersion, and retail, scientific categorization. It is appropriate to feature that we presented many bound-together definitions for these issues. As an outcome, we had the option to make a few interesting conclusions. In the cruciferous vegetable and tomatoes cases of the creation phase, utilizing DL and the correspondence and insight quality altogether impacts applications (e.g., cruciferous vegetable weight assessment, field checking, creature government assistance) where the information is not checked by picture and video records (nonstructured information). Interestingly, we have the instance of suitable ML, which is limited to VSC issues, and for which the goal is to make creation expectations utilizing documented information records (organized information). On account of agriculture creation frameworks, the extent of the SC methodology is more extensive. In particular, we noted that DL, ML, FL, and meta-heuristics are techniques for demonstrating creation issues connected with crop security and yield, climate expectation, and water system and supplementing the executives.

ML, meta-heuristics, and deterministic techniques are the SC method ordinarily utilized in the handling phase.

As for ML, the point is to remove examples and objective factors like interest forecast and expectation of post-collect losses. They plan to upgrade vegetable-producing procedures (e.g., washing, cleaning) and creation, anticipating appropriation concerning meta-heuristics and deterministic methods. Finally, in the retail phase, DL is the robust SC methodology in cases with disorganized accepting information (e.g., variable limiting, nutrition, and nourishment). Traditional ML has been utilized to extract designs (vegetable utilization and vegetable loss) and anticipate purchaser interest and purchasing conduct.

Overall, the scientific classification investigation proposes that there is no group of SC techniques that best suits all VSC issues. Even we express the requirement for a correlation system that permits the portrayal and examination of the exhibition of various SC strategies in different inventory network issues. In this unique circumstance, the scientific categorization introduced sets up the premise for a typical structure that, in additional exploration, will work with trial and error together to figure out which SC methodologies are more suitable for each sort of VSC issue. That may assist with deciding an appropriate pattern of strategies to make fair examinations, dependent upon the group of SC techniques picked for the VSC main issue.

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