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Special Issue Reprint

Current State and Future of International Logistics Networks – The Role of Digitalization and Sustainability in a Globalized World

Edited by
Benjamin Nitsche and Frank Straube

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This is a reprint of articles from the Special Issue published online in the open access journal *Logistics* (ISSN 2305-6290) (available at: www.mdpi.com/journal/logistics/special_issues/CSFILN).

For citation purposes, cite each article independently as indicated on the article page online and as indicated below:

Lastname, A.A.; Lastname, B.B. Article Title. *Journal Name* **Year**, *Volume Number*, Page Range.

ISBN 978-3-0365-9711-9 (Hbk)
ISBN 978-3-0365-9710-2 (PDF)
doi.org/10.3390/books978-3-0365-9710-2

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After finishing his studies in industrial engineering at the Berlin University of Technology (TU Berlin) in 2013, Mr. Nitsche worked as a strategic purchaser in the consumer electronics industry. In 2014, he started as a research associate at the Chair of Logistics at TU Berlin and finished his doctoral thesis in 2018 in the field of supply chain volatility management, for which he was awarded by the German Association of Industrial Engineers. Mr. Nitsche is currently heading the Competence Center for International Logistics Networks (ILNET), which is part of the Chair of Logistics at TU Berlin. At the ILNET, which is endowed by the Kühne Foundation, a team of researchers, jointly with university partners from Africa (e.g., Rwanda, Ethiopia, and Ghana) and China, investigates current trends and strategies in international logistics networks by integrating a variety of industry partners and industry working groups in those regions into the research process. Following this integrative, practice-oriented research approach, the ILNET regularly publishes results in scientific and practice-oriented journals and magazines. Mr. Nitsche also serves as a reviewer for several international journals and is a member of the editorial board of Logistics, special section "Artificial Intelligence, Logistics Analytics, and Automation". He is also a visiting lecturer at the FU Berlin, ESCP Europe, and FOM University of Applied Sciences, and he is also conducting executive education seminars.

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Editorial

Current State and Future of International Logistics Networks—The Role of Digitalization and Sustainability in a Globalized World

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1. Introduction

The management of international logistics networks poses major challenges for companies. Even though international logistics is often seen as the backbone and engine of the global economy, it is regularly put to the test. In a few words, management of international logistics networks describes the planning and design of global value creation systems to fulfill customer orders by efficiently linking goods, information, and financial flows from the procurement of raw materials to delivery to the end customer with the goal of increasing customer satisfaction. Increasing risks and volatility in logistics networks constantly present logistics managers with the challenge of developing innovative solutions for ever-new problems. The importance of logistics has made it one of the most important industries and employers in many regions and countries. To deal with challenges, logistics regularly adapts new technologies and combines them into innovative solutions to better meet customer requirements. Especially in international logistics, the industry often acts as an early adopter of technologies such as machine learning, blockchain, digital supply chain twins, and others. However, the truth is also that logistics, especially international transport, is also one of the major emitters of greenhouse gases, and the industry needs to find answers in the short and medium term on how to reduce the global carbon footprint. In the interplay with the aforementioned technological innovation power of logistics, a huge potential is seen here that has not yet been exhausted. In addition, international logistics can make a decisive contribution to the growth and prosperity of economic regions. Especially in low- and mid-income countries, logistics is an important enabler for economic growth and the integration of those countries into global value creation systems. Supporting these countries, e.g., countries in sub-Saharan Africa, is one of the major challenges of our generation, with it facing society as a whole, and logistics can make a contribution to improving living conditions.

This special issue aims to make a contribution from research to continue the discussion on current trends in international logistics and to make a contribution with solutions that are of great use in industrial practice. To this end, the main trends in international logistics are examined and important sub-topics are analyzed in this context. The following is an introduction to the main trends in international logistics, which form the basis for the articles included in this Special Issue. We will then briefly summarize the articles included in this Special Issue.

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Citation: Nitsche, B.; Straube, F. Current State and Future of International Logistics Networks—The Role of Digitalization and Sustainability in a Globalized World. *Logistics* **2023**, *7*, 83. https://doi.org/10.3390/logistics7040083

Received: 27 October 2023
Accepted: 30 October 2023
Published: 11 November 2023

2. Main Trends Impacting Future Logistics Networks

Over the past few decades, numerous studies have delved into the question of which economic and social trends influence logistics networks. The landscape of trends that could potentially shape logistics planning and design is extensive, and the specific product and customer base addressed play pivotal roles in determining their relevance. However, in the realm of international logistics, four predominant trends have steadily gained significance over time. While not entirely novel, these trends hold paramount importance in shaping the future design of international logistics networks.

The first of these trends is *digitalization*, which has been on the rise for the past decade and is set to usher in significant changes in the planning and management of international logistics networks. Rapid technological advances are poised to bring substantial transformations within the current decade. Furthermore, the global trend towards *sustainability* has emerged as a key driver for future developments in logistics networks. Sustainability has ascended to a prominent position in the global public consciousness, and regulatory interventions in this domain are anticipated. Consequently, logistics networks must adapt and systematically incorporate sustainability considerations into their strategic projects over the next decade. *Digitalization* and *sustainability*, two paramount trends, are posing a growing challenge to current approaches in the design of international logistics networks. These trends also interplay with the enduring mega-trend of *globalization*, which has shaped the landscape of value networks worldwide. While globalization has been a central driver of increased complexity in logistics networks, the current decade raises questions about the role of globalization in international logistics networks, particularly in light of the trends of *digitalization* and *sustainability*. To further complicate this intricate web of trends, the world of logistics networks has been characterized by the persisting trend of *increasing risks and dynamics*. These factors render the study and development of international logistics networks all the more complex. Several research studies have highlighted the growing turbulence in international logistics networks [1,2], a phenomenon that gained even greater prominence with the onset of the COVID-19 pandemic [3,4].

Figure 1 offers an overview of the main trends in international logistics networks, along with their associated sub-trends that exert significant influence on the future design of such networks. The subsequent sections will elaborate on the developments within the main trends of *digitalization*, *sustainability*, and *globalization*, and their implications for the design of future logistics networks.

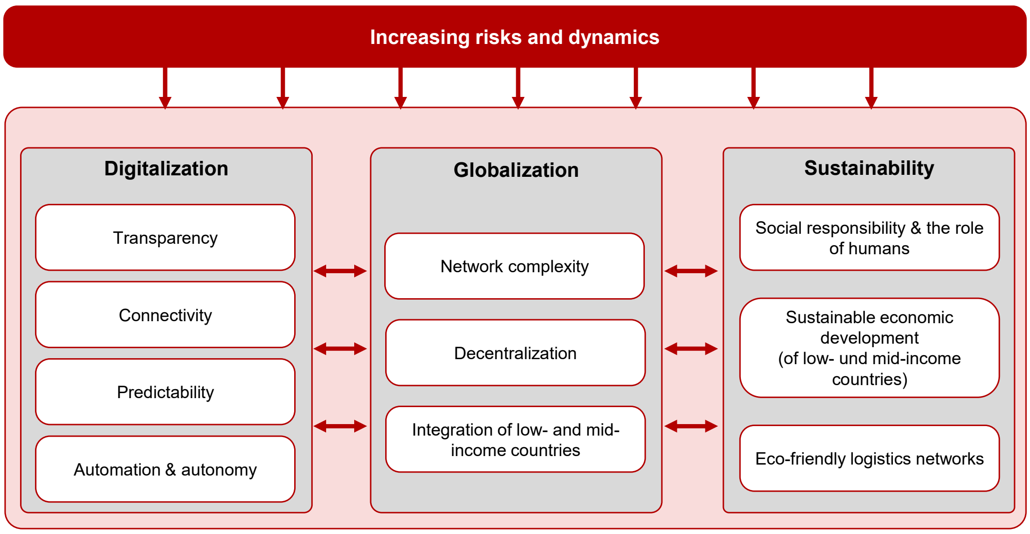

Figure 1. Main trends impacting the design of future international logistics networks.

2.1. Digitalization in International Logistics Networks

In recent years, the digitalization of logistics networks has increased significantly, leading to profound consequences for the future planning and management of logistics systems. Under the broad umbrella of digitalization, a myriad of sub-streams, technologies, knowledge areas, and business functions have converged, closely aligned with the burgeoning technologization of logistics networks. Fundamentally, this movement revolves around the strategic question of how to effectively harness the expanding potential made available through advancing computerization and technologization, along with the corresponding acquisition of data, to positively shape the parameters of logistics goals. A key tenet of this approach is to utilize the vast and ever-growing volume of data generated daily and to deploy emerging technologies mindfully, rather than embracing a technology-driven push, thus playing a pivotal role in this landscape.

The potentials of digitalization are diverse, reflecting the multifaceted motives underpinning its promotion in the field of logistics. One of the initial sub-trends is the establishment of *connectivity* within logistics networks, enabled by the novel possibilities stemming from digitalization. This endeavor seeks to interconnect the various actors in the network, fostering smoother and timelier information exchange. This heightened connectivity lays the foundation for the next sub-trend in the digitalization journey—*transparency*. Given the increasing complexity of global value creation structures, transparency is an absolute imperative across multiple stages on both the supplier and customer sides of the logistics process. It is essential for the purpose of proactive planning and responsive actions. Creating transparency is, and always has been, a core responsibility of logistics managers. However, the new possibilities facilitated by technologies such as digital supply chain twins [5] and blockchain [6] are anticipated to offer fresh avenues for achieving transparency in a simpler, more comprehensible, near-real-time, and secure manner.

Once connectivity and transparency are firmly established, a wealth of data is at hand, facilitating the pursuit of the third sub-trend of digitalization over the long term—enhancing the *predictability* of logistics systems. The need for increased predictability is particularly pronounced in the context of international logistics networks. Timely identification of risks within globally distributed value streams is imperative, enabling early or even preemptive countermeasures. This is critical in international logistics, where forecasting arrival times for extensive, intermodal transport chains remains a challenge, often relying solely on historical data. Encouragingly, the remarkable advances in the realms of artificial intelligence and machine learning underscore the potential of digitalization in delivering marked efficiency gains in terms of prediction accuracy within complex logistics networks [7]. Nonetheless, the industry-wide adoption of artificial intelligence algorithms for early risk detection is still lagging behind expectations, highlighting the need for a collective effort to bridge this gap [8].

As a certain level of connectivity and transparency begins to take shape within international logistics networks, the *automation* of processes within these networks becomes increasingly attainable. Moreover, should a certain level of predictability be established, the prospect of logistics systems operating *autonomously* in the long term, within the context of digitalized logistics networks, becomes conceivable. The automation of logistics processes stands as one of the most vital trends in the ongoing digitalization of logistics [9–11]. The allure of increased efficiency, flexibility, resilience, and reduced dependence on the expertise and decisions of individual logistics decision-makers makes this trend particularly compelling. Automation spans both physical processes, which are already more advanced in certain industries, and informational processes, especially pertinent in the realm of international logistics networks. With the growing degree of automation in these informational processes, accompanied by increasingly intelligent systems, it is conceivable that a significant proportion of these processes may operate autonomously in the evolution of logistics systems. This autonomous operation could include automatic and, at best, intelligent decision-making, e.g., facilitated through intelligent multi-agent systems [12]. Recent studies even propose that the majority of informational processes involved in managing logistics networks may be running autonomously by the end of this decade [13].

It is essential to recognize that while the sub-trends of *connectivity*, *transparency*, *predictability*, and *automation and autonomy* were presented successively, they need not be pursued sequentially. Instead, these sub-trends offer a directional roadmap for the potential evolution of logistics systems. Projects and developments can run in parallel, with connectivity and transparency often being the initial steps in the development process. They set the foundation for more intricate stages, such as predictability or autonomy, to be addressed subsequently. In this way, the digital transformation of logistics networks can take multiple paths, with the ultimate aim of achieving greater efficiency, resilience, and adaptability in the dynamic landscape of international logistics.

2.2. Sustainability in International Logistics Networks

The significance of the global megatrend of sustainability has grown in recent years. Concerning the ecological dimension of sustainability, the scientific community highlighted several decades ago that the escalating emission of greenhouse gases leads to global warming, with dire consequences for the planet's ecosystems. In logistics research, ecological sustainability became a topic of intensive discussion as early as the first decade of the 21st century, even though the urgency of these concerns in logistics practice emerged later. While the ecological perspective on sustainability is undeniably crucial, it is important to recognize that the sustainability concept is much broader, adhering to the more widespread "triple bottom line" approach [14]. This approach incorporates not only the ecological dimension but also economic and social dimensions. The economic facet of sustainability is dedicated to fostering economic activities geared toward long-term sustainability rather than prioritizing short-term profits at the expense of future generations. In a societal context, the economic dimension of sustainability encompasses a society striving for long-term economic stability and prosperity while considering the well-being of future generations. The social dimension of sustainability emphasizes the importance of a socially harmonious, ideally conflict-free society that places a strong emphasis on individuals and their living conditions, both at points of consumption and along value chains.

In the realm of social sustainability, a vital sub-trend within international logistics networks centers on *social responsibility and the role of humans*. In recent years, social sustainability, especially within logistics networks, has been somewhat overshadowed by its ecological counterpart but has grown in prominence. A significant driver for this shift is the evolving societal awareness among end customers who want transparency regarding the production and processing conditions of products, as well as assurances that no individuals, especially children, have been harmed in the process. From a logistics perspective, this presents various challenges in supplier selection and monitoring, particularly in the context of international logistics networks. The role of humans is also gaining increasing importance for another reason. Due to the technological advancements associated with the digitalization trend, processes within international logistics networks are becoming progressively automated and potentially autonomous. This implies that individuals currently engaged in manual logistics processes will need to assume different roles in the near future. This shift is likely to demand new competence profiles and organizational structures in logistics, necessitating corresponding training and education. However, the impact of rationalization and the potential loss of social value associated with tasks should not be underestimated, as this dynamic has the potential to give rise to conflicts.

From the economic sustainability perspective, international logistics networks should facilitate *sustainable economic development, especially for emerging and developing countries*. International logistics plays a pivotal role in this regard since logistics challenges are consistently identified as significant trade barriers that hinder the sustainable growth of developing nations. The African continent, in particular, stands out as a region with considerable potential, characterized by relatively low economic power yet rapid population growth. It is regarded as one of the most crucial future markets for numerous industries. Nevertheless, sustainable economic growth and prosperity are not guaranteed in these countries alone, given the presence of various trade barriers, especially logistics-related challenges tied to inefficient transportation systems. Companies continue to express reservations, especially concerning sub-Saharan Africa [15].

Finally, the establishment of *eco-friendly logistics* networks stands as a crucial subtrend in the domain of ecological sustainability within international logistics networks. Given that most industries feature globally dispersed value creation structures, logistics bears a substantial share of greenhouse gas emissions. Depending on the study and the methodology employed, transportation alone is responsible for roughly 24% of global CO_2

emissions [16]. Furthermore, transportation represents only part of logistics functions, indicating that the actual contribution of logistics to global greenhouse gas emissions is likely even higher. This constitutes a pressing issue which will inevitably prompt greater regulatory intervention in the short and medium term. Consequently, logistics must adapt and explore methods for implementing eco-friendly logistics networks. The coming years will serve as a barometer for the extent to which such changes can be implemented. Potential avenues include the redesign of logistics networks, improved planning algorithms, the utilization of new technologies and transport modes, or, at the very least, enhanced integration of existing transport modes into intermodal transport systems.

2.3. Globalization in International Logistics Networks

Globalization has been a driving force behind international logistics networks for decades, playing a pivotal role in fostering economic growth through the increased global division of labor facilitated by highly interconnected logistics systems. This global trend of globalization within international logistics networks comprises three prominent sub-trends. Firstly, *network complexity* has been steadily rising due to globalization, marked by the expansion of potential suppliers and customer regions. This expansion significantly increases the intricacy of logistics networks that managers need to oversee. This trend aligns closely with another sub-trend: the *decentralization* of decision-making in international logistics networks and the physical *decentralization* of production and logistics activities. Decisions are being made in more distributed locations, and the physical structure of production and logistics activities, such as warehouses, are becoming more decentralized. Moreover, the third sub-trend in this globalization paradigm is the *integration of low- and mid-income countries into international logistics networks*. This is driven by the need for the sustainable development of these developing countries. Integration often begins on the supplier side, gradually expanding to the customer side, with labor cost advantages serving as a primary motivator for manufacturers to incorporate these countries into their logistics networks.

The globalization of the international economy, which has been a dominant trend in recent decades, has yielded various advantages and challenges. However, with the rise of the megatrends of digitalization and sustainability, there is a question of how globalization may evolve. One possible scenario is a reduction in the degree of globalization, motivated by the pursuit of ecological sustainability. International transport is a significant contributor to global greenhouse gas emissions, and localizing logistics networks may help mitigate these emissions. Conversely, the integration and sustainable economic development of developing countries, particularly in sub-Saharan Africa, may drive an increase in globalization. Since more and more potential customers will be located in these regions in the long term, this can also lead to an increase in the decentralization of logistics structures through the addition of further warehouse locations, for example.

The interplay between globalization and sustainability is further complicated by the advent of digitalization. Digitalization, coupled with the technologization of logistics networks, can theoretically lead to highly automated production facilities that can autonomously produce customized products on a large scale with minimal human labor. This could diminish the significance of labor cost advantages in developing countries, potentially prompting a shift of manufacturing back to industrialized nations. Conversely, technology such as digital supply chain twins and blockchain, in conjunction with artificial intelligence, can offer real-time transparency regarding global value chains and predict future states of international logistics networks with intelligent precision. This may facilitate smoother integration of additional suppliers, including those from developing countries, into increasingly complex international logistics networks, ultimately promoting further globalization. These examples underscore the intricate interplay between digitalization, globalization, and sustainability, emphasizing the need to thoroughly assess the potential changes that these focus trends may induce in international logistics networks, both at various levels and in multiple directions.

The interplay of the three trends described above in the context of increasing risks and dynamics makes the discussion about future developments in international logistics both exciting and challenging. Even though industrial practice must find solutions to deal with the challenges described, science can contribute to the solution. This is also the aim of the articles included in this Special Issue, which are located within the interplay of the trends described above and make a contribution to the further development of research in their subfield.

3. Summary of Articles Included in This Special Issue

3.1. The Influence of Technologies in Increasing Transparency in Textile Supply Chains

The international textile industry is a vibrant industry whose logistics networks are constantly reinventing themselves in search of new alternative sources of supply. This reorganization of logistics networks is characterized by two opposing trends. On the one hand, there is the desire for ever more cost-effective production alternatives in developing countries to meet the needs of the fast fashion industry, and on the other hand, there is the customer demand for ever more sustainable logistics networks for textile products, as the industry is considered one of the least sustainable. One of the most important initial levers in the creation of sustainability is the creation of transparency in textile logistics networks. Therefore, the article examines how digital technologies can have an impact on creating more transparency in textile logistics networks and how this can contribute to more sustainability at the same time. A broad range of different technologies is examined on the basis of expert interviews in order to develop a framework that attempts to explain the use of the technologies in the textile industry and their corresponding effect. The article is thus located directly at the interface between digitalization and sustainability of the trend framework in Figure 1 and makes an important contribution to the discussion of future logistics networks.

3.2. Utilization of Free Trade Agreements to Minimize Costs and Carbon Emissions in the Global Supply Chain for Sustainable Logistics

As already mentioned, the pressure on the logistics industry to reduce greenhouse gases is increasing enormously and more and more regulatory interventions will be imposed on the industry to reduce greenhouse gases, for example through carbon tax prices, even if these differ greatly in the regions of the world. This may also lead to companies relocating to take advantage of more favorable carbon taxes. Despite this pressure to reduce, international trade continues to expand and various free trade agreements are being concluded, which, at the very least, risk further increasing greenhouse gas emissions. This article proposes a mathematical model that helps companies set up a cost-optimal logistics network, incorporating carbon taxes and free trade agreements based on suppliers and production locations, quantities of parts and other factors. The resulting logistics networks are also examined and compared with and without the presence of free trade agreements. It is found that free trade agreements do not have a negative impact on greenhouse gas emissions. The article, thus, makes an exciting contribution at the intersection of the trends of globalization and sustainability, especially the creation of eco-friendly logistics networks of the trend framework of Figure 1.

3.3. A Sustainable Two-Echelon Logistics Model with Shipment Consolidation

Even though alternative technologies also play an important role in the context of creating climate-friendly logistics networks, studies repeatedly find that increasing efficiency in logistics in particular can have an enormous impact on reducing greenhouse gases. Logistics networks evolve not always with a view to a cost-optimal and at the same time eco-friendly overall solution, but more as a fast reaction to a volatile market environment. An important lever for increasing efficiency in logistics networks is increasing capacity utilization through shipment consolidation. What sounds logical is often associated with challenges in practice. The article develops a mathematical model that determines an optimal shipment consolidation strategy while reducing costs and emissions. The model is examined and validated on the basis of a case study in the Egyptian dairy industry and it is shown what effects shipment consolidation can achieve. In the example described, costs are reduced by 40% and emissions are significantly reduced due to the significantly lower fuel consumption. the article therefore makes an important contribution in the context of the discussion on eco-friendly in international logistics networks.

3.4. The Impact of Digital Technologies and Sustainable Practices on Circular Supply Chain Management

In the broad and complex field of sustainable logistics, circularity received comparatively little attention in the past. However, the topic of circular supply chains has become increasingly important in recent years, not only in science but also in practice, as it is increasingly realized that limited resources can only be used in the long term if circularity is being created. However, it is also becoming clear that the logistics requirements for such reorganized logistics networks are enormous. This article therefore examines the benefits that companies can derive from the use of digital technologies in the operation of circular supply chains and the extent to which this also has an impact on the sustainability of the logistics network. The study uses a structural equation model based on a survey of 157 companies. The study is located directly at the interface between digitalization and sustainability shown in the trend framework of Figure 1 and makes a significant contribution to research on circular supply chains. Among other things, it can be shown that technologies can make a contribution in the context of circular supply chains, e.g., in identifying the origin of raw materials, in managing complex transport flows within circular supply chains and much more.

3.5. Blockchain Technology and Sustainability in Supply Chains and a Closer Look at Different Industries: A Mixed Method Approach

The discussion about the potential of blockchain technology in the context of international logistics has gained momentum in recent years, and the use of blockchain technology in international logistics networks has become an important field of research, especially in the scientific community. The technology is seen as having particularly high potential for achieving sustainability goals at various levels. This article conducts a content analysis of 185 articles that examine the use of blockchain technology to achieve sustainability goals. The content analysis provides a comprehensive insight into application fields and penetration levels of the technology in diverse industries. Not only is the state of the art in science presented in detail, but above all the industry perspective is highlighted and the advantages and challenges in the use of the technology in industrial practice are explained. The article thus makes an important contribution to the interface between digitalization, sustainability, and globalization.

3.6. Current Trend of Industry 4.0 in Logistics and the Transformation of Logistics Processes Using Digital Technologies: An Empirical Study in the Slovak Republic

When examining the digital transformation of companies and their logistics processes, the concept of Industry 4.0 represents a core element not only in science but above all in industrial practice. Industry 4.0 focuses primarily on the production environment of manufacturing companies, but also goes beyond this with the associated logistics and distribution processes. The article aims on the one hand to classify the concept of Industry 4.0 in the context of logistics, and on the other hand to analyze the extent to which Industry 4.0 technologies have already penetrated Slovakian companies in order to draw conclusions about how to implement digital transformation. The study is based on a survey of 144 Slovakian small-, medium- and large-sized companies. The study of the penetration of Industry 4.0 technologies into production and distribution is informative and makes an important contribution to the field of research on digital transformation in logistics.

3.7. Selecting Partners in Strategic Alliances: An Application of the SBM DEA Model in the Vietnamese Logistics Industry

Managing increasingly complex logistics networks requires strategic alliances between partners to ensure resilience, especially in the context of ever-increasing cost pressures. However, the level of inter-firm relationships in the logistics industry is not strong in all regions of the world, and a high level of competition complicates the situation. The authors of this article argue that while it is highly important to find long-term strategic partners in a logistics network, the level of inter-firm partnerships in Vietnam, among other countries, is comparatively low. In order to contribute to this, the authors develop a model that analyzes logistics service providers in the Vietnamese logistics market and proposes strategic partnerships. The article makes a valuable contribution and proposes a model that helps industrial practice and can certainly be applied beyond Vietnam.

3.8. Analysis of the Activities That Make up the Reverse Logistics Processes and Their Importance for the Future of Logistics Networks: An Exploratory Study Using the TOPSIS Technique

Due to the increasing use of finite raw materials, the topic of reverse logistics or closed-loop supply chains is becoming more and more important in the public perception. Without sensible concepts that organize the return of materials, a sustainable future is hardly conceivable, and logistics has a key role to play here. Using the example of a study of industrial practice in Brazil, this article investigates which processes belong to the subarea of reverse logistics and what their implementation status is in the industry. The article makes an important contribution to the creation of a common understanding of concepts and process responsibilities in the field of reverse logistics, a field of research that will become increasingly important in the future.

3.9. Analyzing the Implementation of Digital Twins in the Agri-Food Supply Chain

Digital supply chain twins are one of the most promising technology concepts for the future management of complex international logistics networks. For this reason, the topic has not only been more thoroughly explored scientifically in recent years but has also been accompanied by industrial practice with prototypes. Many potentials are attributed to digital supply chain twins, especially in creating transparency about possible risks and bottlenecks, increasing efficiency in network management, reducing costs and much more. Especially in agri-food supply chains, the topic of digital twins is strongly accompanied by research and various studies exist. Based on a systematic literature analysis of 50 peer-reviewed articles with a focus on digital supply chain twins in the agri-food industry, the article aims to analyze the status quo of the implementation of digital supply chain twins in the agri-food industry in more detail and to derive its implications. While noting that implementation in practice is still in its infancy, clear research directions are given to overcome current implementation hurdles.

3.10. Warehouse Management Systems for Social and Environmental Sustainability: A Systematic Literature Review and Bibliometric Analysis

Although it has already been explained that international transport accounts for a significant share of global greenhouse gas emissions, it should not go unmentioned that various other logistics-related functions also make a significant contribution, including warehousing in international logistics networks. However, in warehouse management, it is not only the ecological footprint that plays a role, but also social aspects as well. Based on a systematic literature review, the article examines the current state of warehouse management systems in practice and their contribution to achieving environmental and social sustainability goals. Although logistics sites such as warehouses account for a not-so insignificant share of the logistics industry's total greenhouse gas emissions, the authors note that little research has been performed on how warehouse management systems can contribute to environmental and social sustainability. Based on this, clear recommendations are made as to how warehouse operations can make a more decisive contribution to achieving the goals in the future and what can be carried out on the research side to support this.

Author Contributions: Conceptualization, B.N. and F.S.; writing—review and editing, B.N. and F.S. All authors have read and agreed to the published version of the manuscript.

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

References

1. Christopher, M.; Holweg, M. Supply Chain 2.0 Revisited: A Framework for Managing Volatility-Induced Risk in the Supply Chain. *Int. J. Phys. Distrib. Logist. Manag.* **2017**, *47*, 2–17. [CrossRef]
2. Nitsche, B.; Durach, C.F. Much Discussed, Little Conceptualized: Supply Chain Volatility. *Int. J. Phys. Distrib. Logist. Manag.* **2018**, *48*, 866–886. [CrossRef]
3. Fernandes, N. Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy. *SSRN Electron. J.* **2020**. [CrossRef]
4. Belhadi, A.; Kamble, S.; Jabbour, C.J.C.; Gunasekaran, A.; Ndubisi, N.O.; Venkatesh, M. Manufacturing and Service Supply Chain Resilience to the COVID-19 Outbreak: Lessons Learned from the Automobile and Airline Industries. *Technol. Forecast. Soc. Chang.* **2021**, *163*, 120447. [CrossRef] [PubMed]
5. Gerlach, B.; Zarnitz, S.; Nitsche, B.; Straube, F. Digital Supply Chain Twins—Conceptual Clarification, Use Cases and Benefits. *Logistics* **2021**, *5*, 86. [CrossRef]
6. Verhoeven, P.; Sinn, F.; Herden, T. Examples from Blockchain Implementations in Logistics and Supply Chain Management: Exploring the Mindful Use of a New Technology. *Logistics* **2018**, *2*, 20. [CrossRef]
7. Straube, F.; Weinke, M.; Poschmann, P. Hohes Potenzial für Lernende Systeme in Logistischen Entscheidungsprozessen. *Logist. Unternehm*. 2020. Available online: https://www.ingenieur.de/fachmedien/logistikfuerunternehmen/produktionslogistik/hohes-potenzial-fuer-lernende-systeme-in-logistischen-entscheidungsprozessen/ (accessed on 20 October 2023).
8. Nitsche, B.; Straube, F. Defining the "New Normal" in International Logistics Networks: Lessons Learned and Implications of the COVID-19 Pandemic. *WiSt Wirtsch. Stud.* **2021**, *50*, 16–25. [CrossRef]
9. Straube, F.; Nitsche, B. Heading into "The New Normal": Potential Development Paths of International Logistics Networks in the Wake of the Coronavirus Pandemic. *Int. Transp.* **2020**, *72*, 31–35.
10. Klumpp, M. Automation and Artificial Intelligence in Business Logistics Systems: Human Reactions and Collaboration Requirements. *Int. J. Logist. Res. Appl.* **2018**, *21*, 224–242. [CrossRef]
11. Nitsche, B.; Straube, F.; Wirth, M. Application Areas and Antecedents of Automation in Logistics and Supply Chain Management: A Conceptual Framework. *Supply Chain Forum Int. J.* **2021**, *22*, 223–239. [CrossRef]
12. Nitsche, B.; Brands, J.; Treiblmaier, H.; Gebhardt, J. The Impact of Multiagent Systems on Autonomous Production and Supply Chain Networks: Use Cases, Barriers and Contributions to Logistics Network Resilience. *Supply Chain Manag. Int. J.* **2023**, *28*, 894–908. [CrossRef]
13. Junge, A.L.; Verhoeven, P.; Reipert, J.; Mansfeld, M. *Pathway of Digital Transformation in Logistics: Best Practice Concepts and Future Developments*; Scientific Series Logistics at the Berlin Institute of Technology; Special Edition; Straube, F., Ed.; Universitätsverlag der TU Berlin: Berlin, Germany, 2019; ISBN 978-3-7983-3094-8.
14. Elkington, J. *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*; New Society Publishers: Gabriola Island, BC, USA; Stony Creek, CT, USA, 1998; ISBN 978-1-84112-527-5.
15. Straube, F.; Nitsche, B.; Coll, A. *Challenges and Opportunities of Logistics in African Countries*; Technische Universität Berlin: Berlin, Germany, 2022.
16. Ritchie, H. Cars, Planes, Trains: Where Do CO_2 Emissions from Transport Come From? *Our World Data* **2020**.

logistics

Article

The Influence of Technologies in Increasing Transparency in Textile Supply Chains

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Abstract: *Background:* In the current political discourse, supply chain transparency is seen as a key to improving the working and environmental conditions within textile supply chains. Additionally, the use of technology is increasingly being regarded as a means of reducing complexity and increasing transparency within these supply chains. While much research has been conducted to understand the impact of the textile industry on sustainability and the impact of technology on the overall performance of the textile supply chains, little attention has been placed on the following question: How do technologies affect transparency within the textile supply chains? *Methods:* We conducted seven interviews with actors from the textile industry. Based on these collected data, the relevance of selected technologies for improving transparency is established and the challenges of their implementation and impact on the industry are assessed. *Results:* Digital technologies, such as blockchain, the Internet of Things and dialog platforms, are promising instruments for transparency, even though their current implementation is not ideal. Furthermore, great skepticism on platforms for reporting (audits and complaint systems) is still prevalent. *Conclusions:* Since the influence of transparency on sustainability is conditioned by the goal orientation with which the technologies are implemented and used, we propose a framework for the implementation of the selected technologies that account for the interaction between said technologies in the textile supply chains.

Keywords: logistics; supply chain management; textile industry; digital technologies; digitalization; transparency

Citation: Hauschild, C.; Coll, A. The Influence of Technologies in Increasing Transparency in Textile Supply Chains. *Logistics* **2023**, *7*, 55. https://doi.org/10.3390/logistics7030055

Academic Editor: Robert Handfield

Received: 5 June 2023
Revised: 3 August 2023
Accepted: 14 August 2023
Published: 21 August 2023

1. Introduction

Today, with 78 million workers along the supply chains, the textile industry is the second largest consumer goods industry in the world after the food industry [1,2]. Over the past decades, production in this industry has been outsourced to South-East Asian and Sub-Sahara African countries in an effort to remain profitable as fast fashion strategies reduce order volumes and product life cycles [3]. In response to this aggressive business model, globally fragmented and complex textile supply chains have developed [4]. As a result of these complex supply chains, the challenge for companies to track and trace their activities and generate transparency has increased [2].

At the same time, diverse stakeholders have been placing more pressure on companies in the textile industry to improve their sustainability, especially concerning human rights violations [5]. Nevertheless, "without better knowledge about the size of the industry and the scope of the problem [. . .], approaches designed to address these issues will not be able to solve the problem comprehensively" [6] (p. 45). Additionally, Straube et al. [7] cements the importance of transparency as the basis for supply chain sustainability when integrated into the corporate strategy. Therefore, technologies are being increasingly used by companies to facilitate data collection in textile supply chains, with which retailers hope to improve efficiency, product quality, sustainability, customer satisfaction and regulatory compliance [8]. From a business perspective, technologies are considered essential for achieving greater visibility to identify and address challenges in complex supply chains, such as increasing data volume [9,10].

Technologies seem to be seen as a panacea for transparency and, at the same time, transparency as a panacea for sustainability. However, so far, it has not yet been studied, in a practical and industry-specific way, to what extent technologies have a positive influence on transparency in order to improve the sustainability of the textile industry.

Past research has been conducted on supply chain sustainability and its connection to transparency [2,11–13], on transparency and sustainability in the textile industry [1,5,14–18] or on the influence of technologies on transparency [9,10,19–23], partly connected to the textile industry [8,24–26]. Partly, technology use is associated with the sustainability of the textile industry, but often economic sustainability is the focus. Additionally, McGrath et al. [9] have investigated the roles of different types of technology on transparency.

In order to enrich previous knowledge, this research aims to investigate the impact of selected technologies on transparency for the purpose of improving social sustainability within the textile industry.

Therefore, the following research questions were formulated for this research:

- Which technologies are being used in the textile industry to increase transparency along supply chains?
- To which extent does the use of the respective technologies influence the increase in transparency along the supply chains of the textile industry?

2. Materials and Methods

The basis for the selection of technologies for this paper is found in the work of McGrath et al. [9], who examined across industries which technologies are being used in practice to increase sustainability visibility. They distinguish the effect of technologies on transparency according to collecting, processing and disseminating information. Since the focus of this paper is on the generation of information, or internal transparency, only technologies that collect information are included in the research scope, an overview of which technologies are analyzed in this paper.

This paper is based on qualitative research. In order to collect the necessary data to answer the research questions, we conducted semi-structured interviews following the criteria of Lamnek and Krell [27]. Since there may be differences of interest, especially between companies and NGOs, the two perspectives were the focus of the selection.

1. Textile and apparel companies that see themselves as sustainable and are responsible for the production itself and the possible implementation of technologies;
2. NGOs working for occupational safety and environmental protection in the textile industry. NGOs were chosen that advocate for workers and environmental conditions in the industry by publishing reports or campaigning, among other things. The advocacy group's point of view is particularly interesting, as they have direct channels to the workers, the companies as well as the government;
3. Service companies that help trading companies trace their supply chains;
4. Textile factories, as actors at the beginning of the supply chain, can assess the impact of technologies.

This work is limited to German-speaking contacts to avoid language barriers and the resulting scope for interpretation. Following this criteria, seven interviews were performed, as shown in Table 1. While the sample size is rather small considering the size of the textile industry worldwide, the insights obtained are still representative of the overall situation of technology implementation in the textile industry in Germany. The targeted interviewees were selected for their efforts in improving sustainability and transparency within the textile supply chains so that their expertise could be leveraged for the advancement of the textile industry in general.

Table 1. Composition of the sample; interviewees.

Person ID	Role within the Institution	Actor in the Supply Chain	Institution ID
P1	CEO/Founder	Blockchain as a service (BaaS) and sustainability platform provider for textile companies	NP1
P2	Consultant for sustainable supply chains and clothing	NGO	NGO2
P3	CSR Manager	Textile company	TBU3
P4	Auditor	Certification company	ZU4
P5	Sustainability Advocate & Consultant; former CSR Manager	Freelance; former textile company	TBU5
P6	Founder of the German NGO6; reg. coordinator	NGO	NGO6
P7	Technical coordinator	NGO	NGO6

The interview guideline consisted of the following three main blocks:

(i) General questions about the organization's activities in the textile industry and especially in sustainability and transparency;

(ii) Transparency in the supply chain, where the interviewees were asked about their understanding of transparency as well as the main challenges in the textile industry concerning transparency and its importance;

(iii) Technologies for transparency, where the interviewees were asked about the relevance of the technologies for the industry, their role in generating transparency and the risks and challenges in their implementation.

Furthermore, the data collected in the interviews were evaluated with the help of qualitative content analysis, a widely used method designed by Mayring [28]. Firstly, the technologies mentioned by the interviewees were identified—during this step, a new technology category was created, namely, "Others". Within this category, we then proceeded to classify all technologies named by the interviewees that did not correspond to the initial set (i.e., the technologies shown in Figure 1). In the second step, the corresponding information provided by the interviewees was classified into a category (in this case: each technology mentioned). Subsequently, the indications concerning the impact of each technology were summarized and visualized in an impact matrix with the following dimensions: "transparency" and "information on sustainability". This allows for a clearer picture of the overall potential impact of the selected technologies.

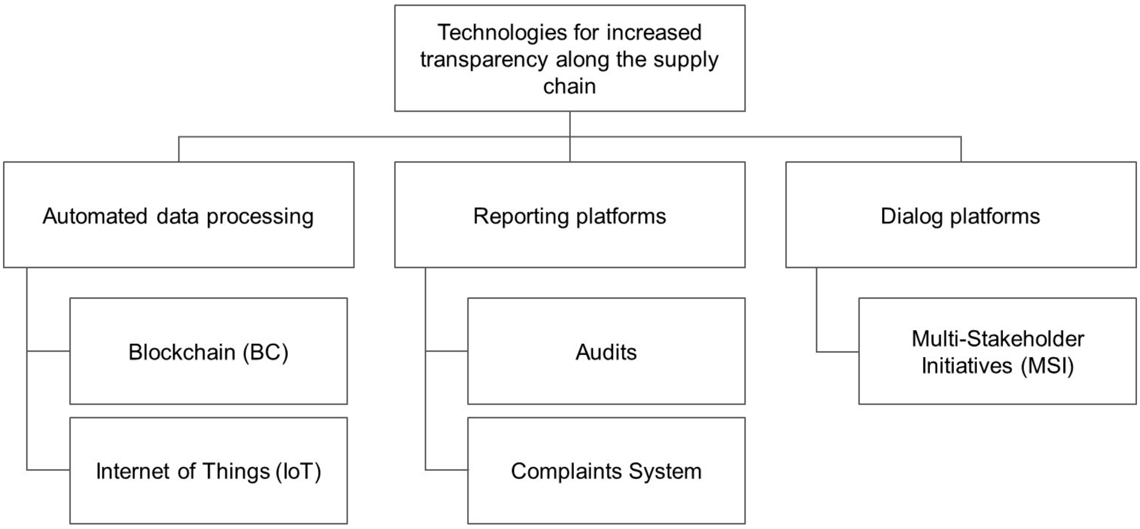

Figure 1. Overview of technologies for increased transparency along the supply chain.

3. Results

A detailed description of the information obtained within this research for each technology is given in this section. Table 2 shows the incidence of the technologies in the interviews.

Table 2. Breakdown of interviewees' statements on the technologies.

Person.	IoT	BC	Audits	Complaint Systems	Dialog Platforms	Others
P1		x	x		x	Sustainability Management Platform
P2			x	x		
P3		x	x	x	x	
P4			x	x		
P5		x	x	x	x	
P6		x	x	x	x	Unions
P7	x	x	x	x	x	DNA-Analysis. Fine dust analysis

3.1. Automated Data Processing

3.1.1. Internet of Things (IoT)

According to P7, the use of the IoT is significantly limited by the fact that the sensors and RFID tags cannot be installed at each stage of production but only after the manufacturing process of the fabric has been completed. Currently, according to P7, IoT for product tracking is only applied at the container level, i.e., during transportation. However, P7 sees great potential in the use of the IoT in earlier stages of the supply chain, especially in environmental monitoring. As an example, P7 cites the use of the IoT for monitoring air quality by measuring levels of toxins or temperature in factories. Currently, temperatures are measured annually via audits, but the IoT could collect data 24/7. For P7, the implementation is possible because it is not expensive, and the sensor can be set "so that it is not tampered with by the factory owner by hanging a cold rag over it", to lower the temperature.

3.1.2. Blockchain (BC)

Different assessments of the influence of BC emerge from the interviews. P1, P5 and P7 have dealt with the technology in more detail; P2, P3 and P6 have expressed their basic assessment of the technology.

In the interviews, BC was positively evaluated in that data can be collected, passed on securely and stored in a decentralized manner. BC creates trust, as the registered data can be assigned to the respective suppliers. In addition to information related to traceability, information on sustainability conditions can also be collected and evaluated. P3 and P5, who both work or have worked in textile companies, see great benefits in using BC. The data entered in the BC are based on the certificates previously issued by auditors. The use of the BC, in this case, is mainly for data preparation and disclosure of information via QR codes attached to the final products.

In contrast, P7 is critical, seeing no advantage in BC over a "quite banal database". However, the following example from TBU5 illustrates the advantage of using BC over simple databases, such as Excel lists: the supply chain of TBU5's products was nominated completely, from fiber origin to finished product (Nomination means that when a retail company awards a contract, it determines which suppliers its direct suppliers should purchase from), so it was assumed that the supply chain, including sustainability information, was fully known. After BC implementation, testing worked for 98 percent, but 2 percent had unknown fibers in the product. According to P5, they would not have found the error through their existing certification systems. However, P5 also mentions that BC cannot offer a 100% guarantee due to the dependence of the data quality and veracity on people. Nonetheless, both the system of Excel lists or on-site visits by the companies themselves and the cooperation with a certification system are prone to errors because the control instances behind them are not sufficient. Therefore, according to P5, BC's solution approaches are promising.

Several interviewees emphasize that BC technology as a whole is portrayed "in glowing descriptions" as being better than it actually is. It is seen as a "panacea" or "solver of everything". P7 is also "not convinced it's the best way to go, but it's just hip and makes money. [...] Some people are so enthusiastic about blockchain that they think it means information is always accurate." This interviewee remarks the positive attention BC receives and the trust it brings to the data as negative impacts of BC and is concerned with the energy consumption that the implementation of this technology requires. However, if BC is not public and does not go through the proof-of-work consensus mechanism, but only a few parties are allowed to write on BC, the energy problem would be solved and BC can be useful. According to P5, a verified life cycle assessment on BCs would be necessary to evaluate the energy consumption issue. Though, P5 questions whether a little more energy consumption, which may not be much when broken down to a garment, should take precedence over human rights security along supply chains. The interviewee criticizes that there is a lot of discussion around BC's CO_2 emissions rather than bringing change to the industry. Also, according to P1, the energy consumption of BC is only criticized because there is ignorance about how it works, which has neither a scaling nor an energy problem when applied to supply chains. P7, P6 and P3 express concern about tamper-proofness and trust and that immutability can lead to problems once the information entered is incorrect. False information can be entered consciously or unconsciously. According to P5, BC is more secure than the manual systems regarding deliberate misrepresentation. P1 explains a case that is an exception for tamper-proof storage of data as follows: In NP1, company IDs are entered into the system rather than the specific names of the suppliers. This aspect allows companies to exit the blockchain by registering another company for the respective ID. This mainly serves the privacy of the companies, as they must have the option under German or European law not to share their data. In addition, this circumvents the problem of incorrect data since the data can be changed via this detour. Nevertheless, P1 also believes that it is not through BC that the correctness of the entered data can be ensured, but through the logic of NP1's platform.

3.2. Platforms for Reporting

3.2.1. Audits

As a criterion for transparency, the interviews asked about the assessment of the coverage of subcontractors through audits. P4 and P5 both explained that the ingredients (Ingredients are the individual components of the end products, some of which are bought in from subcontractors) of the products are nominated and can be traced well by means of the product catalogs. Products and all ingredients are certified in terms of traceability, mainly through transaction certificates, which can and should be verified. According to P4, when a product certificate is created, each actor in the supply chain must be checked for it. According to P5, this is a lot of work, which, nevertheless, "has to be done by everyone, because otherwise we can't sit down here and say: everything is fair and sustainable". Most of the time, certificates are not awarded after the first inspection but only after corrective actions have been taken. According to P4, when checking ingredients against the product catalog, there is little chance of not telling the auditors the truth. This is contrasted with P5's statement, as this actor has seen "more fake certificates than not fake". Depending on the standard the audit is guided by, audits differ in whether ingredient verification and subcontracts are covered. Since the standards leave room for interpretation, the claims and implementation of audits differ greatly between audit companies and between auditors. Audits are, according to P4, also situation- and operation-dependent. However, if audits are carried out conscientiously, they are a good system in their estimation. In the audit team of ZU4, so-called witness audits are carried out annually, in which a team-internal person accompanies the audit and checks whether the auditor is proceeding correctly.

P3 describes that supply chains can be fully traced due to the certifications given after verification through audits. Therefore, according to P3, audits are generally effective and furthermore a neutral procedure. When asked about the criticism that is raised against audits, P3 gives an example of discrepancies that have become known only after further examinations. P6 describes a similar situation but also points out that audits can have the following negative effects: worker interviews in a factory revealed that catastrophic conditions prevailed while the company's audits assessed the situation as being fine. "That makes it more difficult and structurally can't lead to truthful information".

Interviews with employees are an important part of the audits in order to obtain information about sustainability conditions that is as close to reality as possible. However, according to the interviewees, the implementation has shortcomings in several aspects. One criticism is that no offsite interviews are conducted, although they would be more likely to lead to truthful information. Workers in the factory would not disclose anything if there were possibly factory managers in the immediate vicinity who, for example, might threaten to fire the workers. Furthermore, the gender-parity composition of the audit team is relevant. P7 states that in a patriarchal environment, female workers would not respond to questions about gender-based violence. P2 mentions the check criterion on sexual assault from the PSCI reports as an example. An indication of one hundred percent compliance in the report means no sexual assault at all: "This is the indicator par excellence that no trust at all could be built to talk about such issues. It's not an indicator that the factories are so great, but rather that the factories are so bad." P4 doubts the statements of the workers, especially when the audit is announced. P7 implies that this is a main problem of a truthful audit. P4 disputes the criticism that only announced audits take place, stating that they conduct a certain percentage of unannounced audits per year. The coronavirus has exacerbated the problem of inspections in general and, specifically, the possibility of anonymous interviews.

Furthermore, the following structural weaknesses of the audit system were mentioned during the interviews: The long checklists are worked through under time pressure, which leads to gaps or errors. A two-day audit costs EUR 150: "That's spectacularly cheap. You can't do a real audit for that". The time required and the simultaneous pressure of time mean that neither more controls can be carried out nor can there be closer cooperation between the actors. According to P5, double-entry bookkeeping takes place in most countries, e.g., working hours are documented and presented to auditors in a way that is different from the truth.

P2 mentions several requirements that need to change, as audits do not accurately reflect the situation at the audited sites. These include "cooperation with local actors", where certain standards have to be met, and contractual and financial independence between the auditor and the audited site. Moreover, it is important to look more closely at how the on-site inspections were carried out, and the results of each audit should "inform the reformulation or redesign of audits". According to P4, in order to fill information gaps and to have the opportunity as an auditor to take more effective action, a very different system rather than audits is needed. P7 says the following: "The best auditors would be [. . .] the workers. If they could mark the grievances without threat of consequences and also get time and opportunity to do so and the guarantee that it doesn't mean they will be dismissed, then those are the best auditors you could wish for".

When asked about possible solutions to certificate counterfeiting, P5 suggests the implementation of technologies. As concrete examples, though not yet scalable, she mentions BC, DNA analysis of fibers and materials or chip inlays. However, "Audits are still necessary to establish a status quo. [. . .] An audit is basically a status survey of a system. That means BC technologies also need to be regularly revised and audited by external entities, i.e., the system behind it".

3.2.2. Complaint Systems

According to P5, hotlines are "very important for the survey of social working conditions". P2 and P3 are also positive about hotlines, including as a useful complement to audits, as long as certain conditions are met. These include the local integration of the mechanism, especially considering language barriers and illiteracy, the level of knowledge on the topic on the part of the contact person, and that women are also included in the hotlines. P6 and P4 specify that the contact persons should not be auditors, but locally based NGOs, the ILO or trade unions. Anyway, it must be independent of the company so that workers have confidence. Even more effective would be "an anonymous complaint system within the company." In addition, there must be a protection for the reporters that guarantees the secrecy of their identity; otherwise, they could be exposed to repression. P7 describes the current situation of hotlines as follows: "Until now, there are almost only hotlines that are either made directly by factories, where it is unclear what happens with it, or it is said that it goes to the factory management. Of course, no one will call there". Another core factor for the current non-use is the workers' mistrust in the follow-up effect of the mechanisms. Interviews with workers by NGO6 concluded that the "biggest frustration was that it was completely unclear to them what would happen next".

FWF has a good process after P6 and P7. Nevertheless, according to P6, the entire system "must be structured differently. This is [. . .] not a question of technology", i.e., whether it is a hotline or something else. Central to this is the presence of trusted people on-site. Overall, it is a "complex thing that actually has to be set up in a social work way."

P6 presents the following scenario as effective: "Ideally, there would be a local office. In the production countries, partner networks would have to be established for NGOs or trade unions, which could then be the point of contact for complaints. [. . .] For example, Tierra eine Welt e.V. would be a local partner that would have competence and where workers would also go". Also, according to P4, an anonymous complaints office on-site is the best solution, just especially not the management of the company. A certain level of transparency is necessary in advance in order to find out at which company a complaint mechanism can be effective.

3.3. Dialog Platforms

Functioning as a learning space is crucial for MSIs to have a positive impact on transparency. According to P6, the fashion company Armed Angels, for example, is more knowledgeable about its own supply chain since becoming a member of FWF. However, the effectiveness of an MSI as a learning space is highly dependent on which corporate strategy the member companies pursue.

NGO6 nevertheless withdraws from MSI because membership costs a lot of work but does not achieve much, even after years. The meeting of trading companies and trade unions takes place only very rarely and rather as a result of urgent actions. P7 criticizes that in many MSIs, contrary to the definition, only industries or brands are members, but not unions or the population. The only exception with real worker representation is FWF.

The main problems are the voluntary nature of MSI membership and the lack of sanctions for violating the codes of conduct. With a view to improving transparency and production conditions, there is no reason why firms should join MSI. It is more important to introduce effective laws and regulate labor inspections by the state. "All the bells and whistles with MSIs and audits is really just a stuffing box because this government institution doesn't exist [in producing countries]. Ideally, there should be one and minimum conditions should be laid down in law". Until now, there has been a lack of effective state institutions in production countries because the countries are unstable and, in some cases, very corrupt, lack the necessary financial resources and have to compete against each other on the world market. As an effective law, P7 cites the Uyghur Forced Labor Prevention Act in the U.S., which states that companies must prove that their goods imported from China were not produced with forced labor. P7 assumes that the EU will follow suit and that sustainability claims can no longer be made by companies if they cannot be proven.

The aspect of collaboration itself was discussed several times in the interviews, including MSI as a horizontal form. From the company's perspective, it is necessary to work closely with suppliers and establish a basis of trust in order to obtain the necessary information about the supply chain. Communication at eye level is seen by P1, P3 and P5 as the basis. With good cooperation, "you will also convince the supplier to work more transparently", as understanding and intrinsic motivation build up on the part of the suppliers. Moreover, it is important to be aware of possible language barriers and to make it as easy as possible for the suppliers.

According to P3, technologies that promote dialog are very important overall. A central aspect is also the exchange with network partners or other stakeholders about sustainability and the joint discussion of problems and search for solutions. However, communication costs time and money. Finding the right contacts also requires financial investment and is partly dependent on luck. Furthermore, according to P3, it is important to have been on-site in production locations as an entrepreneur to gain awareness about production conditions. P6 emphasizes that collaboration must not only take place between brand and factory management, but brands must also be in contact with workers.

3.4. Other Technologies

3.4.1. DNA and Fine Dust Analysis

DNA or fine dust analysis of fibers or materials can be used to determine their origin quite accurately, according to P7. For DNA analysis, actors in the supply chain cooperate by marking materials, such as organic cotton, with artificial DNA at the origin. The technology is cheap and ready for the market. If the actors in the supply chain do not cooperate, the fine dust analysis is a good alternative. Here, no artificial DNA marking has to be applied. By analyzing the dust, it is possible to say very precisely where materials come from. Even if the supply chain includes several countries, the origin and all the places where the material has been can be located with a 10 km radio accuracy.

3.4.2. Sustainability Management Platform

From P1's perspective, it is not BC but the logic of the *sustainability management platform* that is the technology that leads to transparency. Through the platform, suppliers enter their production and delivery data, risks are managed and actors along the supply chain can communicate through the platform. P1 compares the system to social networks such as Instagram, as the participating actors each have a profile that can be linked to the other profiles. A network effect is created because the upload of a document is not only sent to one partner but can be seen by all actors linked to the profile. According to P1, the platform works as follows: data are collected from three dimensions. From the enterprise dimension, information about factories is obtained through audits and certificates, among others. The verification mechanism of audits uploaded to the platform is limited to checking the authenticity of documents. On the product dimension, documents about products and materials are collected. The supply chain dimension refers to the transparency of the chain: from a company perspective, information is generated about which suppliers are in the network. By creating an order in the platform, a brand can ask its known suppliers: "nominate through the system the suppliers, your suppliers, which you needed to fulfill this order". Through a step-by-step process, the supply chain can thus be better tracked and information on sustainability conditions can be requested. It is important that the platform considers possible language barriers and is intuitively designed so that suppliers are motivated to enter information. Mandatory training during supplier onboarding is crucial to ensure that suppliers share their information truthfully. In this context, it is also crucial to convey a sense of community to the suppliers so that, for example, information gaps are worked out jointly.

3.5. Transparency as Means to an End

According to P6, one problem is that companies often see transparency as the ultimate goal. "Transparency [however] is not an end in itself, but a means to an end". P5 describes it as follows: "Transparency and traceability is the basis for sustainability; the key to sustainability is which data and information is collected and, how they are evaluated." Also, according to P1, transparency is "the basis for efficient sustainability management". Data on production locations, as well as certificates through audits, are the basis for prioritization in sustainability management. Furthermore, several interviewees emphasized the importance of carrying out risk management after collecting information.

In addition, external transparency is stated as being indispensable. According to P7, internal transparency is useless without disclosure due to a lack of control. In contrast to common approaches that information is mainly disclosed to end consumers and stakeholders, according to P7, it should happen in a systemic way "so that workers, unions, scientists also have access to the data." P7 reasons, "One of the bigger problems is: when there are grievances, often it's unclear to workers what brand they actually worked for. Many can't read Western characters and simply don't know who they produced for and, therefore, where to go for compensation or some form of justice".

The interviewees point to further advantages but also to risks of more transparency, as follows: data protection must be considered when, for example, the addresses of farmers or home workers are published. They also include the safeguarding of interests by trade unions, whereupon disclosure can be viewed critically from a company perspective for reasons of competition. According to P3, the competitive risk arises from the fact that a trading company can be deprived of its suppliers by its competitors. Regarding the LkSG, companies like TBU3 have a competitive advantage if they can show several certificates about the supply chain. According to P5, "the competitive argument when it comes to transparency and traceability is [. . .] not valid." P5 justifies the statement by saying that the "taking away" of suppliers, which P3 mentions as a competitive risk, is not a realistic problem since it is time-consuming until a brand has established a production process.

"Anyone who, when it comes to traceability, transparency and sustainability, comes around the corner with the idea of competition, I don't think they should be producing products". According to P5, the problem with the textile industry is rather that many trading companies do not have in-depth knowledge of the industry itself.

3.6. The Schallmauer Effect

P6 explains a principle called the Schallmauer (sound barrier) effect. There is a sound barrier between trading companies and the upstream supply chain, which means that, for example, solutions resulting from MSI conferences do not reach the actors along the supply chain and the effectiveness of trade unions and NGOs is severely limited. This aspect is often not considered in academic research "because most academic research deals with local stakeholders from a local perspective-and does not break through this "sound barrier" itself. It's also simply difficult and impossible to do without good networks in the countries where production takes place". P6, thus, highlights that the appropriate management system is the basis for companies to pursue subcontracting along the supply chain and penetrate the sound barrier. In addition, there is a disparity of power and influence from the trading companies with the highest influence on the home-based workers with the lowest. "Conversations about technology systems and management systems happen at the executive or middle management level". The narrative of retail companies, according to P5, is that they create jobs in the Global South and are therefore valued as good. However, according to P5, suppliers have a better insight into the complexity of networks, local structures and are better organized. Suppliers are also more open to technical innovations. In addition, with production planning on an equal footing, the competitive idea of external transparency would not be necessary. In addition, the workers have no influence or decision-making power. NGO6 "strongly plead[s] for workers and unions to be seen as full partners and not as disturbers of the peace".

Several interviewees mentioned that the information collected and passed on via the technologies always depends on the people who collect the information in the first place. Therefore, a certain degree of trust in the accuracy of the information is necessary. Core to trust, according to P3, is a long-standing working relationship with suppliers. With own visits on-site and a direct connection, trust can be built and transparency can be ensured. According to P1, intrinsic motivation must be created among suppliers, e.g., through an accurate onboarding of suppliers, to provide correct and detailed information.

4. Discussion

A key result of the interviews is the evaluation of the quality of information in the supply chain processes. Accordingly, it is not only important to examine which technologies are suitable for generating information, but also which technologies generate the right information. Figure 2 shows which technology can capture which information. The dark-colored technologies are those that were selected during the literature review for this work. The light coloring indicates the technologies that were presented initiatively in the interviews and for which no results from the literature were included. The results from the interviews confirm that traceability is the first step needed to collect further information about sustainability conditions along the supply chain and that both together create internal supply chain transparency.

4.1. Impact of Technologies on Traceability

As shown in Figure 2, digital technologies, i.e., IoT and BC, as well as DNA and fine dust analysis, are the focus of creating traceability. From the interviews, it has emerged that the IoT has a high potential to track the supply chain of the textile industry. Furthermore, DNA and fine dust analysis seem to be promising for tracing as a technique for checking audit certificates. A key difference is that DNA analysis requires supplier participation, so it could be subject to a similar limitation as RFID tags. With both methods, it is important to respect the privacy of the workers.

Different results are available on the assessment of BC. From the interviews, two narratives from practice stand out as significant. On the one hand, there is the example of TBU5, which received an error message for two percent of the fibers due to the implementation of BC, which would not have been detected via other systems. On the other hand, P1 highlights that BC only creates confidence in the data, while a sustainability platform is a technology that creates traceability in a practical context. When using BC, it seems crucial that it is connected to other systems. Essentially, there is agreement among the interviewees that BC leads to secure information through improved documentation and automation. Regarding the aspect of traceability, the potential is thus seen in BC through tracking and tracing.

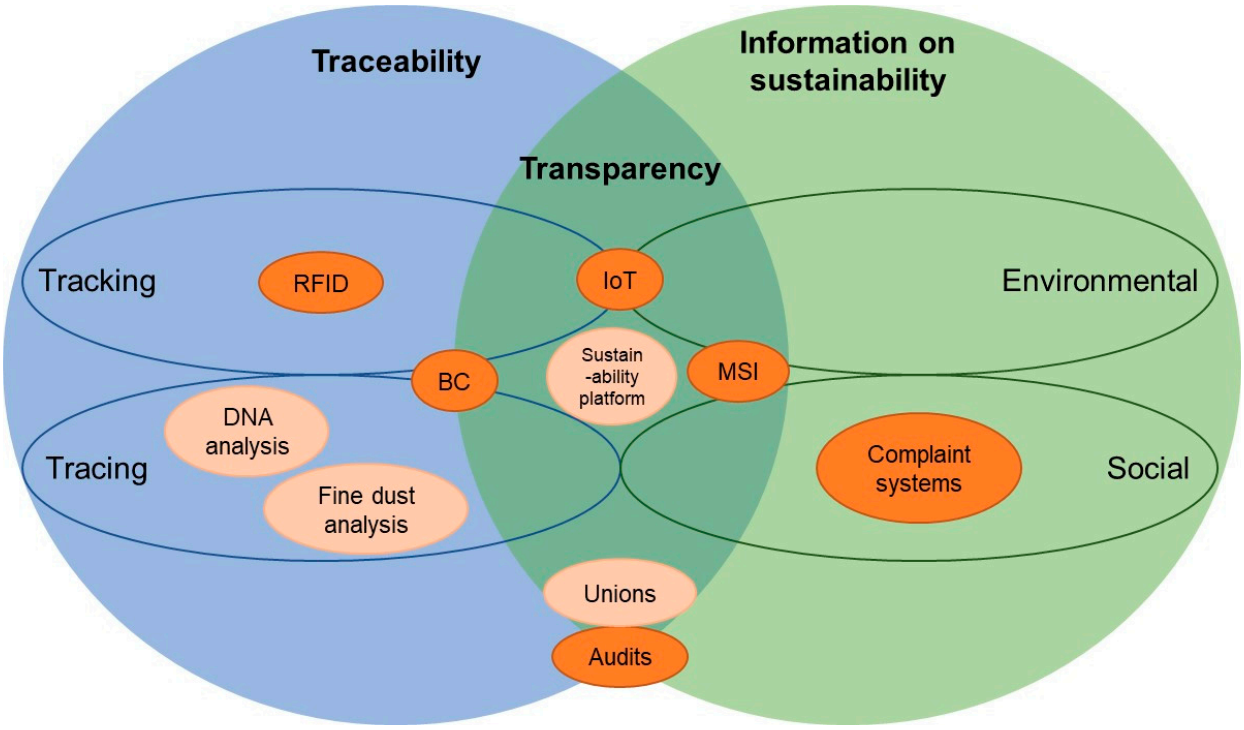

Figure 2. Technologies and their possibilities to capture information.

Both complaint systems and audits are primarily conducted at locations that are already known, with the aim of recording conditions on-site. Therefore, they are not directly associated with their contribution to traceability. One aspect that was highlighted during the interviews is the possibility to check where the ingredients, i.e., inputs, come from using the product catalogs and transaction certificates during audits. It is clear from the interview with P2 that many subcontractors are not recorded, and the certificates are criticized for not being sufficient [26]. Thus, it is questionable to what extent only the direct suppliers are included in a product certificate and not the subcontractors. Additionally, audits, in the same way as RFID tags, could cause a break in the flow of information.

The complexity of the supply chain is largely caused by the involvement of intermediaries and subcontractors, which is particularly common in the textile industry [2,6,29]. Reducing these instances is one way to improve traceability. In interviews, product nomination was presented as a way to bypass them. If the corporate strategy is focused on sustainability, e.g., explicitly through the integration of a sustainable supply chain management, it is assumed that the extra effort to nominate products is a realistic step to establish traceability.

4.2. Influence of Technologies on the Information on Sustainability

It was possible within this research to identify a trend in which technologies can capture information on sustainability and whether differences exist between capturing environmental and social conditions. The challenges to capture have been found to be the conscientiousness of people and the organizational structures of the textile industry.

According to P5, the information on sustainability can be easily entered into the BC. The fact that the data are entered directly by the suppliers can be seen as an opportunity but also as a challenge. On the one hand, this indirectly creates an exchange along the supply chain, and the suppliers can act self-determined. On the other hand, the information must either be trusted, or audits are still necessary to control the situation on-site.

Since the scope of audits depends on the standard according to which audits are carried out, the influence of audits on increasing transparency depends on the standard. It can be evaluated positively that the audits monitor the situation on-site as comprehensively as possible using the checklists. However, the way it is carried out leads to information gaps, mainly in the following three areas: Firstly, not all information is shared with trading companies as reports are aggregated [30]. Secondly, the information about social conditions is sometimes not entrusted to the auditors by the workers. And, if information is given, it cannot be included in the audit report without verification through documents. Thirdly, certain aspects of the checklist, such as the inspection of buildings, cannot be properly performed by auditors. Because audits can therefore have large information gaps, but certificates are nevertheless issued, which companies refer to, e.g., when accidents occur in factories [31], the influence of audits on information on sustainability is sometimes even classified as negative.

In the interviews, it emerged that the complaint systems tend not to be affiliated with the companies themselves, but they were increasingly addressed as part of the audits or as an affiliation with an MSI (Defined by the OECD as a "multi-stakeholder grievance mechanism"). Overall, they are found to be very relevant for capturing information on sustainability at the social dimension. Like complaint systems, unions could also tend to represent workers' voices. Specifics of unionization were not explored further within this research.

4.3. Authenticity of Information for Transparency

Within this research, it was found that the authenticity of the data is a major challenge in the generation of information and has an impact on the effectiveness of transparency. This gives importance to looking at which technology can best generate the right data.

In this work, authenticity is attributed primarily to the dependence on the people who capture and transmit the information. It is reasonable to assume that technologies that function independently of humans capture more truthful information. Figure 3 depicts a scale on which the assessment of each technology is plotted. On the right-hand side, the technologies to which the highest information authenticity is assigned are shown.

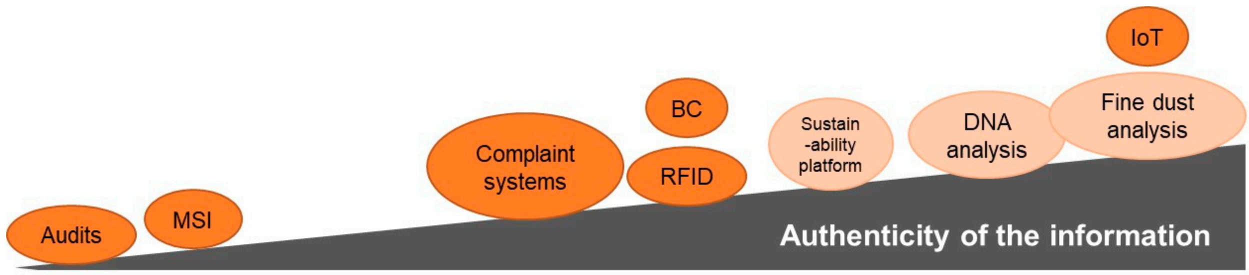

Figure 3. Classification of technologies with regard to the authenticity of their information.

IoT technologies or especially fine dust analysis, are credited with being able to collect data independently of suppliers [9]. In connection with BC, the concept of trust in the information is at the top of the list. However, RFID tags can be easily falsified [32], and the information that is entered into a BC is at the discretion of the network participants and is based, among other things, on the audit results. Deliberate misstatements are nevertheless more likely to occur with manual systems than with the use of BCs. The overall tendency is that digital technologies are attributed more authenticity than audits, complaint systems and MSIs.

The authenticity of the information provided during audits is, to some extent, strongly criticized. Neither is the information provided by the auditors trusted, nor do the auditors trust all the data they receive from the factories about the conditions on-site. The fact that audits are relatively heavily criticized may also be due to the fact that they have been used for longer and are more deeply integrated into the processes of the textile industry than the newer technologies such as IoT and BC.

Complaint systems are considered to have a high potential, as the information comes directly from the workers and is therefore not distorted via intermediate stages. It is crucial that neither auditors nor factory managers are the contact persons, but independent, locally based entities such as trade unions or NGOs so that the workers can build trust and provide real information. As there are currently few grievance systems in place that workers trust, they are ranked rather than left on the scale, with the comment that there is much potential for improvement.

4.4. Implementation of Technologies in the Textile Industry

Table 3 shows how the technologies described affect the two aspects of transparency, traceability (here T) and information on sustainability (here IoS), from the point of view of the interviewees. It thus provides an overview of which technologies are classified as implementable or worthy of implementation.

Table 3. Overview of the interviewees' assessment of the technologies.

	IoT		**BC**		**Audits**		**Complaint System**		**MSI**	
	T	**IoS**	**T**	**IoS**	**T**	**IoS**	**T**	**IoS**	**T**	**IoS**
P1			Reference to sustainability platform						Cooperation	
P2										
P3									Cooperation	
P4										
P5									Cooperation	
P6									MSI	
P7									MSI	

Legend: Dark green—positive effect. Magenta—no or negative effect. Blue positive and negative aspects mentioned or undecided. Light green—currently no effect with growth potential. Empty—No comment.

Since IoT for traceability in the textile industry is seen to have high development potential and economic benefits for companies, it can be assumed that the technology will continue to develop and find increased applications. The use of the technology appears to make sense for real-time detection, primarily from the fabric manufacturing stage onwards.

Opinions about BC vary widely. On the one hand, it is seen as a forward-looking and overall suitable technology; on the other hand, its use is seen as redundant and the focus on technology as negative because the risks of the textile industry should be solved differently. In addition, it is doubted whether some companies implement BC primarily because they are aligned with the competition, although it is not aligned with their business risks [33]. The interviewees who work in NGOs, i.e., P2, P6 and P7, are rather negative towards BC and do not see it as purposeful (Table 3), whereas it is seen as having great potential in the current scientific discourse.

However, the use of audits is the most widespread technology in the textile industry and their effectiveness is much debated, with opinions differing between actors [9,18]. The current audit systems' effectiveness is fundamentally questioned by several interviewees. It is assumed that, in the future, there will be an increased focus on the use of dialog-promoting technologies instead of controls through audits.

No potential is seen in complaint systems for traceability, but all the greater for information on sustainability. All interviewees see great potential in the technology for the textile industry as long as certain requirements are given. In addition to the necessary confidentiality of the systems, educating workers on how to manage the complaint system is fundamental to its use. Without these aspects, workers would not use a complaint system, and implementation would be redundant.

MSIs are already represented in the industry with different orientations. Since several NGOs and interviewees highlighted the FWF as a positive example [34,35], the recommendation is to align complaint systems and the structure of MSIs with the FWF's mode of operation. In addition, MSIs should be legally binding.

The Schallmauer effect is particularly interesting because it fundamentally questions both the system of how transparency is created and the individual technologies that are either already widely used for this purpose (especially audits) or are now increasingly being used (IoT and BC). In order to create comprehensive transparency that incorporates the perspective of workers and, based on this, identifies proposed solutions for the risks of the textile industry, the inclusion of the Schallmauer effect is essential.

5. Conclusions

Regarding the extent to which the use of a respective technology influences transparency, it was found that several technologies can capture partial aspects of traceability or information on sustainability. Nevertheless, the interaction between technologies is necessary to create overall transparency along the textile supply chains.

The way the technologies work differs fundamentally. While MSIs and sustainability management platforms, for example, tend to indirectly lead to companies collecting data, DNA and fine dust analyses are more meaningful for traceability, IoT for ecological conditions or complaint systems for social conditions. It, therefore, seems of little use to evaluate the technologies alone. Here, we present a proposal for the textile industry that builds on the strengths of the technologies addressed in this paper and considers the risks of the textile industry.

First, DNA and fine dust analyses should be used to determine the origin of the products. Especially with these two technologies, it is important to treat the data confidentially and not to create any disadvantages for workers, e.g., by making home workplaces known. In cooperation with suppliers, RFID tags can be used as a technology of the IoT, as they are seen as having the potential to record the flow of goods in real-time. In this way, trading companies can identify possible production difficulties or routes via intermediaries. In addition, IoT techniques can measure conditions at production sites, such as temperature. If possible, risks are identified, real-time monitoring could be used to contact suppliers directly when the problem arises and to enter into a dialog.

Combining a sustainability management platform with the use of BC seems promising to ensure secure documentation of data along the supply chain and, at the same time, to promote exchange between actors. By using BC, for example, companies can more easily find errors in data along supply chains, which are complex, especially in the textile industry.

One approach to improving the impact of audits would be for the auditors to work in teams that include people with different expertise, for example, to check the building statics and to be able to hold sensitive discussions with the workers. There should be enough time for the auditors and the possibility to build up a relationship of trust with the workers. However, in the case of financing by the textile companies, conflicts of interest still cannot be ruled out. It would also be conceivable for auditors to collect information along the entire supply chain based on the information in the transaction certificates. However, from the information obtained directly from auditors for this paper, it can be concluded that this is not currently performed. Audits at least lead to the fact that companies create documentation and thus remain aware of the tasks.

More promising are complaint systems, which should be implemented by each production site to provide a space for workers to share information directly.

Dialog-enabling technologies are the foundation on which all technologies can build. Recognition of suppliers and workers as the ones who make the supply chain work is important for effective dialog. Mutual trust is important to ensure that the information passed along supply chains is accurate and not distorted. MSIs are particularly useful when different actors come together and use the exchange as a learning space and can thus exchange ideas at eye level. The "Schallmauer effect" could be overcome through the membership of trade unions in MSIs. However, MSIs should also establish binding force.

5.1. Limitations

The limitations to which this research is subject result from the sample selection and the openness of the questionnaire. On the one hand, this had the advantage that aspects were included in the results that were new and had not been constructed on the basis of the theoretical foundations. On the other hand, the openness has a limiting effect on the generalizability of the results. In addition, qualitative research is associated with the possible influence of subjectivity.

5.2. Outlook

This work has shown that it could be worthwhile not only to look at the individual transparency technologies in more detail, but also to consider the interaction of the technologies in particular. It also seems useful to conduct further interviews with different actors in order to consolidate the results of the respective perspectives. In doing so, it would be especially important to set a new focus on actors who can accurately reflect the perspective of production sites.

In this regard, it is considered particularly relevant to include the Schallmauer effect in future scientific research on textile industry supply chains, as this is not yet considered in research despite its system-wide relevance. To this end, networks within the textile industry and eye-to-eye dialog need to be strengthened. Also, the research question could be investigated not from the perspective of a trading company, but from the perspective of the workers. This assumes that workers can more easily file complaints or demand compensation if they have information about the supply chain.

Author Contributions: Conceptualization, A.C. and C.H.; data curation, C.H.; formal analysis, C.H.; investigation, C.H.; methodology, A.C.; supervision, A.C.; validation, A.C.; writing—original draft, C.H.; writing—review and editing, A.C. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would like to thank the Federal Ministry for Economic Cooperation and Development and German Academic Exchange Service for the financial support of this research project (grant number 57504899).

Data Availability Statement: Data available on request due to restrictions, e.g., privacy or ethical.

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

References

1. Stamm, A.; Altenburg, T.; Müngersdorff, M.; Stoffel, T.; Vrolijk, K. *Soziale und Ökologische Herausforderungen der Globalen Textilwirtschaft: Lösungsbeiträge der Deutschen Entwicklungszusammenarbeit*; German Development Institute/Deutsches Institut für Entwicklungspolitik (DIE): Bonn, Germany, 2019.
2. Dohmen, C. *Lieferketten: Risiken globaler Arbeitsteilung für Mensch und Natur*; Verlag Klaus Wagenbach: Berlin, Germany, 2021; ISBN 3803137063.
3. Tewari, M. Can place-based network contracting foster decent work in informal segments of global garment chains? Lessons from Mewat, India 1. In *Labor, Global Supply Chains, and the Garment Industry in South Asia*; Saxena, S.B., Ed.; Routledge: Oxfordshire, UK; New York, NY, USA, 2019; pp. 173–191, ISBN 9780429430039.
4. Shih, W.C.; Agrafiotis, K. Detoxifying the Supply Chains: Production Networks of Slow Garment Factories in South-Eastern Europe. In *Detox Fashion*; Muthu, S.S., Ed.; Springer: Singapore, 2018; pp. 1–27, ISBN 978-981-10-4782-4.
5. Egels-Zandén, N.; Hansson, N. Supply Chain Transparency as a Consumer or Corporate Tool: The Case of Nudie Jeans Co. *J. Consum. Policy* **2016**, *39*, 377–395. [CrossRef]
6. Saxena, S.B.; Baumann-Pauly, D. Off the radar: Subcontracting in Bangladesh's RMG industry. In *Labor, Global Supply Chains, and the Garment Industry in South Asia: Bangladesh after Rana Plaza*; Saxena, S.B., Ed.; Routledge Taylor & Francis Group: London, UK; New York, NY, USA, 2020; pp. 45–61, ISBN 9781138366800.

7. Straube, F.; Wutke, S.; Doch, S. Nachhaltigkeit in der Logistik: Messbarkeit ökologischer und sozialer Faktoren und die Einbindung von Supply Chain Partnern. In *Industrie Management*, *5/2013*; GITO mbH Verlag: Berlin, Germany, 2013; pp. 7–10. ISSN 1434-1980.
8. Ahmad, S.; Miskon, S.; Alabdan, R.; Tlili, I. Towards Sustainable Textile and Apparel Industry: Exploring the Role of Business Intelligence Systems in the Era of Industry 4.0. *Sustainability* **2020**, *12*, 2632. [CrossRef]
9. McGrath, P.; McCarthy, L.; Marshall, D.; Rehme, J. Tools and Technologies of Transparency in Sustainable Global Supply Chains. *Calif. Manag. Rev.* **2021**, *64*, 67–89. [CrossRef]
10. Zelbst, P.J.; Green, K.W.; Sower, V.E.; Bond, P.L. The impact of RFID, IIoT, and Blockchain technologies on supply chain transparency. *J. Manuf. Technol. Manag.* **2020**, *31*, 441–457. [CrossRef]
11. Gardner, T.A.; Benzie, M.; Börner, J.; Dawkins, E.; Fick, S.; Garrett, R.; Godar, J.; Grimard, A.; Lake, S.; Larsen, R.K.; et al. Transparency and sustainability in global commodity supply chains. *World Dev.* **2019**, *121*, 163–177. [CrossRef] [PubMed]
12. Müller, M.; Siakala, S. *Nachhaltiges Lieferkettenmanagement: Von der Strategie zur Umsetzung*; De Gruyter: Berlin, Germany, 2019; ISBN 9783110652628.
13. UN Global Compact. *A Guide to Traceability: A Practical Approach to Advance Sustainability in Global Supply Chains*; United Nations Global Compact Office: New York, NY, USA, 2014.
14. Garcia-Torres, S.; Albareda, L.; Rey-Garcia, M.; Seuring, S. Traceability for sustainability—literature review and conceptual framework. *Supply Chain. Manag. Int. J.* **2019**, *24*, 85–106. [CrossRef]
15. Garcia-Torres, S.; Rey-Garcia, M.; Sáenz, J.; Seuring, S. Traceability and transparency for sustainable fashion-apparel supply chains. *J. Fash. Mark. Manag. Int. J.* **2022**, *26*, 344–364. [CrossRef]
16. Saxena, S.B. (Ed.) *Labor, Global Supply Chains, and the Garment Industry in South Asia: Bangladesh after Rana Plaza*; Routledge Taylor & Francis Group: London, UK; New York, NY, USA, 2020; ISBN 9781138366800.
17. Egels-Zandén, N.; Hulthén, K.; Wulff, G. Trade-offs in supply chain transparency: The case of Nudie Jeans Co. *J. Clean. Prod.* **2015**, *107*, 95–104. [CrossRef]
18. Gill, K.; Khanna, A. Emerging solutions to the global transparency problem. In *Labor, Global Supply Chains, and the Garment Industry in South Asia: Bangladesh after Rana Plaza*; Saxena, S.B., Ed.; Routledge Taylor & Francis Group: London, UK; New York, NY, USA, 2020; pp. 192–205, ISBN 9781138366800.
19. Linich, D. *The Path to Supply Chain Transparency: A Practical Guide to Defining, Understanding, and Building Supply Chain Transparency in a Global Economy*; Deloitte University Press: London, UK, 2014.
20. Sunny, J.; Undralla, N.; Madhusudanan Pillai, V. Supply chain transparency through blockchain-based traceability: An overview with demonstration. *Comput. Ind. Eng.* **2020**, *150*, 106895. [CrossRef]
21. Ellebrecht, A. Chain of Custody and Transparency in Global Supply Chains. In *Sustainable Global Value Chains*; Schmidt, M., Giovannucci, D., Palekhov, D., Hansmann, B., Eds.; Springer International Publishing: Berlin/Heidelberg, Germany, 2019; pp. 227–238, ISBN 978-3-319-14876-2.
22. Esmaeilian, B.; Sarkis, J.; Lewis, K.; Behdad, S. Blockchain for the future of sustainable supply chain management in Industry 4.0. *Resour. Conserv. Recycl.* **2020**, *163*, 105064. [CrossRef]
23. Straube, F.; Verhoeven, P.; Nitsche, B. *Potenzielle Anwendungsgebiete der Blockchain-Technologie in der Logistik*; GITO mbH Verlag: Berlin, Germany, 2021; Volume 17.
24. Nayak, R.; Singh, A.; Padhye, R.; Wang, L. RFID in textile and clothing manufacturing: Technology and challenges. *Fash. Text.* **2015**, *2*, 9. [CrossRef]
25. Terwindt, C.; Saage-Maass, M. *Liability of Social Auditors in the Textile Industry*; Friedrich-Ebert-Stiftung: Berlin, Germany; Available online: https://www.ecchr.eu/fileadmin/Publikationen/Policy_Paper_Liability_of_Social_Auditors_in_the_Textile_Industry_FES_ECCHR_2016.pdf (accessed on 4 June 2023).
26. Terwindt, C.; Burckhardt, G. Sozialaudits in Der Textilbranche: Wie Kann Man Kontrolleure Kontrollieren? Available online: https://www.business-humanrights.org/de/blog/sozialaudits-in-der-textilbranche-wie-kann-man-kontrolleure-kontrollieren/ (accessed on 1 June 2022).
27. Lamnek, S.; Krell, C. *Qualitative Sozialforschung: Mit Online-Material, 6*; überarbeitete Auflage; Beltz Verlag: Weinheim, Germany; Basel, Switzerland, 2016; ISBN 978-3-621-28269-7.
28. Mayring, P. *Qualitative Inhaltsanalyse: Grundlagen und Techniken, 12*; überarbeitete Auflage; Beltz Verlag: Weinheim, Germany; Basel, Switzerland, 2015; ISBN 978-3-407-25730-7.
29. Markschläger, F. *Schritt Für Schritt Zu Mehr Transparenz in Der Lieferkette*; Deutsche Gesellschaft Für Internationale Zusammenarbeit (GIZ) Gmbh: Bonn, Germany; Available online: https://www.textilbuendnis.com/download/schritt-fuer-schritt-zu-mehr-transparenz-in-der-lieferkette-2020/ (accessed on 4 June 2023).
30. Müller-Hoff, C.; Leifker, M.; Paasch, A.; Keller, A.; Bause, M.; Sodji, L. *Menschenrechtsfitness von Audits und Zertifizierern?—Eine sektorübergreifende Analyse der aktuellen Herausforderungen und möglicher Antworten*; European Center for Constitutional and Human Rights e.V. (ECCHR), Brot für die Welt, Bischöfliches Hilfswerk MISEREOR e.V.: Berlin, Germany; Aachen, German, 2021; Available online: https://www.ecchr.eu/fileadmin/Fachartikel/ECCHR_AUDITS_DS_WEB.pdf (accessed on 4 June 2023).
31. Marx, S. *Sozialaudits: Wie sie Unternehmen Schützen und Arbeiter*innen im Stich Lassen*; Kampagne für Saubere Kleidung, FEMNET e.V.: Berlin, Germany; Available online: https://saubere-kleidung.de/2019/11/sozialaudits-lassen-arbeiterinnen-im-stich/ (accessed on 4 June 2023).
32. Linares Barbero, M. Trazabilidad con Blockchain. *Actas Del Congr. Int. De Ing. De Sist.* **2019**, 99–106. [CrossRef]

33. Grünrock-Kern, U. Die Sache mit dem Hype—Schein und Sein der Blockchain: BVL Dossiers. Available online: https://www.bvl.de/dossiers/blockchain (accessed on 4 June 2023).
34. Burckhardt, G.; Marx, S. Fact Sheet Transparenz und Audits: Wer passt auf, dass Unternehmen Verantwortung Übernehmen? Available online: https://saubere-kleidung.de/wp-content/uploads/2018/01/FEMNET-factsheet_transparenz.pdf (accessed on 4 June 2023).
35. Wimberger, C.; Fincke, J.; Rodríguez, E.Y. Vertrauen Ist Gut, Kontrolle Ist Besser! Überprüfung von Arbeitsrechten Durch die Öffentliche Hand am Beispiel Einer Textilfabrik in Vietnam; Münster, Germany. 2016. Available online: https://www.ci-romero.de/wp-content/uploads/2018/06/CIR-Studie-WfkmS_Vietnam-1.pdf (accessed on 4 June 2023).

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Utilization of Free Trade Agreements to Minimize Costs and Carbon Emissions in the Global Supply Chain for Sustainable Logistics

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Abstract: *Background*: Since global warming is a crucial worldwide issue, carbon tax has been introduced in the global supply chain as an environmental regulation for the reduction of greenhouse gas (GHG) emissions. Costs, GHG emissions, and carbon tax prices differ in each country due to economic conditions, energy mixes, and government policies. Additionally, multiple countries have signed a Free Trade Agreement (FTA). While FTAs result in their economic benefit, they also increase the risk of carbon leakage, which increases GHG emissions in the global supply chain due to relocation production sites from a country with stricter emission constraints to others with laxer ones. *Method*: This study proposes a mathematical model for decision support to minimize total costs involving carbon taxes with FTAs. *Results*: Our model determines suppliers, factory locations, and the number of transported parts and products with costs, FTAs, carbon taxes, and material-based GHG emissions estimated using the Life Cycle Inventory (LCI) database. The FTA utilization on the global low-carbon supply chain is examined by comparing the constructed supply chains with and without FTAs, and by conducting sensitivity analysis of carbon tax prices. *Conclusions*: We found that FTAs would not cause carbon leakage directly and would be effective for reducing GHG emissions economically.

Keywords: low carbon emission; global supply chain; custom duty; Asian life cycle inventory (LCI) database; mathematical modeling

Citation: Kinoshita, Y.; Nagao, T.; Ijuin, H.; Nagasawa, K.; Yamada, T.; Gupta, S.M. Utilization of Free Trade Agreements to Minimize Costs and Carbon Emissions in the Global Supply Chain for Sustainable Logistics. *Logistics* **2023**, *7*, 32. https://doi.org/10.3390/logistics7020032

Academic Editors: Benjamin Nitsche and Frank Straube

Received: 31 December 2022
Revised: 3 May 2023
Accepted: 12 May 2023
Published: 1 June 2023

1. Introduction

A global supply chain consists of a series of supply, production, storage, transportation, and sales connections crossing international borders [1]. In the 21st century, supply chains also need to address sustainability. Sustainable supply chains are broadly defined in literatures as various interactions among stakeholders of three pillars (economic, environmental, and social aspects) [2]. One of the vital and emergent challenges for sustainable supply chains is to seek an economical way to reduce greenhouse gas (GHG) emissions to overcome global warming [3]. Carbon taxes have been introduced in a lot of countries and regions for the reduction of GHG emissions in supply chains [4]. Waltho, Elhedhli, and Gzara [4] reviewed over 100 papers published between January 2010 and July 2017, and found that the application of carbon taxes in supply chain network design has been successful in achieving large-scale emission reductions, with only a small increase in total costs. This can be achieved by switching suppliers to ones with lower GHG emissions [5]. As examples of real carbon tax prices, Sweden's carbon tax price is set at 130 [USD/t-CO_2eq], while other countries, such as Malaysia and Indonesia, have not instituted carbon taxes at all [6]. Different carbon taxes should be levied based on where the parts are manufactured since the carbon tax price is set by each government, even if they are of the same quality. Different carbon taxes pose the risk of carbon leakage [4,7]. This occurs when different carbon tax prices are introduced in different countries and companies relocate to geographical regions that are less restrictive [4,6,7]. As a result, there are risks of an increase in the amount of GHG emissions in the global supply chain.

One of the challenges in constructing a global supply chain with carbon taxes is the different GHG emissions and costs. This is because the energy mix of fossil fuels, nuclear, and renewable energies [3] and the economic situations differ in each country. Generally, developed countries have lower GHG emissions and higher procurement costs for manufacturing materials [3]. Meanwhile, emerging countries have higher GHG emissions and lower procurement costs [3]. Life cycle assessment (LCA) is often used as an estimation method of GHG emissions. LCA refers a measuring method of environmental loads in entire product life cycle or certain stages from mining of natural resources, through material production, production, use, recycling, to disposal [2]. However, it is difficult to estimate GHG emissions in each country for constructing a global low-carbon supply chain, since collecting data requires much cost, time, and lots of information. The multi-region input–output (MRIO) database is helpful for estimating GHG emissions in multiple countries [8].

On the other hand, to construct a global supply chain economically, manufacturers have to take into account different tariffs. There are also free trade agreements (FTAs) within specific areas to reduce or abolish tariffs [9]. One example is the Trans Pacific Partnership (TPP), a multinational pact involving Japan, Singapore, Brunei, Chile, and New Zealand, among other countries [10]. Since FTAs can enhance international transportation by eliminating tariffs, carbon leakage could be promoted by the switch to countries with lower carbon tax prices. Tian et al. [11] surveyed CO_2 emissions effects of Regional Comprehensive Economic Partnership (RCEP) tariff reductions, and found that CO_2 emissions in RCEP countries would increase significantly due to increment in international trade between them.

To capture actual GHG emissions in supply chains correctly and to monitor carbon leakage, it is ideal to collect real-time GHG emissions in all phases such as material production, transportation, and assembly in global supply chains automatically using databases such as the MRIO database. Nitsche [12] stated the automation in supply chains has the potential of automated collection and exchange of data within the supply chain for improvement of its management. While the digitalization of supply chains will improve in the future, it will be more difficult to construct global supply chains with lower GHG emissions economically. This is because the candidate international suppliers or factories will increase developing logistic networks such as the Belt and Road Initiative [13], and The World Bank pointed out the needs of increment in the carbon price in a lot of countries and regions [6].

The configuring of the global low-carbon supply chain should simultaneously consider factors such as carbon taxes, tariffs, and FTAs. Carbon taxes are based on each country's GHG emissions and tariffs are with and without FTA. To reduce GHG emissions economically using advantages of FTAs, it requires a decision support model for constructing a global low-carbon supply chain with tariffs and carbon taxes. Moreover, FTA utilization should be examined whether they bring positive effects such as cost reduction by eliminating tariffs, or negative effects such as carbon leakage by enhancing international transportation. Here, we evaluated the following two research questions (RQs):

(1) (RQ1) Do FTAs have a positive or negative effect on the economical construction of a global low-carbon supply chain?
(2) (RQ2) How should manufacturers take advantages of FTAs for the construction of supply chain to reduce costs and GHG emissions simultaneously?

This study proposes a mathematical model of a global low-carbon supply chain network taking into account the FTA's role in minimizing total costs including the levy of carbon taxes in order to support decision makers to construct global low-carbon supply chain economically. The objectives of this study are to provide a decision support model for a global low-carbon supply chain with costs, tariffs, FTAs, carbon tax, and GHG emissions, and to examine FTAs utilization whether they bring positive or negative effects. The contribution of this paper is to consider tariffs, FTAs, and carbon tax simultaneously, and to examine if FTAs would reduce GHG emissions economically, rather than cause carbon leakage.

The rest of this paper is as follows. Section 2 reviews previous studies about global supply chains and low-carbon supply chains. Section 3 models and formulates a global low-carbon supply chain network considering tariffs, FTAs, carbon taxes, and GHG emissions. Section 4 explains assumptions of the numerical example, and estimation methods of GHG emissions and costs. Section 5 illustrates the design examples of a supply chains, and conducts a sensitivity analysis by changing carbon tax prices. Section 6 discusses the answers of RQs and the effects of carbon tax prices on future logistics. Section 7 concludes this paper and suggests how further studies can be performed.

2. Literature Review

Table 1 shows a literature review of global supply chains and low-carbon supply chains. In the literature on the global supply chain, Cohen, Fisher, and Jaikumar [14] developed a basic supply chain network model to decide the supplier and the amount of manufacturing products at each factory, including the custom duty and exchange rate. Vidal and Goetschalckx [15] invented a global supply chain model for an international corporation with explicit transfer prices and custom duty. The model could simultaneously select the transportation mode and cost allocation to maximize the profit of the international company [15]. Tsiakis and Papageorgiou [16] presented a global supply chain model with custom duty by taking into account operational constraints such as the balance of utilization days among production plants and the maintenance days at each plant. Amin and Baki [17] proposed a global closed-loop supply chain model including the custom duty and uncertainty of demand so as to maximize the on-time delivery rate from the supplier as well as the profit. These studies addressed global supply chains; however, they did not consider FTAs. Nakamura et al. [18] and Nakamura, Yamada, and Tan [19] modeled a global supply chain network with FTAs to consider each part's different values and custom duty.

Regarding low-carbon supply chains, Kuo and Lee [20] investigated a Pareto-Optimal supplier selection method to minimize environmental impacts and costs. Their model addressed different environmental impacts of material production and the transportation mode at each supplier [20]. This previous study considered GHG emissions in supply chains, while it did not take into account the carbon polices.

The carbon policies can be divided into four types, namely, Carbon cap policy, Carbon tax, Carbon cap-and-trade, and Carbon offset. The carbon cap policy is that the maximum amount of allowed GHG emissions is decided in advance, and that excess of the allowed volumes is prohibited [21]. The carbon tax is levied considering the amount of GHG emissions [5]. The carbon cap-and-trade refers to trading system of selling and buying rights of GHG emissions. In the carbon cap policy, the quota is decided in advance at each firm. If the actual GHG emissions are less than the quota, the firm can profit by selling unused quota, while the firm has to buy the excess quota if actual GHG emissions are higher than the quota [22]. The carbon offset is comparable to the carbon cap-and-trade system, while it cannot sell unused quota [21].

Table 1. Literature review.

Literature	Global Supply Chain Management				Consideration of GHG Emissions in Supply Chain Decisions					Carbon Policy			
	Supplier	**Factory Location**	**Tariff**	**FTA**	**Raw Material Production**	**Product Production**	**Transportation**	**Holding Inventory**	**Disposal EOL Product**	**Carbon Cap Policy**	**Carbon Tax**	**Carbon Cap-and-Trade**	**Carbon Offset**
Cohen, Fisher, and Jaikumar [14]	✔		✔										
Vidal and Goetschalckx [15]			✔										
Tsiakis and Papageorgiou [16]		✔	✔										
Amin and Baki [17]	✔	✔	✔										
Nakamura et al. [18]	✔	✔	✔	✔									
Nakamura, Yamada, and Tan [19]	✔	✔	✔	✔									
Kuo and Lee [20]	✔				✔		✔						
Shen et al. [23]						✔						✔	
Liu et al. [22]						✔						✔	
Fahimnia et al. [24]		✔				✔	✔				✔		
Zakeri et al. [25]		✔				✔	✔	✔			✔	✔	
Abdallah et al. [26]	✔	✔			✔	✔	✔					✔	
Sherafati et al. [27]		✔				✔	✔	✔		✔	✔	✔	✔
Alkhayyal and Gupta [28]		✔				✔	✔			✔	✔	✔	
Aldoukhi and Gupta [21]	✔	✔				✔	✔		✔	✔	✔	✔	✔
Urata et al. [29]	✔	✔			✔								✔
Kondo, Kinoshita, and Yamada [5]	✔				✔						✔		
This paper	✔	✔	✔	✔	✔						✔		

Shen et al. [23] studied a low-carbon e-commerce supply chain that consisted of a manufacturer, an e-commerce platform, and customers to examine the influence of the commission rate and carbon cap-and-trade. Liu et al. [22] proposed a simulation model considering carbon cap-and-trade to analyze the effects of carbon reduction cost sharing between a manufacturer and a retailer, consumer's preferences of low-carbon products, and the rate of a product's CO_2 emission reduction on the supply chain profit. Fahimnia et al. [24] presented a bi-objective tactical supply chain model for costs and air emissions such as GHG emissions with carbon taxes. Their model treated air emissions regarding product production and transportations depending on the manufacturing technology and transportation mode, respectively [24]. Zakeri et al. [25] investigated a model of a supply chain with two types of carbon policies, namely, carbon tax and carbon cap-and-trade. They analyzed desirable carbon prices in the carbon cap-and-trade scenario to achieve each reduction target of GHG emissions in the supply chain [25]. Abdallah et al. [26] developed a carbon sensitive supply chain design method with carbon cap-and-trade. They compared and analyzed CO_2 emissions using SimaPro in different supply chain configurations obtained from three scenarios: No carbon cost, $100 carbon cost, and Minimum carbon emissions [26]. The SimaPro is one of the most famous software used in the world to calculate environmental impacts such as GHG emissions [30].

Sherafati et al. [27] developed a sustainable supply chain model to address not only GHG emissions and but also the development levels of regions. Their model could consider and switch from one of four carbon policies listed in Table 1 [27]. Moreover, their model could balance the differences in the developed levels, between developed and developing regions by assuming the development levels increasing based on the volumes of manufacturing products [27]. Alkhayyal and Gupta [28] illustrated a reverse supply chain that consisted of collection centers, remanufacturing facilities, and reselling facilities with GHG emissions through the remanufacturing process and transportations for air conditioners. They compared the profit margins obtained from selling remanufactured products in different carbon policies, namely, carbon cap policy, carbon tax, and carbon cap-and-trade [28]. Aldoukhi and Gupta [21] presented a closed-loop supply chain model with carbon emissions of product production, transportation, and EOL product disposal so as to be switched for taking account of one of four carbon policies listed on Table 1. Their model also addressed uncertainties of product demands and the number of returned products [21]. Urata et al. [29] modeled a global low-carbon supply chain network by developing models found in Yoshizaki et al. [31] to determine suppliers and factory locations based on costs and CO_2 emissions calculated using the Asian international I/O table. They conducted sensitivity analysis of carbon prices based on carbon offset [29]. Kondo, Kinoshita, and Yamada presented a supplier selection method with different carbon tax prices in multiple countries, and analyzed the effects of carbon tax prices on GHG emissions and total costs in supply chains. They also discussed the situation where carbon leakages happened [5].

Previous studies about low-carbon supply chains addressed and modeled one or multiple carbon policies as shown in Table 1. Most of those studies considered GHG emissions at product production or transportation, and did not focus on those at material production. According to a case of Ricoh Company Ltd. (Tokyo, Japan), which is one of the Japanese largest manufacturers, the volume of GHG emissions at material production occupied over 50% in the forward supply chain from material production to distribution to users [32]. Moreover, the volume of GHG emissions at transportation is much less than one during material production in the forward supply [32].

As shown in Table 1, the previous studies about low-carbon supply chains did not take into account the tariffs and FTAs in spite of the important considerable matters for global supply chains. To cover these research gaps, this study addresses and proposes a mathematical model for a global low-carbon supply chain with tariffs, FTAs, and carbon taxes. The proposed model treats GHG emissions at material production since it occupies largely in the forward supply chain [32]. Furthermore, this study uses MRIO database to estimate GHG emissions at each country with the same manner.

3. Modeling of a Global Low-Carbon Supply Chain Network with Carbon Taxes and FTAs

This section models and formulates a global supply chain with FTAs under different carbon taxes and tariffs in multiple countries. The overview of the proposed model consisting of suppliers, factories, and markets in multiple countries is described in Section 3.1. Then, Section 3.2 lists the notations used in the mathematical model and formulations using integer programming.

3.1. Overview of Global Supply Chain with FTAs under Different Carbon Taxes and Tariffs in Multiple Countries

The proposed supply chain network consists of suppliers, factories, and markets in multiple countries as shown in Figure 1, which shows a global supply chain network incorporating carbon taxes and FTAs. A market in this study is defined as a city where a certain volume of demand for an assembly product is expected. Figure 1 illustrates an overview of the proposed mathematical model to determine suppliers, factories, and the number of transporting parts and products so as to meet all demands in markets. The black arrows among suppliers, factories and markets indicate the transportations of parts or products between them. These arrows are determined by using the mathematical model. In the model, markets are predetermined, while suppliers and factories are determined from candidates set in advance using the mathematical model.

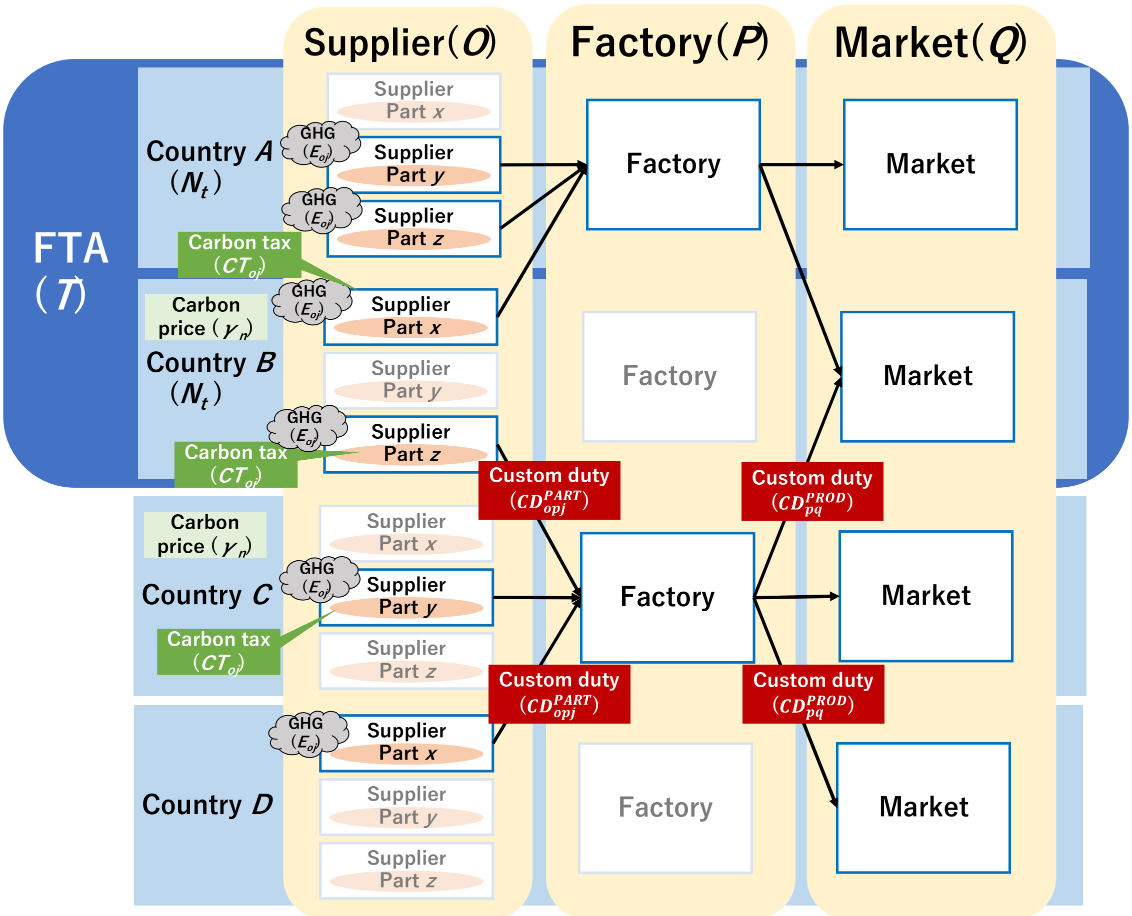

Figure 1. Global supply chain network incorporating carbon taxes and FTAs.

As shown in Figure 1, parts are procured and delivered from suppliers and assembled at factories. The assembled products are transported to each market. The suppliers and factories are selected to minimize the total cost, including procurement costs, transportation costs, manufacturing costs, fixed opening factory costs, fixed opening route between a factory and market costs, and carbon taxes and tariffs. Fixed costs for opening a route means constant indirect costs. These are for opening offices and for expatriate labor costs needed for transportation and trading of products from factories to markets.

Each country sets different carbon tax prices and tariffs. Moreover, FTAs are considered in the proposed model. In Figure 1, FTAs exist between countries A and B. Tariffs are then imposed for the international transportation of parts and products between countries without the FTA. For example, the international transportation of parts and products between countries B and C cause tariffs, as shown in Figure 1.

With respect to carbon taxes, only countries B and C introduced different carbon tax prices, as shown in Figure 1. The proposed model only considers GHG emissions for material production at the suppliers. Hence, the carbon taxes are imposed based on the amount of GHG emissions for material production and carbon tax prices of supplier countries. The GHG emissions in this study include not only CO_2 but also CH_4, N_2O, HFCs, PFC, and SF_6. A unit of g-CO_2eq denotes an amount of GHG that is equivalent to 1 g of CO_2 [3].

3.2. Formulation

Notations used in the mathematical model for the global supply chain network with FTAs under different carbon taxes and tariffs are listed as follows:

I. Sets		
T	:	Set of tariff partnerships, $t \in T$
N	:	Set of countries, $m,n \in N$
N_t	:	Set of countries agreed to tariff partnership t, $N_t \subseteq N$
J	:	Set of parts, $j \in J$
O	:	Set of suppliers, $o \in O$
P	:	Set of factories, $p \in P$
Q	:	Set of markets, $q \in Q$
II. Decision variables		
l_{oj}	:	Quantity of part j produced at supplier o [units]
k_p	:	Quantity of the product manufactured at factory p [units]
v_{opj}	:	Number of units of part j transported from supplier o to factory p [units]
v_{pq}	:	Number of units of product transported from factory p to market q [units]
z_{pq}	:	1, when route from factory p to market q is open 0, otherwise
u_p	:	1, when factory p is open 0, otherwise
III. Parameters		
TC_{op}^{PART}	:	Transportation cost per unit of part from supplier o to factory p [USD]
TC_{pq}^{PROD}	:	Transportation cost per unit of product from factory p to market q [USD]
PC_{oj}	:	Procurement cost per unit of part j from supplier o [USD]
MC_p	:	Manufacturing cost per unit of product at factory p [USD]
ORC_{pq}	:	Fixed cost of opening a route between factory p and market q [USD]
OFC_p	:	Fixed cost of opening factory p
NP_j	:	Number of part j composing product [units]
S_{oj}	:	1, when supplier o can supply part j 0, otherwise
CAP_p^{PROD}	:	Production capacity of products at factory p [units]
D_q	:	Number of product units demanded in market q [units]
$\delta(h)$	:	Country of facility h, $h \in O \cup P \cup Q$
CD_{opj}^{PART}	:	Custom duty on the importation of a part j from supplier o to factory p [USD/unit]
CD_{pq}^{PROD}	:	Custom duty on the importation of a product from factory p to market q [USD/unit]
α_{mnj}	:	Custom duty rate on the importation a part j between countries m and n [%]
β_{mn}	:	Custom duty rate on the importation a product between countries m and n [%]
CT_{oj}	:	Carbon tax of a part j procured from supplier o [USD/unit]
γ_n	:	Carbon tax price in countries n [USD/t-CO_2eq]
E_{oj}	:	Material-based greenhouse gas emissions produced by the manufacturing of part j at supplier o [g-CO_2eq]
M	:	An extremely large number (big M)

This study formulates the global low-carbon supply chain network considering carbon tax and FTAs via integer programming [33]. The objective function of this study is to minimize total costs, including procurement costs, manufacturing costs, transportation costs, fixed costs of opening factory and routes, tariffs, carbon taxes. Component 1 in Equation (1) is procurement costs, transporting costs, and custom duties between suppliers and factories. Component 2 is manufacturing costs, transporting costs, and custom duties between factories and markets. Components 3 and 4 are fixed costs of opening routes between factories and markets, and opening factories. Component 5 is carbon taxes levying material-based GHG emissions.

$$\begin{aligned}&\sum_{o\in O}\sum_{p\in P}\sum_{j\in J}(PC_{oj}+TC_{op}^{\text{PART}}+CD_{opj}^{\text{PART}})v_{opj}+\\&\sum_{p\in P}\sum_{q\in Q}\left(MC_p+TC_{pq}^{\text{PROD}}+CD_{pq}^{\text{PRDC}}\right)v_{pq}+\\&\sum_{p\in P}\sum_{q\in Q}ORC_{pq}z_{pq}+\sum_{p\in P}OFC_pu_p+\sum_{o\in O}\sum_{j\in J}CT_{oj}l_{oj}\rightarrow\ min\end{aligned} \tag{1}$$

Constraints:

Equations (2)–(5) are constraints that all the needed parts are supplied to factories for assembly, and then, demands of all markets are satisfied without inventories of the parts and products. Equation (2) represents all the parts procured from each supplier that must be transported to factories. Equation (3) expresses a constraint that the suppliers can provide only certain parts based on their production ability and that the number of required parts at each factory is met by selected suppliers. Equation (4) presumes all manufactured parts at each factory are sent to markets. All the demand in each market must be satisfied as shown in Equation (5).

$$\sum_{p\in P}v_{opj}=l_{oj}\qquad\forall o\in O,\ \forall j\in J \tag{2}$$

$$\sum_{o\in O}S_{oj}v_{opj}=NP_jk_p\qquad\forall p\in P\ ,\ \forall j\in J \tag{3}$$

$$\sum_{q\in Q}v_{pq}=k_p\qquad\forall p\in P \tag{4}$$

$$\sum_{p\in P}v_{pq}=D_q\qquad\forall q\in Q \tag{5}$$

Equation (6) ensures that products are transported via opened routes only. The manufactured number of products at each factory must be equal to or under its production capacity, as shown in Equation (7).

$$v_{pq}\le Mz_{pq}\qquad\forall p\in P,\ \forall q\in Q \tag{6}$$

$$k_p\le CAP_p^{PROD}u_p\qquad\forall p\in P \tag{7}$$

Equations (8)–(11) are constraints about the custom duties with FTAs. Equation (8) defines the custom duty for each part between suppliers and factories with FTA (CD_{opj}^{PART}). The custom duty for each part is calculated based on the procurement cost (PC_{oj}) and the custom duty rate on the importation a part j between countries m and n (α_{mnj}), as shown in Equation (8). The $\delta(o)$ and $\delta(p)$ represent each country of a supplier and a factory, respectively. For example, in a case of a supplier in Boston and a factory in Tokyo, $\delta(\text{Boston})$ and $\delta(\text{Tokyo})$ represent the U.S. and Japan, respectively. Then, $\alpha_{\delta(\text{Boston})\delta(\text{Tokyo})j}$ means the custom duty rate of part j between the U.S. and Japan.

In addition to the custom duty of parts, the custom duty of products between a factory and a market is based on the manufacturing costs (MC_p) and the custom duty rate (β_{mn}), as shown in Equation (9).

$$CD_{opj}^{PART} = PC_{oj}\alpha_{\delta(o)\delta(p)j} \quad \forall o \in O, \forall p \in P, \ \forall j \in J \tag{8}$$

$$CD_{pq}^{PROD} = MC_p\beta_{\delta(p)\delta(q)} \quad \forall p \in P, \ \forall q \in Q \tag{9}$$

The custom duty rate for each part (α_{mnj}) is set as 0 if there is any FTAs agreed between the countries m(supplier) and country n(factory) regarding a part j. Otherwise, a proper value should be set as custom duty of part j to import country m(supplier) to country n(factory). Note the custom duty of part j should be set as 0 if a supplier and a factory are in the same country. N_t in Equation (10) represents a subset of countries agreed FTA t.

Along with the custom duty rate for each part (α_{mnj}), the custom duty rate for each product (β_{mn}) is set as shown in Equation (11).

$$\alpha_{mnj} = \begin{cases} 0 & if \ \exists t \in T \ \ s.t. \ \ m, n \in N_t \\ any \ given \ value & otherwise \end{cases} \quad \forall m, n \in N, \forall j \in J \tag{10}$$

$$\beta_{mn} = \begin{cases} 0 & if \ \exists t \in T \ s.t. \ \ m, n \in N_t \\ any \ given \ value & otherwise \end{cases} \quad \forall m, n \in N \tag{11}$$

Equation (12) expresses the carbon tax calculated based on material-based GHG emissions (E_{oj}) and carbon tax price (γ_m). The carbon tax price (γ_m) differs in each country in suppliers. As well as custom duty rates, the $\delta(o)$ means the county of a supplier o.

$$CT_{oj} = E_{oj}\gamma_{\delta(o)} \quad \forall o \in O, \ \forall j \in J \tag{12}$$

Equation (13) enforces that the transported number of parts and products are not negative.

$$v_{opj}, \ v_{pq} \geq 0 \quad \begin{array}{c} \forall o \in O, \ \forall p \in P, \\ \forall j \in J, \forall q \in Q \end{array} \tag{13}$$

4. Numerical Example

To illustrate a design example of carbon taxes and tariffs with FTAs in supply chain, a vacuum cleaner composed of 23 parts is used as an example product as well as Nakamura, Yamada, and Tan [19]. Example problems and parameters are set and detailed below.

4.1. Assumptions

- China, Malaysia, the U.S., and Japan are used to illustrate a design example. China and Japan have already introduced carbon tax. The carbon tax prices of China and Japan are 9.00 [USD/t-CO_2eq] and 2.00 [USD/t-CO_2eq], respectively [6]. Regarding FTA, the TPP Agreement is considered. Then, the tariff between Malaysia and Japan is set as 0.00 [USD];
- Each country has 13 suppliers. Four cities are chosen as factory candidates: Shanghai, Kuala Lumpur, Seattle, and Tokyo. Tokyo is selected as the market; the numbers of products demanded are set at 6000. The production capacity of products at each factory is set at 3000;
- The quality of parts and assembly products is the same even though the supplier or factory is different. In other words, only costs and GHG emissions at material production depend on the country located in suppliers and factories;
- Nakamura, Yamada, and Tan [19] indicated that part #19, the motor, accounted for over half of supply costs, so part #19 was excluded from numerical experiments.

4.2. Estimation Method and Assumptions Regarding Costs and GHG Emissions

The procurement costs and GHG emissions of each part are calculated by using the same method proposed in Yoshizaki et al. [31]. First, a material type and weight of each part are obtained from the 3D-CAD model. Next, the unit material price [USD/g] is estimated based on the census of manufactures [34] by assuming the exchange rate between yen and USD as 100 [yen] = 1 [USD]. Then, the procurement cost in each country is calculated using the "Residential Devices, Equipment, and Maintenance" comparison of price levels in various countries [35], as shown in Table A1 in Appendix A as follows:

$$\text{Procurement cost [USD]} = \text{weight [g]} \times \text{material unit price [USD/g]} \times \text{price level}.$$

GHG emissions of each part in each country are estimated based on the LCI database with the Asian international I/O table listing the GHG emission intensity of Asian countries and the U.S. [36]. By inputting the calculated procurement cost of each part in each county to the LCI database, the material-based GHG emissions can be calculated. Table 2 shows GHG emissions and procurement cost of parts in each country.

Table 2. GHG emissions and procurement cost of parts in each country.

No.	Part Name	Required Number for a Product	Procurement Cost [USD]				GHG Emissions [g-CO_2eq]			
			China	Malaysia	The U.S.	Japan	China	Malaysia	The U.S.	Japan
1	Wheel of nozzle	2	0.0056	0.0051	0.0062	0.0098	39.82	17.16	7.48	7.51
2	Wheel stopper	2	0.0014	0.0012	0.0015	0.0024	9.63	4.15	1.81	1.82
3	Upper nozzle	1	0.0401	0.0365	0.0444	0.0698	283.59	122.20	53.25	53.51
4	Lower nozzle	1	0.0328	0.0299	0.0364	0.0572	232.33	100.11	43.62	43.84
5	Nozzle	1	0.0275	0.0250	0.0305	0.0478	194.31	83.73	36.49	36.67
6	Right handle	1	0.0390	0.0355	0.0432	0.0678	275.59	118.75	51.75	52.00
7	Switch	1	0.0033	0.0030	0.0037	0.0058	23.65	10.19	4.44	4.46
8	Left handle	1	0.0412	0.0375	0.0456	0.0716	291.19	125.47	54.67	54.95
9	Left body	1	0.1491	0.1359	0.1653	0.2595	1054.76	454.50	198.05	199.02
10	Right body	1	0.1432	0.1305	0.1588	0.2493	1013.13	436.56	190.23	191.17
11	Dust case cover	1	0.0554	0.0505	0.0614	0.0964	391.89	168.87	73.58	73.95
12	Mesh filter	1	0.3441	0.3136	0.3816	0.5990	2967.54	1211.26	557.95	438.22
13	Connection pipe	1	0.0581	0.0530	0.0644	0.1012	409.95	72.76	63.58	47.03
14	Dust case	1	0.2661	0.2425	0.2951	0.4632	1882.72	811.27	353.51	355.25
15	Exhaust tube	1	0.0230	0.0210	0.0255	0.0401	162.99	70.23	30.60	30.76
16	Upper filter	1	0.3309	0.3015	0.3669	0.5759	2853.34	1164.65	536.47	421.36
17	Lower filter	1	0.0234	0.0213	0.0259	0.0406	165.19	71.18	31.02	31.17
18	Protection cap	1	0.0251	0.0229	0.0278	0.0437	177.60	76.53	33.35	33.51
20	Rubber of outer flame of fan	1	0.0319	0.0291	0.0354	0.0556	332.83	125.15	65.88	55.96
21	Outer flame of fan	1	0.0679	0.0619	0.0753	0.1182	478.96	85.01	74.29	54.94
22	Lower fan	1	0.0120	0.0109	0.0133	0.0209	84.93	36.60	15.95	16.03
23	Fan	1	0.0765	0.0697	0.0848	0.1332	539.71	95.79	83.71	61.91

Our model assumes two different types of costs. One type of costs depends on the types of part and procured country, namely, procurement costs, listed in Table 2. The other depends on facilities such as the transportation costs, fixed costs of opening a factory, and fixed cost of an opening route between a factory and a market, as shown in Table 3. In numerical experiments in the paper, only Tokyo is set as a market. Then, transportation costs and fixed costs of opening routes between factories and markets can be determined by only locations of factories, as well as manufacturing costs, production capacity, and fixed costs of opening a factory. The detailed assumptions and calculated methods costs are shown in Table 3 as follows:

- Vacuum cleaner production costs use vacuum cleaner production costs in Japan found in Urata et al. [37]. The production cost is estimated using the Assembly Reliability Estimation Method, which is a method and software developed by Hitachi Ltd. [38,39]. The production cost in other countries is taken from the same documentation used for part supply costs, which is used to give a ratio for the gross domestic product for each country (Table A1) [35];
- The opening factory and opening route costs in each country are determined based on the gross domestic product [35] as well as the production cost;
- Transportation cost is estimated based on the direct distances between cities.

Table 3. Costs and production capacities at each factory.

Factory	Manufacturing Cost [USD]	Opening Factory Cost [USD]	Production Capacity [unit]	Transportation Cost [USD] (to Tokyo)	Opening Route Cost [USD] (to Tokyo)
Shanghai	2.54	726	3000	0.1760	1566
Kuala Lumpur	2.23	638	3000	0.5328	1532
Seattle	4.67	1338	3000	0.7700	1800
Tokyo	6.29	1800	3000	0.0001	600

All numerical experiments are conducted based on the data described in Tables 2 and 3 and Table A2 in Appendix A. The optimization software Nuorium Optimizer [40] is used on an Intel®Core™i5-9400 CPU @ 2.90 GHz PC with Windows 10 Pro installed.

5. Results and Discussion

FTAs can absorb additional procurement costs owing to introducing carbon taxes by exempting customs duty. Hence, FTAs can bring a positive effect in terms of cost reduction in constructing global supply chain with carbon tax. FTAs may, however, cause a switch to a supplier with a lower carbon tax price. This economical advantage of no tariff by FTAs would provoke this phenomenon, known as carbon leakage. It occurs when the different carbon tax prices are introduced in countries and indicates increased amounts of GHG emissions in the global supply chain. Therefore, FTAs can also bring this negative effect of carbon leakage.

Manufacturers have been required to reduce GHG emissions in current supply chains. Efforts to avoid carbon leakage and reduce GHG emissions globally might unintended setbacks due to situations and conditions of FTAs and should be examined by answering RQ1. Manufactures would then need practical implications to answer RQ2, to examine cost reduction and carbon leakage by FTAs in the global low-carbon supply chain thorough numerical experiments. Section 5.1 compares the total costs and GHG emissions in the global low-carbon supply chain with and without TPP. Sensitivity analysis of carbon tax prices to identify trends or conditions for the construction of global low-carbon supply chain economically is discussed in Section 5.2, and Section 5.3 observes cost breakdowns and networks of constructed supply chain with different total costs and GHG emissions.

5.1. With vs. without FTAs for Economic Benefit and Carbon Leakage in Supply Chain

As described in Section 4, China, Malaysia, the U.S., and Japan are used as suppliers, factories, and markets. Only TPP is considered as the FTA, and then, tariff exemption is adopted for the transportation of parts and products between Malaysia and Japan. Carbon tax is introduced in China and Japan as 9 [USD/t-CO_2eq] and 2 [USD/t-CO_2eq], respectively.

First, the effects of TPP and carbon tax are examined in the design examples, in four cases with and without TPP and carbon taxes as shown in Table 4, which shows the total costs and GHG emissions in the four cases. Even though Chinese and Japanese carbon tax prices are set to simulate real situations in two out of the four cases, GHG emissions in all cases were the same. Thus, currently introduced carbon tax prices in China and Japan were not effective in the design examples. In contrast to the GHG emissions, the total costs with TPP are different and lower than ones without TPP.

Table 4. Total costs and GHG emissions with vs. without TPP and carbon taxes.

		Carbon Tax	
		with	**without**
TPP	With	33,490 [USD]	33,116 [USD]
		5.81×10^7 [g-CO_2eq]	5.81×10^7 [g-CO_2eq]
	Without	34,159 [USD]	33,784 [USD]
		5.81×10^7 [g-CO_2eq]	5.81×10^7 [g-CO_2eq]

Previous findings show that despite increasing carbon taxes in the past, most of the carbon tax prices in each country remains sufficiently low to drive the transformative change needed for reaching the 1.5 °C target [6]. The carbon price corridor to reach the target is estimated as 50–250 [USD/tCO_2-eq] [6]. The carbon tax prices in China and Japan would be increased and ones in Malaysia and the U.S. would be introduced. The cases of increase in Chinese and Malaysian carbon tax prices were examined to determine whether FTAs could bring positive or negative effects such as cost reduction by the elimination of tariff or carbon leakage by different carbon taxes.

In the numerical experiments, the Chinese carbon tax price was changed to 9, 90, 180, and 270 [USD/t-CO_2eq]. The Malaysian carbon tax price was also changed to 0, 100, 500, and 2000 [USD/t-CO_2eq]. The carbon tax prices of Japan and the U.S. were steady and set as 2 and 0 [USD/t-CO_2eq], respectively. Regarding tariff, the custom duties of parts and products were set at 10% in international transportation between the exception of Malaysia and Japan. In cases without TPP in the numerical experiments, the custom duty between Malaysia and Japan was also set as 10%. The results of experiments with and without TPP using these carbon tax prices are shown in Figure 2.

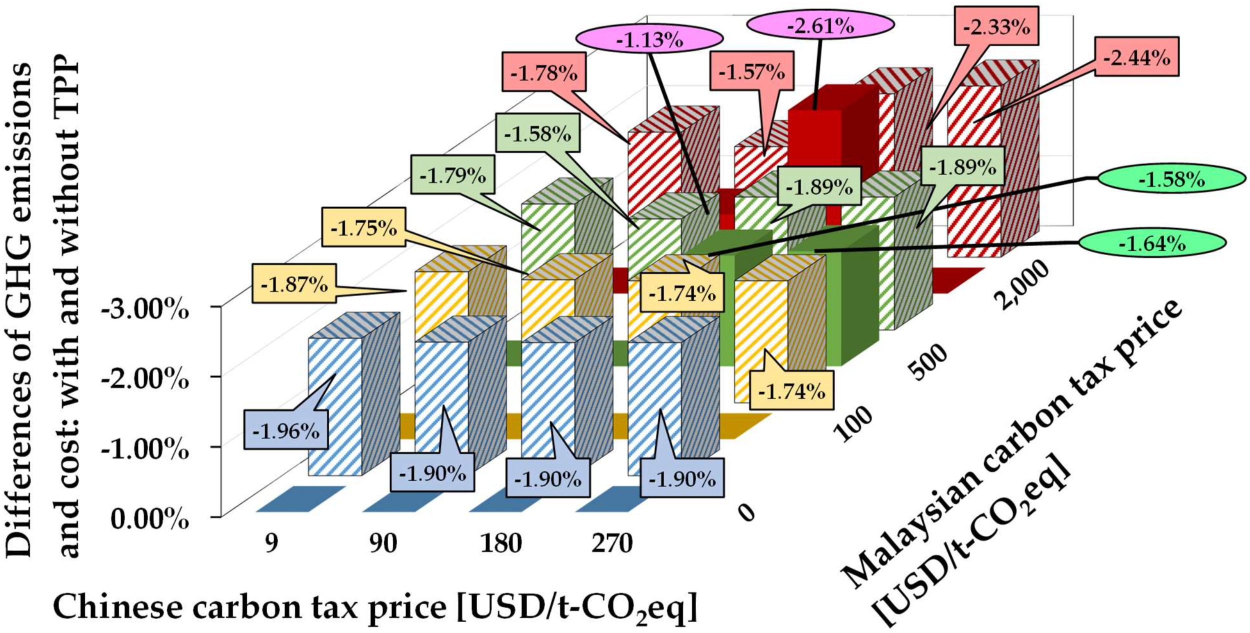

Figure 2. Differences in GHG emissions and cost in supply chain with and without TPP.

Figure 2 shows the differences in GHG emission and total cost in supply chain with TPP against ones without TPP. The solid bars in Figure 2 refer to the differences in GHG emissions. By contrast, the slashed bars in Figure 2 refer to the differences in total costs. For example, in the case of Chinese and Malaysian carbon tax prices set as 180 and 2000 [USD/t-CO_2eq], respectively, the GHG emission and total cost with TPP were lower by 2.61% and 2.33%, respectively, compared with ones without TPP.

Owing to TPP, the total costs in supply chain with TPP were 1.83% lower on average than ones without TPP, as shown in Figure 2. Comparing the selected factories in supply chain with and without TPP, the same factories in Shanghai and Kuala Lumpur were selected in all cases. Suppliers, however, were generally switched from ones in China and Malaysia to ones in the U.S. and Japan. From these findings, it was considered that the differences in the total costs between with and without TPP were due to changing tariffs and costs of procurement and parts transportation.

In terms of GHG emissions, most supply chains with and without TPP had the same GHG emissions, as shown in Figure 2. Only 4 out of 16 supply chains with TPP had lower GHG emissions compared to ones without TPP. One of the notable findings regarding GHG emissions (obtained from Figure 2) is that TPP did not cause carbon leakage in all cases.

When the GHG emissions in supply chains with TPP were lower than those without TPP, Chinese or Malaysian suppliers switched to Japanese ones. They had lower GHG emissions, but higher procurement costs than those in China or Malaysia, when providing parts. Therefore, international transportations of parts between Malaysia and Japan without tariffs could be increased economically. As a result, the GHG emissions in supply chains with TPP were lower than those without TPP. Based on these discussions, FTAs such as TPP may well contribute to GHG reduction with carbon tax, by enhancing international transportation from developed countries with lower GHG emissions compared to those of emerging countries.

5.2. Sensitivity Analysis of Chinese and Malaysian Carbon Tax Prices with TPP

FTAs such as TPP could bring positive effects, that is, cost reduction by elimination of tariffs compared with those without FTA. The current carbon tax prices set at 9 and 2 [t-CO_2eq] in China and Japan were, however, too low to transform the global supply chain configuration into ones with lower GHG emissions. Sensitivity analysis of Chinese and Malaysian carbon tax prices was conducted to identify the proper or desirable carbon tax prices to reduce GHG emissions in the whole supply chain.

At the sensitivity analysis, Chinese and Malaysian carbon tax prices were changed, while Japanese and the U.S. were steady and set at 2 and 0 [USD/t-CO_2eq], respectively. Chine carbon tax prices was changed to 9, 27, 45, 63, 90, 180, 270 [USD/t-CO_2eq]. Malaysian carbon tax prices were also changed to 0, 2, 20, 100, 200, 500, 2000 [USD/t-CO_2eq]. To understand the reduction in GHG emissions and increment in total costs, the GHG emissions and total costs in the constructed supply chain in current carbon taxes with TPP, that is, 5.81×10^7 [g-CO_2eq] and 33,490 [USD], as shown in Table 4 in Section 5.1, were set as baseline.

Figure 3 shows the differences in GHG emissions and total costs compared to the ones in the baseline in the sensitivity analysis with TPP. From the upper graph in Figure 3, three findings were observed. First, the GHG emissions decreased with increasing Chinese carbon tax. Second, Chinese carbon taxes higher than 180 [USD/t-CO_2eq] were not effective in reducing GHG emissions. This could be because GHG emissions in Chinese carbon tax prices set at 270 [USD/t-CO_2eq] were almost the same as Chinese carbon tax prices set at 180 as shown in the upper graph in Figure 3. Finally, carbon leakages occurred in 11 cases. The carbon leakages were observed at the Chinese carbon tax prices equal to or lower than 63 [USD/t-CO_2eq] and at Malaysian carbon tax prices equal to or higher than 200 [USD/t-CO_2eq]. Especially, in the cases of Malaysian carbon tax set at 2000 [USD/t-CO_2eq], the GHG emissions in other supply chains increased by 40% compared to the ones at the baseline.

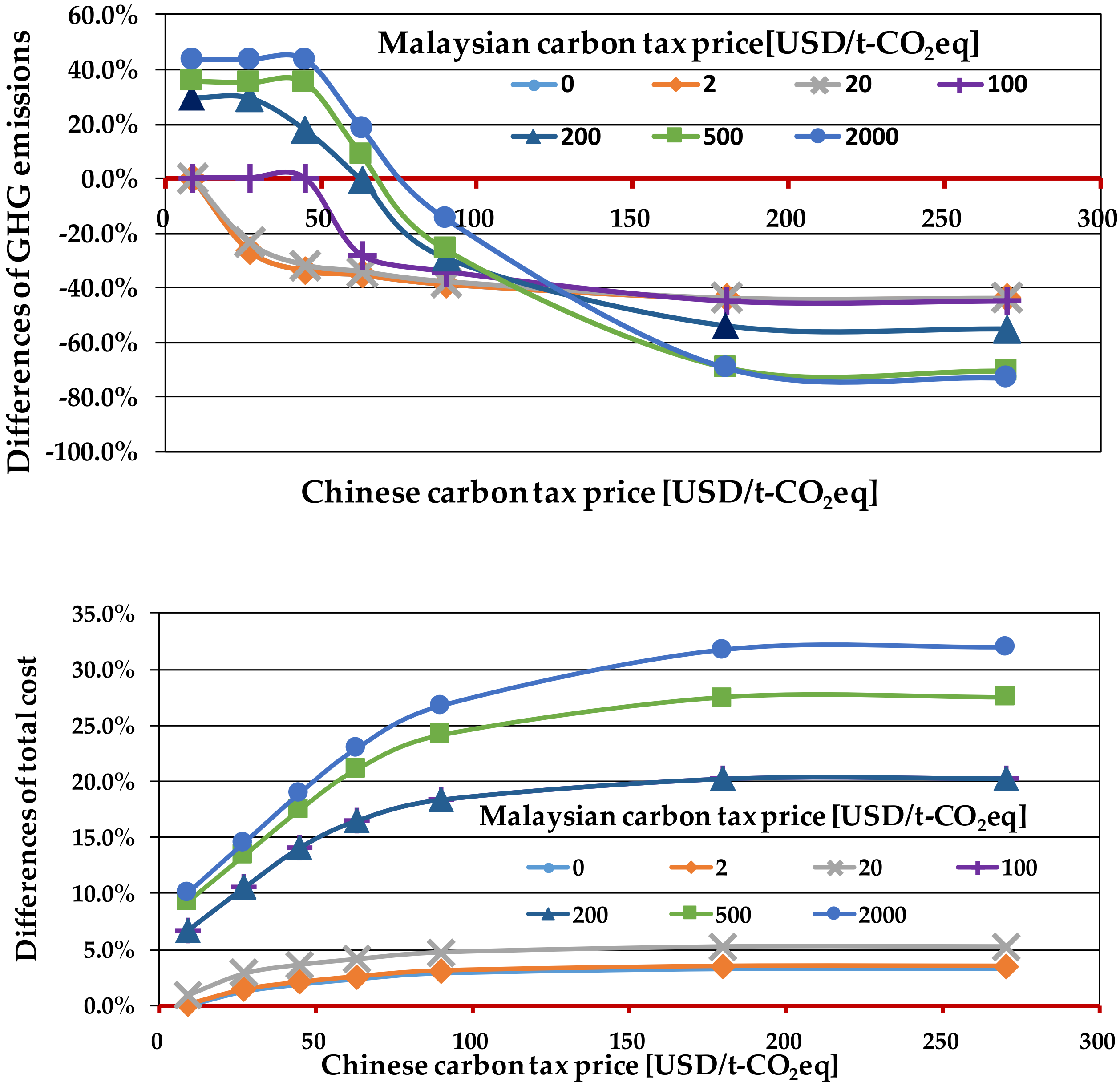

Figure 3. GHG emissions (upper) and total costs (lower) in sensitivity analysis compared to baseline.

In the case of Malaysian carbon tax prices equal to or higher than 500 [USD/t-CO_2eq], significant reductions in GHG emissions were achieved, by approximately 70%. Based on these findings, the Malaysian carbon tax prices may be more sensitive than Chinese ones for GHG emissions. The higher Malaysian carbon tax prices, more than 200, might have the potential to reduce GHG emissions in the supply chains significantly despite risks of carbon leakages.

The lower graph in Figure 3 shows total costs in sensitivity analysis compared to the baseline. Compared to the behaviors of GHG emissions in the upper graph in Figure 3, the behaviors of the total costs were uncomplicated and increased generally as the Chinese and Malaysian carbon prices increased. Regarding the cases with Chinese carbon tax prices set at 270, the total costs were almost the same as the cases of the Chinese carbon tax prices set at 180. This trend was observed for all the different Malaysian carbon tax prices set. Thus, in contrast to GHG emissions, total costs can be predicted from the carbon tax prices of each country, without employing the mathematical optimization models.

5.3. Analysis of GHG Emissions, Cost Breakdowns, and Constructed Supply Chain Network

The four featured cases are represented as four scenarios so that practical implications will be sought to reduce GHG emissions. This is to avoid carbon leakages by comparing GHG emissions, cost breakdowns, and constructed supply chain networks. Table 5 summarizes the four scenarios. "Baseline" indicates the current actual carbon tax prices. "Little lower GHG emissions" is the most cost-effective scenario for GHG reduction. "Much lower GHG emissions" is a scenario in which the Japanese target of reducing GHG emissions by 2030 is achieved. In "Carbon leakage", carbon leakage occurs such that the total GHG emission in the supply chain increases. This was compared to the baseline despite introducing carbon taxes.

Table 5. Summary of scenarios.

Scenario	Chinese Carbon Tax [USD/t-CO_2eq]	Malaysian Carbon Tax [USD/t-CO_2eq]	Difference of GHG Emissions [%]	Difference of Total Costs [%]
Baseline	9	0	-	-
Little lower GHG emissions	27	0	−26.30	1.28
Much lower GHG emissions	180	200	−54.00	20.26
Carbon leakage	9	200	29.40	6.73

Table 6 shows the cost breakdowns and GHG emissions in each scenario. The percentages of cost and GHG emissions denote the ratio against total costs and total GHG emissions, respectively. It is important for the decision makers to grasp cost breakdown and GHG emissions at each country so as to deal with cost fluctuation. This is because the tariffs and carbon tax prices would be changed largely and rapidly since they are affected by political decisions. Comparing "Baseline" and "Little lower GHG emissions," the total costs and cost breakdowns were almost the same. One main difference between them was the Malaysian GHG emissions, as shown in Table 6. The Malaysian GHG emissions in a "Lower GHG emissions" scenario was approximately 65% higher than that in "Baseline". For the Malaysian government, this situation would be undesirable but could become desirable if the GHG emissions could be reduced globally by switching Chinese suppliers to Malaysian ones.

Table 6. Cost breakdowns and GHG emissions in each scenario.

Scenario		Baseline		Little Lower GHG Emissions		Much Lower GHG Emissions		Carbon Leakage	
Procurement cost [USD]		10,360.75	30.94%	10,072.33	29.70%	11,115.34	27.60%	10,688.82	29.90%
Manufacturing cost [USD]		14,293.81	42.68%	14,293.81	42.14%	14,293.81	35.49%	14,293.81	39.99%
Transportation cost [USD]		3235.58	9.66%	3612.00	10.65%	4803.98	11.93%	3685.60	10.31%
Open route cost [USD]		3098.00	9.25%	3098.00	9.13%	3098.00	7.69%	3098.00	8.67%
Open factory cost [USD]		1363.48	4.07%	1363.48	4.02%	1363.48	3.39%	1363.48	3.81%
Custom duty [USD]		764.06	2.28%	1060.50	3.13%	1367.03	3.39%	1134.07	3.17%
Carbon tax [USD]	China	374.55	1.12%	417.59	1.23%	153.14	0.38%	638.38	1.79%
	Malaysia	0.00	0.00%	0.00	0.00%	4078.13	10.13%	843.11	2.36%
	The U.S.	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%
	Japan	0.05	0.00%	0.05	0.00%	2.27	0.01%	0.05	0.00%
Total costs [USD]		33,490.27		33,917.76		40,275.18		35,745.31	
GHG emissions [g-CO_2eq]	China	4.16×10^7	71.64%	1.55×10^7	36.13%	8.51×10^5	3.18%	7.09×10^7	94.36%
	Malaysia	1.65×10^7	28.32%	2.73×10^7	63.82%	2.04×10^7	76.31%	4.22×10^6	5.61%
	The U.S.	0.00	0.00%	0.00	0.00%	4.34×10^6	16.26%	0.00	0.00%
	Japan	2.43×10^4	0.04%	2.43×10^4	0.06%	1.13×10^6	4.24%	2.43×10^4	0.03%
Total GHG emissions [g-CO_2eq]		5.81×10^7		4.28×10^7		2.67×10^7		7.52×10^7	

In "Much lower GHG emissions", the transportation costs and custom duty increased by 48% and 79% compared to that in "Baseline," respectively. Figure 4 shows constructed global supply chains in "Baseline" and "Much lower GHG emissions". The circles and squares express locations of suppliers and factories in each country. The selected suppliers and opened factories are marked with a stronger color. The contribution of Figure 4 is that the locations of selected suppliers can be understood at a glance. It also indicates one example that how a global low-carbon supply chain should be constructed for the reduction of GHG emissions. The decision makers of supply chains need to decide which suppliers should be selected and where factories should be opened to reduce GHG emissions economically by comparing costs and GHG emissions. However, the locations of suppliers and factories, cost breakdown, and GHG emissions at each country cannot be grasped from Figure 3 since they have only total GHG emissions and costs in whole supply chains.

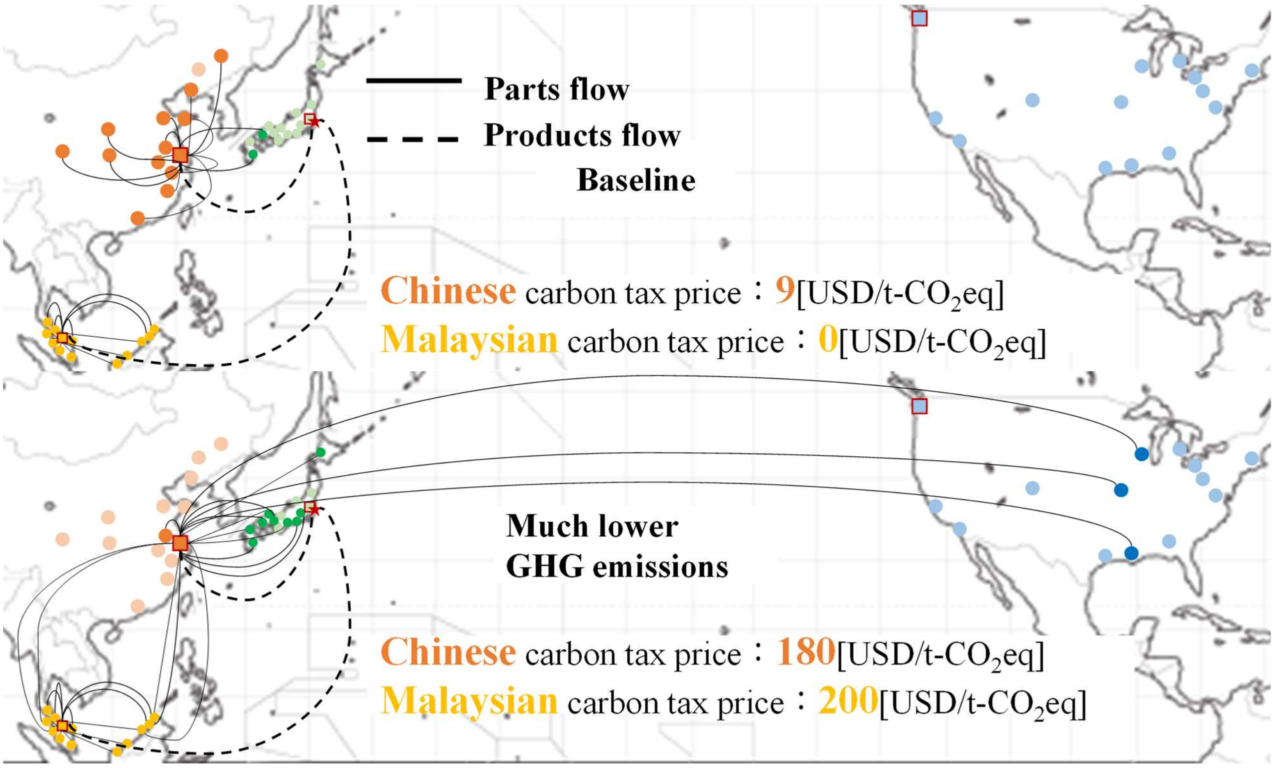

Figure 4. Constructed global supply chains in the "Baseline" and "Much lower GHG emissions" scenarios. Map source: 3kaku-K [41].

As shown in Figure 4, the Chinese and Malaysian factories were opened at both scenarios. In contrast to the factories, the selected suppliers were different since most suppliers in China was switched to ones in Malaysia in "Much lower GHG emissions", as shown in Figure 4. In the "Baseline" scenario, the Chinese factory procured parts from 11 Chinese and 2 Japanese suppliers. That is, most of domestic suppliers were selected at the Chinese factory in the "Baseline" scenario. On the other hand, at the Chinese factory in "Much lower GHG emissions", one Chinese, nine Japanese, five Malaysian, and three U.S. suppliers were selected. Thus, the international transportation of parts for assembling at the Chinese factory increased, and therefore, the transportation costs and custom duty increased.

In the "Carbon leakage" scenario, Chinese GHG emissions increased but the Malaysian ones decreased compared to that in the "Baseline" scenario, as shown in Table 6. This indicates that switching Malaysian suppliers to Chinese ones caused carbon leakages. In "Carbon leakage", the Malaysian carbon tax prices was over 20 times higher than that of

China, as shown in Table 5. Actual differences in carbon tax prices of suppliers can increase by more than 20 times because higher carbon tax prices such as the ones in Sweden and Switzerland are over 130 [USD/t-CO_2-eq] but lower carbon tax prices such as the Japanese one are under 5 [USD]. The percentage of the Chinese GHG emissions against the total GHG emissions was about 94% in the "Carbon leakage" scenario. Thus, in the "Carbon leakage" scenario, the total costs could increase largely if Chinese government decided the increment in the Chinese carbon tax price.

In "Little lower GHG emissions", "Much lower GHG emissions", and "Carbon leakage" scenarios, the custom duty increased compared to one of the "Baseline" scenarios. Thus, the cost reduction without tariff by TPP might be small. By considering other FTAs such as the RCEP that agreed to 15 countries including China, Malaysia, and Japan, the total costs in "Little lower GHG emissions" and "Much lower GHG emissions" would be lower than those with TPP only. Furthermore, there is a possibility to prevent carbon leakage by enhancing international transportation of parts from developed countries with lower GHG emissions.

6. Discussion

This Section discuss the results shown in Section 5 in detail to answer RQs described in Section 1, and to state the practical implications.

(1) (RQ1) Does FTA have a positive or negative effect on the economical construction of a low-carbon supply chain?

From the numerical experiments and discussions in Section 5.1, FTAs such as TPP can bring positive effects to reduce GHG emissions by enhancing international transportation from countries with lower GHG emissions. However, the effects of FTAs to reduce GHG emissions would not be strong since only 4 out of 16 cases with TPP could reduce GHG emissions compared to those without TPP, as shown in Figure 2.

One remarkable finding observed from Figure 2 was that the negative effects of FTAs to cause carbon leakage directory were not observed. Figure 2 denotes the differences in GHG emissions and total costs with TPP compared to those without TPP. Thus, the direct positive and negative effects of TPP can be seen from it. Therefore, FTAs such as TPP could have little effects to reduce GHG emissions, while it would also have a little possibility to be a main cause of carbon leakage.

(2) (RQ2) How should manufacturers take advantages of FTAs for the construction of supply chain to reduce costs and GHG emissions simultaneously?

Manufactures should utilize FTAs for cost reduction by eliminating tariffs since, as described in preceding subsection, FTAs such as TPP could bring positive effects. In the "Little lower GHG emissions" and "Much lower GHG emissions" scenarios in Section 5.3, the international transportation increased, and then, custom duty increased. Taking account into other FTAs such as RCEP, the GHG emissions would be reduced with lower costs than those in "Little lower GHG emissions" and "Much lower GHG emissions" scenarios. As increasing the international transportation, the need of addressing the GHG emissions at transportation will increase. Note that the proposed model does not consider GHG emissions at transportations.

(3) Effect of carbon tax prices on future logistics

Carbon tax can reduce GHG emissions in the whole supply chain since most of the cases in the sensitive analysis of carbon tax prices, in Figure 3 can reduce GHG emissions by switching suppliers only. However, it was also observed to cause carbon leakage due to much differences in carbon tax prices among countries. There are possibilities that differences in carbon price tax will be larger since The World Bank states carbon tax prices will increase globally [6]. Therefore, it is expected to collect and share GHG emissions in supply chains automatically [12] to prevent carbon leakage.

On the other hand, higher carbon tax prices would have both the potential to cause carbon leakages and reduce GHG emissions significantly. When the Malaysia carbon tax prices were equal to or over 200 [USD/t-CO2eq] with FTAs, carbon leakages occurred. These cases could, however, achieve over 50% reduction in GHG emissions compared to that of the baseline provided the Chinese carbon tax price was equal to or over 180 [USD/t-CO_2eq].

7. Conclusions and Future Studies

This study addressed the global low-carbon supply chain with FTAs under different carbon tax prices introduced in multiple countries. A mathematical model to minimize the total costs including carbon taxes and custom duty was proposed as a decision support model and then validated through numerical experiments. Sensitivity analysis of carbon tax prices was conducted to examine whether FTAs bring positive effects such as cost reduction without tariffs or negative effects such as causing carbon leakages.

From the numerical experiments, FTAs would not cause carbon leakage directly, and could reduce GHG emissions economically by eliminating tariffs. The possibilities were demonstrated to reduce total costs keeping with lower GHG emissions globally by taking other FTAs such as RCEP. Additionally, the high differences in carbon tax prices, such as over 20 times among countries, have the risks of carbon leakage.

Future studies should consider other carbon policies such as carbon cap-and-trade. To prevent global warming, carbon neutrality [42] (which meets the actual GHG emissions and absorption of GHG volumes by forests, etc.) should be globally achieved by in the early 2050s for a 1.5 °C (2.7 °F) target [43]. Moreover, the reverse supply chain [44] should be considered in future studies because re-useable parts and material recycling can save additional GHG emissions at the virgin material production stage [45,46].

Author Contributions: Conceptualization, Y.K., T.Y. and S.M.G.; methodology, Y.K., T.N., K.N. and T.Y.; validation, Y.K., T.N., H.I. and K.N.; formal analysis Y.K., T.N. and H.I.; investigation, T.N., H.I. and T.Y.; resources, Y.K. and T.Y.; data curation, Y.K. and T.N.; writing—original draft preparation, Y.K. and T.N.; writing—review and editing, Y.K., T.N., H.I., and T.Y.; visualization, Y.K.; supervision, K.N., T.Y. and S.M.G.; project administration, T.Y.; funding acquisition, T.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This study was partially supported by the Japan Society for the Promotion of Science (JSPS), KAKENHI, Grant-in-Aid for Scientific Research (B), JP23H01635, from 2023 to 2024, Grant-in-Aid for JSPS Fellows, JP22KJ1363, from 2023 to 2024.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Katsunori Hayashi and Ryohei Matsumoto for constructing prototyped models and conducting preliminary numerical experiments.

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

Appendix A

Table A1. Comparison of price levels among countries, with Japan set as 1 [35].

Price Level Index	Equipment Residential Devices Maintenance	The Total Domestic Production
China	0.57	0.40
Malaysia	0.52	0.35
The U.S.	0.64	0.74
Japan	1.00	1.00

Table A2. Transportation costs between suppliers and factories.

Supplier	Factory			
	Shanghai	**Kuala Lumpur**	**Seattle**	**Tokyo**
Guangzhou	0.0121	0.0255	0.1273	0.0291
Chongqing	0.0144	0.0299	0.1280	0.0317
Nanjing	0.0027	0.0368	0.1279	0.0197
Harbin	0.0168	0.0533	0.1299	0.0158
Xian	0.0122	0.0355	0.1294	0.0280
Chengdu	0.0166	0.0306	0.1297	0.0335
Changchun	0.0144	0.0509	0.1255	0.0152
Dalian	0.0086	0.0447	0.1239	0.0164
Hangzhou	0.0017	0.0359	0.1206	0.0192
Jinan	0.0072	0.0405	0.0339	0.0203
Qingdao	0.0055	0.0414	0.1165	0.0174
Suzhou	0.0008	0.0371	0.1238	0.0184
Fuzhou	0.0061	0.0317	0.1280	0.0222
Alor Setar	0.0356	0.0036	0.0351	0.0519
Penang	0.0363	0.0027	0.0112	0.0525
Kuantan	0.0359	0.0020	0.0312	0.0515
Malacca	0.0381	0.0012	0.0282	0.0536
Kuala Lumpur	0.0375	0.0000	0.0327	0.0533
Johor Bahru	0.0380	0.0030	0.0401	0.0532
Kuching	0.0351	0.0098	0.0343	0.0486
Sibu	0.0337	0.0113	0.0155	0.0470
Miri	0.0309	0.0137	0.0307	0.0437
Kota Kinabalu	0.0287	0.0163	0.0339	0.0409
Sandakan	0.0285	0.0184	0.0372	0.0399
Ipoh	0.0365	0.0018	0.0277	0.0525
Penang	0.0363	0.0027	0.0163	0.0525
Atlanta	0.1230	0.1586	0.0351	0.1103
San Jose	0.0995	0.1366	0.0112	0.0833
Detroit	0.1146	0.1494	0.0312	0.1012
Chicago	0.1136	0.1492	0.0282	0.1134
Cleveland	0.1158	0.1504	0.0327	0.1045
Boston	0.1173	0.1490	0.0401	0.1079
Pittsburgh	0.1174	0.1517	0.0343	0.1063
Los Angeles	0.1043	0.1414	0.0155	0.0881
Houston	0.1220	0.1593	0.0307	0.1073
New Orleans	0.1244	0.1613	0.0339	0.1105
Washington D.C.	0.1198	0.1534	0.0372	0.1090
Saint Louis	0.1158	0.1521	0.0277	0.1045
Denver	0.1078	0.1452	0.0163	0.0933
Fukuoka	0.0088	0.0451	0.1039	0.0088
Hiroshima	0.0109	0.0472	0.1014	0.0068
Yokohama	0.0175	0.0531	0.0927	0.0003
Osaka	0.0136	0.0495	0.0767	0.0040
Nagoya	0.0150	0.0509	0.0954	0.0026
Sapporo	0.0219	0.0592	0.1017	0.0083
Kumamoto	0.0089	0.0448	0.0787	0.0089
Kobe	0.0134	0.0493	0.0849	0.0042
Shizuoka	0.0163	0.0518	0.0934	0.0014
Kyoto	0.0140	0.0499	0.0894	0.0036
Sendai	0.0193	0.0558	0.0882	0.0031
Niigata	0.0177	0.0542	0.0924	0.0025
Wakayama	0.0132	0.0490	0.0977	0.0044

References

1. Ravindran, A.R.; Warsing, D.P., Jr. *Supply Chain Engineering: Models and Applications*; CRC Press: Boca Raton, FL, USA, 2013.
2. Joshi, S. A review on sustainable supply chain network design: Dimensions, paradigms, concepts, framework and future directions. *Sustain. Oper. Comput.* **2022**, *3*, 136–148. [CrossRef]

3. Kokubu, K.; Itsubo, N.; Nakajima, M.; Yamada, T. *Low-Carbon Supply Chain Management*; Chuokeizai-sha, Holdings, Inc.: Tokyo, Japan, 2015. (In Japanese)
4. Waltho, C.; Elhedhli, S.; Gzara, F. Green supply chain network design: A review focused on policy adoption and emission quantification. *Int. J. Prod. Econ.* **2019**, *208*, 305–318. [CrossRef]
5. Kondo, R.; Kinoshita, Y.; Yamada, T. Green procurement decisions with carbon leakage by global suppliers and order quantities under different carbon tax. *Sustainability* **2019**, *11*, 3710. [CrossRef]
6. The World Bank. State and Trends of Carbon Pricing 2022. Available online: https://openknowledge.worldbank.org/handle/10986/37455 (accessed on 31 December 2022).
7. Martin, R.; Muûls, M.; de Preux, L.B.; Wagner, U.J. On the empirical content of carbon leakage criteria in the EU Emissions Trading Scheme. *Ecol. Econ.* **2014**, *105*, 78–88. [CrossRef]
8. Onat, N.C.; Kucukvar, M. Carbon footprint of construction industry: A global review and supply chain analysis. *Renew. Sustain. Energy Rev.* **2020**, *124*, 78–88. [CrossRef]
9. JETRO. *Jetro Trade Handbook 2017*; Japan External Trade Organization: Tokyo, Japan, 2017. (In Japanese)
10. Ministry of Economy, Trade and Industry. Trans Pacific Partnership (TPP). Available online: https://www.meti.go.jp/policy/external_economy/trade/tpp/index.html (accessed on 2 May 2023). (In Japanese).
11. Tian, K.; Zhang, Y.; Li, Y.; Ming, X.; Jiang, S.; Duan, H.; Yang, C.; Wang, S. Regional trade agreement burdens global carbon emissions mitigation. *Nat. Commun.* **2022**, *13*, 408. [CrossRef]
12. Nitsche, B. Exploring the Potentials of automation in logistics and supply chain management: Paving the way for autonomous supply chains. *Logistics* **2021**, *5*, 51. [CrossRef]
13. Nitsche, B. Decrypting the Belt and Road Initiative: Barriers and development paths for global logistics networks. *Sustainability* **2020**, *12*, 9110. [CrossRef]
14. Cohen, M.A.; Fisher, M.; Jaikumar, R. International Manufacturing and Distribution Networks: A Normative Model Framework. In *Managing International Manufacturing*; Ferdows, K., Ed.; Elsevier: Amsterdam, The Netherlands, 1989; pp. 67–93.
15. Vidal, C.J.; Goetschalckx, M.A. A Global supply chain model with transfer pricing and transportation cost allocation. *Eur. J. Oper. Res.* **2001**, *129*, 134–158. [CrossRef]
16. Tsiakis, P.; Papageorgiou, L.G. Optimal production allocation and distribution supply chain networks. *Int. J. Prod. Econ.* **2008**, *111*, 468–483. [CrossRef]
17. Amin, S.H.; Baki, F. A facility location model for global closed-loop supply chain network design. *Appl. Math. Modell.* **2017**, *41*, 316–330. [CrossRef]
18. Nakamura, K.; Ijuin, H.; Yamada, T.; Ishigaki, A.; Inoue, M. Design and analysis of global supply chain network with trans-pacific partnership under fluctuating material prices. *Int. J. Smart Comput. Artif. Intell.* **2019**, *3*, 17–34. [CrossRef]
19. Nakamura, K.; Yamada, T.; Tan, K.H. The impact of brexit on designing a material-based global supply chain network for Asian manufacturers. *Manag. Environ. Qual. Int. J.* **2019**, *30*, 980–1000. [CrossRef]
20. Kuo, T.C.; Lee, Y. Using Pareto optimization to support supply chain network design within environmental footprint impact assessment. *Sustainability* **2019**, *11*, 452. [CrossRef]
21. Aldoukhi, M.A.; Gupta, S.M. A robust closed loop supply chain network design under different carbon emission policies. *Pamukkale Univ. J. Eng. Sci.* **2019**, *25*, 1020–1032. [CrossRef]
22. Liu, M.; Li, Z.; Anwar, S.; Zhang, Y. Supply chain carbon emission reductions and coordination when consumers have a strong preference for low-carbon products. *Environ. Sci. Pollut. Res.* **2021**, *28*, 19969–19983. [CrossRef]
23. Shen, L.; Wang, X.; Liu, Q.; Wang, Y.; Lv, L.; Tang, R. Carbon trading mechanism, low-carbon e-commerce supply chain and sustainable development. *Mathematics* **2021**, *9*, 1717. [CrossRef]
24. Fahimnia, B.; Sarkis, J.; Choudhary, A.; Eshragh, A. Tactical supply chain planning under a carbon tax policy scheme: A case study. *Int. J. Prod. Econ.* **2015**, *164*, 206–215. [CrossRef]
25. Zakeri, A.; Dehghanian, F.; Fahimnia, B.; Sarkis, J. Carbon pricing versus emissions trading: A supply chain planning perspective. *Int. J. Prod. Econ.* **2015**, *164*, 197–205. [CrossRef]
26. Abdallah, T.; Farhat, A.; Diabat, A.; Kennedy, S. Green supply chain with carbon trading and environmental sourcing: Formulation and life cycle assessment. *Appl. Math. Modell.* **2012**, *36*, 4271–4285. [CrossRef]
27. Sherafati, M.; Bashiri, M.; Tavakkoli-Moghaddam, R.; Pishvaee, M.S. Achieving sustainable development of supply chain by incorporating various carbon regulatory mechanisms. *Transp. Res. Part D Transp. Environ.* **2020**, *81*, 102253. [CrossRef]
28. Alkhayyal, B.A.; Gupta, S.M. The impact of carbon emissions policies on reverse supply chain network design. *Doğuş Üniversitesi Derg.* **2018**, *19*, 99–111. [CrossRef]
29. Urata, T.; Yamada, T.; Itsubo, N.; Inoue, M. Global supply chain network design and Asian analysis with material-based carbon emissions and tax. *Comput. Ind. Eng.* **2017**, *113*, 779–792. [CrossRef]
30. SimaPro, About SimaPro. Available online: https://simapro.com/about/ (accessed on 28 April 2023).
31. Yoshizaki, Y.; Yamada, T.; Itsubo, N.; Inoue, M. Material based low-carbon and economic supplier selection with estimation of GHG emissions and affordable cost increment for parts production among multiple Asian countries. *J. Jpn. Ind. Manag. Assoc.* **2016**, *66*, 435–442.
32. Ministry of the Environment. "Supply-Chain Emissions" in Japan. Available online: https://www.env.go.jp/earth/ondanka/supply_chain/gvc/en/files/supply_chain_en.pdf (accessed on 23 April 2023).

33. Hiller, F.S.; Lieberman, G.J. *Introduction to Operations Research*, 8th ed.; McGraw-Hill Higher Education: New York, NY, USA, 2005.
34. Ministry of Economy, Trade and Industry. Census of Manufacture. Available online: http://www.meti.go.jp/statistics/tyo/kougyo/result-2/h17/kakuho/hinmoku/index.html (accessed on 2 May 2023). (In Japanese).
35. Ministry of Internal Affairs and Communication. New International Comparisons of GDP and Consumption Based on Purchasing Power Parities for the Year 2014 Gross Domestic Product at Current PPPs and Current Exchanges Rates. Available online: https://www.soumu.go.jp/toukei_toukatsu/index/kokusai/icp.html (accessed on 2 May 2023). (In Japanese).
36. Horiguchi, K.; Tsujimoto, M.; Yamaguchi, H.; Itsubo, N. Development of greenhouse gases emission intensity in eastern Asia using Asian international input-output table. In Proceedings of the 7th Meeting of the Institute of Life Cycle Assessment, Chiba, Japan, 7–9 March 2012; pp. 236–239. (In Japanese).
37. Urata, T.; Yamada, T.; Igarashi, K.; Inoue, M.; Kinoshita, Y. Case study on comparison analysis of assembly/disassembly operations and systems between product and production designs. *J. Soc. Plant Eng. Jpn.* **2015**, *27*, 82–91. (In Japanese)
38. Suzuki, T.; Arimoto, S.; Ueno, Y.; Kawasaki, H.; Matsumoto, Y.; Tanase, H. Study of the assembling reliability. In *Evaluation 13th Design Engineering, System Section Lecture*; Japan Society of Mechanical Engineers: Kanazawa, Japan, 2003; pp. 262–265. (In Japanese)
39. Ueno, Y.; Tanase, H.; Suzuki, T.; Arimoto, S.; Kawsasaki, H.; Matsumoto, Y. Study of the Assembling Reliability Evaluation (Application to the Plumbing Work of the Heavy Industrial Machine Product). In *The 14th Design Engineering, System Section Lecture*; Japan Society of Mechanical Engineers: Fukuoka, Japan, 2014; pp. 168–171. (In Japanese)
40. NTT Data Mathematical Systems Corporation. Nuorium Optimizer. Available online: http://www.msi.co.jp/nuopt/ (accessed on 31 December 2022). (In Japanese).
41. 3kaku-K, Blank Map Specialty Store. Available online: https://www.freemap.jp/ (accessed on 31 December 2022). (In Japanese).
42. European Parliament. What Is Carbon Neutrality and How Can It Be Achieved by 2050? Available online: https://www.europarl.europa.eu/news/en/headlines/society/20190926STO62270/what-is-carbon-neutrality-and-how-can-it-be-achieved-by-2050 (accessed on 2 May 2023).
43. The Intergovernmental Panel on Climate Change (IPCC). The Evidence Is Clear: The Time for Action Is Now. We Can Halve Emissions by 2030. Available online: https://www.ipcc.ch/2022/04/04/ipcc-ar6-wgiii-pressrelease/ (accessed on 2 May 2023).
44. Ijuin, H.; Kinoshita, Y.; Yamada, T.; Ishigaki, A. Designing individual material recovery in reverse supply chain using linear physical programming at the digital transformation edge. *J. Jpn. Ind. Manag. Assoc.* **2022**, *72*, 259–271. [CrossRef]
45. Kinoshita, Y.; Yamada, T.; Gupta, S.M.; Ishigaki, A.; Inoue, M. Analysis of cost effectiveness by material type for CO_2 saving and recycling rates in disassembly parts selection using goal programming. *J. Adv. Mech. Des. Syst. Manuf.* **2018**, *12*, 1–18. [CrossRef]
46. Hasegawa, S.; Kinoshita, Y.; Yamada, T.; Bracke, S. Life cycle option selection of disassembly parts for material-based CO_2 saving rate and recovery cost: Analysis of different market value and labor cost for reused parts in German and Japanese cases. *Int. J. Prod. Econ.* **2019**, *213*, 229–242. [CrossRef]

logistics

Article

A Sustainable Two-Echelon Logistics Model with Shipment Consolidation

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Abstract: *Background*: Shipment consolidation is a concept in logistics management in which two or more shipments are transported by using the same vehicle with the aim of using less resources. *Methods*: The objective of this manuscript is to study shipment consolidation and assess its impact on cost environment, to achieve this, a mathematical model was developed to optimize shipment consolidation while reducing the emissions and minimizing the costs. *Results*: A case study from major dairy products manufacturers in Egypt was used to validate the model and evaluate the outcomes. A comparison was made between two transportation models, with and without consolidation. Results show that shipment consolidation reduced the total costs by 40% in addition to consuming less fuel, and consequently producing less emissions. *Conclusions*: These findings emphasize the importance of shipment consolidation and how it can be used to achieve more sustainability in logistics management.

Keywords: shipment consolidation; transportation model; sustainability; mid-income countries; dairy supply chain

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Citation: Mostafa, N.A.; Eldebaiky, O. A Sustainable Two-Echelon Logistics Model with Shipment Consolidation. *Logistics* **2023**, *7*, 18. https://doi.org/10.3390/logistics7010018

Academic Editors: Benjamin Nitsche and Frank Straube

Received: 14 January 2023
Revised: 3 March 2023
Accepted: 6 March 2023
Published: 19 March 2023

1. Introduction

In the modern business environments, logistics are not only important in manufacturing or goods-based industries, but also for service-based industries such as shipping and delivery services [1]. Furthermore, well implemented logistics is directly linked to enhancing business performance and increasing market share. Consequently, logistics management is considered as one of the most important strategic keys in successful businesses, and if used properly it can be a huge competitive advantage as shown in Figure 1. The basic concept of logistics is to improve the efficiency and effectiveness of several operational activities, such as transportation, warehousing and storage, order processing, material handling, and other information management concerning any related data from the origin point to end user. These include either nationally shipped products or internationally shipped products. Integrating these techniques achieves accurately timed and cost-efficient deliveries that meet the requirements of the contract or the business plan [2].

Logistics has been facing increasing challenges, especially in the recent years with high uncertainties due to crises such as the COVID-19 pandemic, the Russian–Ukrainian war, natural calamities, and increasing global orientation towards sustainable business practices [3]. That is why traditional methods of logistics management are no longer valid to face such challenges. Shipment consolidation is considered one of the most important modern techniques in logistics that many shippers now consider indispensable, due to its huge benefits. Shipment consolidation is combining two or more less than container load (LCL) from different shippers into single full container load shipments (FCL). As soon as the full container shipment is delivered to the desired destination, the shipments are disassembled into LCL again to be sent to its final customer. This method is very convenient as it offers better rates to the shippers than using the LCL. Moreover, shipment consolidation is not only suitable for shippers that have small shipments or few pallets but is also suitable for shipments from different locations and different suppliers to be collected in one shipment to avoid high rates. Consolidation helps small business owners to deliver their goods as this convenient solution offers them affordable prices [4]. Shipment consolidation plays an important role during crises and pandemics, as in these situations there are certain procedures and measures to be taken such as limiting cargo shipping and transportations between countries. Therefore, shipment consolidation was a supportive option during the COVID-19 pandemic, and it helped a lot of countries to overcome the crisis [5]. Shipment consolidation is cost-efficient since the shippers must pay for the full container even if the used space is less than half of the entire space. Thus, by combining multiple LCL shipments into one FCL shipment, better value for money will be achieved [6].

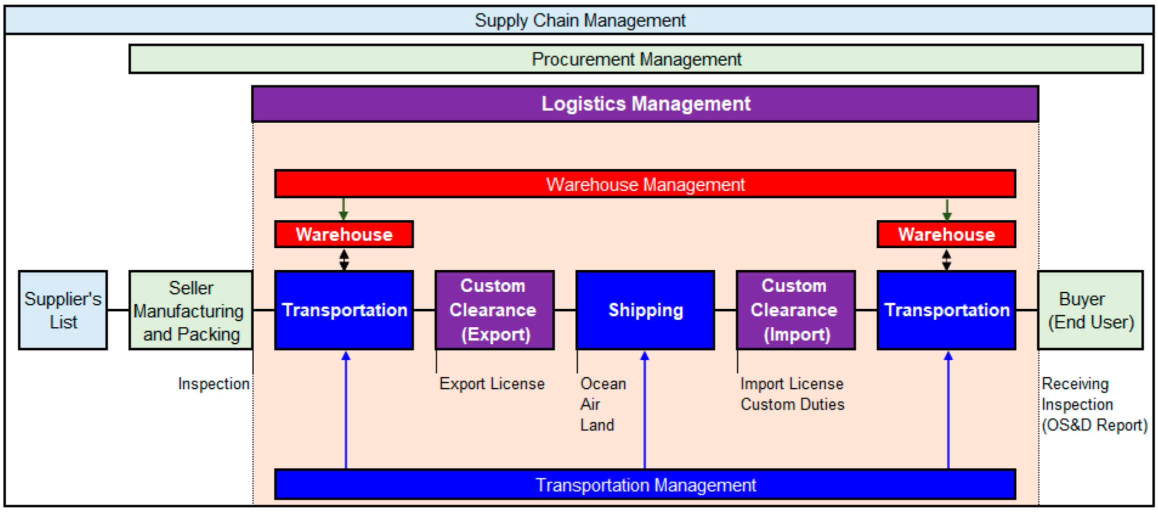


Figure 1. Scope of logistics management.

Traditionally, shipment consolidation was all about cost reduction purposes; however, consolidation can also contribute to greening the supply chain. Green Supply Chain Management (GSCM) can be defined as "integrating environmental thinking into supply chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life" [7]. To achieve this in logistics management, several functions can be addressed in addition to consolidation, such as purchasing, inbound logistics, outbound logistics, after-sale service and product returns, recycling, re-manufacturing, and centralised distribution [8].

Moreover, consolidation reduces the damage risk, as fewer touchpoints are offered by the consolidation model reducing the on-again, off-again handling of shipments. Comparatively, the normal freight shipping models contain many stops and multiple touchpoints which increase the chances of damaging the products. One of these models is the hub and spoke distribution method, which mainly allows delivery partners to arrange their daily delivery routes nearby a hub centre, then after finishing all the deliveries in a particular zone relocate to another hub centre for any additional or on-demand deliveries. This can also help against demand volatility [9].

However, there are some challenges that face shipment consolidation that might affect this process. The first problem is securing a carrier, due to the extra complications that come with this process. Even if a good carrier that can transport consolidated shipments was found successfully, there is still the problem of not being charged correctly for only the exact space used. This problem could be solved by dealing with the right carriers with good reputations, or some carriers offer access to their network. This offers a great help to the shippers, as dense networks make it easier to consolidate shipments either nationally or overseas [10]. Secondly, shipment consolidation takes a lot of time and organising to be planned correctly since there are many factors that should be taken into consideration such as dimensions, estimating the price, timing, and other factors to make sure that the shipment will be delivered safely and on time [11]. Finally, there is the problem that comes when combining the LCL into an FCL as every shipment has certain requirements, such as temperature, humidity, and other factors. For example, if the container contains fast moving consumer goods (FMCG) it cannot be shipped in the same container with electronics, as FMCG have shorter expiry dates, while electronics take more time to be processed due to different customs and procedures, which makes is it hard to keep up with the time limit for the FMCG [12].

The scope of this research paper is the optimisation and sustainability of shipment consolidation in logistics management. Works that considered shipment consolidation were reviewed to understand the analytical models that reduce the carbon footprint, cost, and time in an efficient way that satisfies the requirements of the end user. The main contribution of this paper is to explore how shipment consolidation can achieve improvements in the supply chain, and to develop a model that optimises shipment consolidation while reducing the environmental damage, minimising the costs, and enhancing the process.

2. Literature Review

The scope of most of the works on shipment consolidation was to develop new models to control the main factors affecting the consolidation process. These factors include the pickup of the shipments, the delivery method and vehicle routing, cost analysis, and the environmental impact of the model [13]. Each paper has discussed a different model to optimise the best process for shipment consolidation to choose an efficient model to be applied to get the best out of this process. Additionally, a new research direction is to discuss more sustainable options in delivering products and combine them with the shipment consolidation methods to propose a model that is efficient and sustainable. Four shipment consolidation models will be discussed to understand the difference between them and how each model has handled the consolidation method itself. Finally, works that addressed sustainable models are reviewed.

2.1. Multi-Product Pickup and Delivery with Location-Routing and Direct Shipment vs. Shipment Consolidation

Currently, most supply chains depend on third party logistics providers (3PL) to outsource their warehousing and logistics operations to improve the efficiency of the supply chain and focus on the production operations. Such activities have been adopted successfully in many companies across multiple industry sectors, such as Wal-Mart [14], Bosch [15], Goodyear [16], and Toyota [11]. 3PL providers integrate the logistics services, warehousing, and operations aiming to meet contractors or end-users needs, such as transportation and pickup services for materials and products. This can be achieved by consolidating shipments that come from different suppliers then store all the shipments for some time and then initiating the delivery process distributing the shipments or products with a fleet of delivery vehicles. This leads to developing a distribution system with low cost and time efficiency, but due to the complexity of arrangements and coordination, optimisation models must be designed to arrange and control the distribution network. The main concern of such models is to specify the vehicle routing, determine the locations of distribution centres, and solve delivery problems that might face the suppliers or the customers.

The main research problems discussed in the literature are the vehicle routing problem (VRP), the location routing problem (LRP), and the vehicle routing problem with cross-docking (VRPCD). The previous literature models mentioned in this paper introduced a multicommodity LRP and solved it with a branch and cut algorithm. In [17], a hybrid heuristic incorporating simulated annealing and artificial algae algorithm to solve the location routing problem with two-dimensional loading constraints. In [11], the problem of integrating cross-docking and vehicle routing was studied and solved through a mathematical model to find the optimal number of vehicles with main objective to reduce the overall costs. In this model, products were collected by a fleet of vehicles to a distribution centre before delivering it to the customers. Then, in the distribution center the sorting process started, where the goods were to be delivered according to the destinations in a time-saving manner with specific routes timed perfectly to reach the customer quickly. In [18], a Tabu search algorithm was used to improve the solution methods developed by the previous authors. These improvements in the algorithms reached a range of 10% to 36% in some cases. In [19], the objective was to optimise the timing of cross-docking operations for food or fast moving goods to be delivered on time and to reduce the total costs of the system. The system costs consisted of the costs holding of the inventory, the penalty of late or early deliveries, and the delivery costs.

Moreover, most of the previous studies considered the design of single distribution centre in a fixed location, while in [20], a model with two routing types and one distribution centre was proposed. The first type of routing was for a transportation process that was initiated at the cross-dock; after that, it reached a subset of suppliers. The second type started after passing by a subset of suppliers without stopping at the cross-docks. In [21], the VRPCD was discussed relative to different routing for vehicle fleet and scheduling of trucks routes in a multi-door cross-dock system. An estimated sweep-based model was developed to consider several constraints simulating the sweep algorithm. The model was responsible for nodes assigned to vehicles to reduce the search and enhance branch. This model was validated by solving numerical examples for more than fifty transportation requests and different ten vehicle fleets, and the results displayed a reasonable running time. In [22], a mixed integer programming model was used to control the outbound and inbound scheduling of trucks in a cross-docking system. A hybrid algorithm that combines particle swarm with simulated annealing was used to help in solving complex problems in very short time. In [23], the problem of scheduling cross-docking and vehicle routes was addressed for a three-echelons supply chain network. The objective was to reduce late deliveries and delivery costs.

Last mile distribution is one of the most important research topics in supply chain and logistics management. The best example of this process is the last transportation process of the products from supply chains to its last delivery points such as retail stores. Last mile delivery is usually the routing of a fleet of vehicles to stop at a set of delivery destinations, using less than truckload (LTL) or truckload (TL). Various techniques were used throughout the literature to overcome the problems of last mile deliveries and optimise the whole process, such as solving the vehicle routing problem with split deliveries (VRPSD). Although the concept of split deliveries has many benefits in terms of cost, it does not take full advantage of using multiple vehicles to deliver multiple shipments to customers on the same day.

2.2. Sustainable Models

A great interest has been into achieving sustainability and greener transportation while creating an efficient system in terms of cost and time. This will inspire the business owners to act and reduce the damage that their companies are responsible for while also making profits to make it a win–win situation. Examining the demand and sustainability of critical metals has focused on light-duty vehicles. Heavy-duty vehicles have often been excluded from the research scope due to their smaller vehicle stock and slower pace of electrification [24]. In 2017, Tesla announced the production of electrical semi-truck with an estimated production start in 2019, but due to the pandemic there was a delay in the production plan. In 2022, Tesla announced the delivery of the first batches to some large companies including Pepsi, Amazon, and Walmart. These semi-trucks raised the level of expectations as it will have a range of 800 km, with a Tesla Mega charger giving 640 km of charge in 30 min. The semi-truck can also use on-site 150 kW charging, taking six to eight hours [25]. There is no doubt, that the electrical heavy-duty vehicles will be considered a game changer in reducing emissions and carbon offsetting. Unfortunately, there are not enough studies to give an exact number or percentage for emissions compared to diesel trucks as the Tesla vehicles are still new to the market, but certainly this will contribute toward more sustainable delivery model [26].

Another model is the parcel delivery model that identifies the different parameters in the delivery model while considering many combinations of traditional operators (e.g., trucks and vans that use fossil fuel) and green operators (e.g., electric or hybrid vehicles, bikes, and cargo bikes), investigating their business models and behaviours from a managerial perspective [27]. The aim of this model is to form an operational point of view on how to mix low-emission and traditional logistics, especially in urban areas. In [27], a Monte Carlo-based simulation optimisation framework was developed for analysing mixed-fleet board policies related to managing freight delivery in urban areas, clarifying their cost mix (economic and environmental). In [28], the impact of shipment consolidation on home delivery in the retail industry was assessed; the results confirmed the positive role of shipment consolidation on delivery time, total cost, and fuel consumption.

Recent works on the role of logistics in Industry 4.0 have recognised major challenges including cost reduction and resource management [29], which is why shipment consolidation can play a role in enabling Industry 4.0 adoption in logistics management. Shipment consolidation can be seen as an agile method as it improves collaboration in the supply chain and promotes trust among several players [30]. According to [31], shipment consolidation can be beneficial for upstream suppliers and also can achieve Pareto improvement of both economic and environmental sustainability.

2.3. Research Questions and Contribution

Most of the discussed models proved that shipment consolidation is a good option in terms of enhancing and optimising logistics efficiency. However, there are not enough works on industrial applications, especially on the food industry, which has the critical perishability factor. In this work, the scope is to develop a new analytical model aiming at reducing costs, saving time, and making the transportation process as environmentally friendly as possible.

This research paper discusses optimising shipment consolidation and categorisation in logistics management and with considering sustainability. The concept of "mid-route shipment consolidation" is discussed to show its benefits and implementation. To do so, two research questions were developed to drive this research:

RQ1: How can all the possible vehicle capacity be utilised in last mile distribution in order to reduce the number of dispatched vehicles, and the on-road time of the vehicles?
RQ2: How can the emissions and pollutants produced by the vehicles be reduced?

3. Problem Statement and Mathematical Model

The paper discusses the problem of decision making in a distribution network consisting of customers, suppliers, and distribution centres. A problem statement and network description will be given in addition to the assumptions to be used for the model.

3.1. Problem Statement and Network Description

Suppliers provide the goods to be delivered to customers by two ways, either through direct shipping to the customers or consolidating the shipments in a distribution centre then delivering it to the customers. The objective of the model is to make a decision regarding the delivery mode to reduce costs and minimise the delivery time, both in the transportation process of the products and in the consolidation of shipments in the distribution centre. The significance of the problem appears significant when there are different delivery routes to each subset of customers to satisfy the needs of the market that is usually dealing with multiple products as shown in Figure 2. In the case that a special group of customers need a single product, the process changes into single product delivery plan with different delivery and pick up routes as shown in Figure 3.

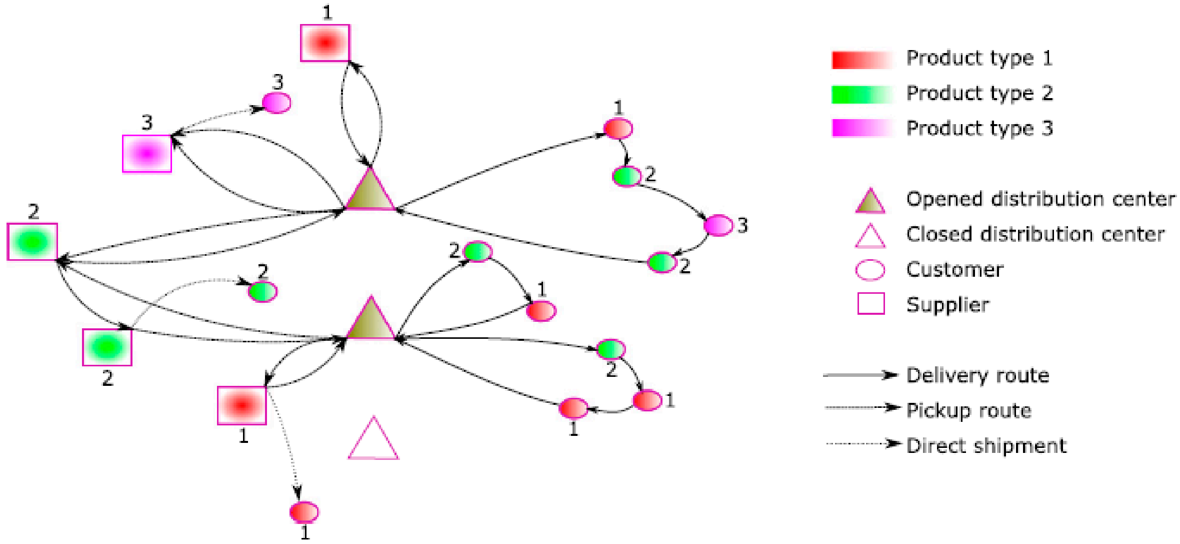


Figure 2. Multi-product delivery network (Azizi and Hu).

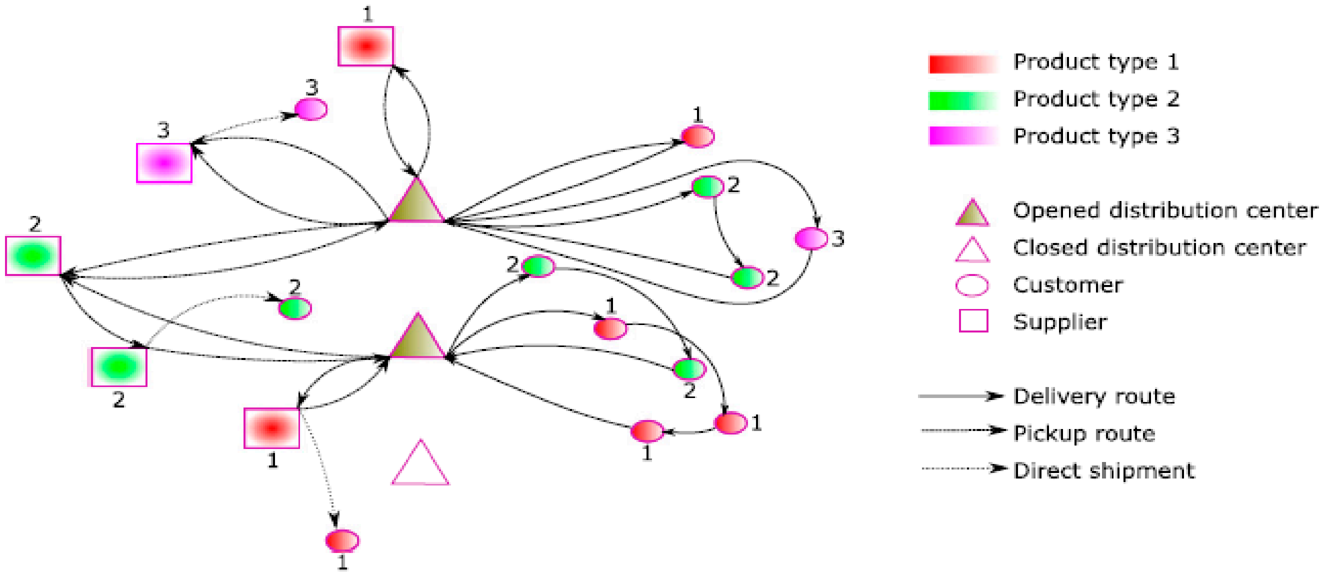


Figure 3. Single-product delivery network (Azizi and Hu).

3.2. Model Assumptions

The following assumptions will be considered while modelling the problem:

- Each node must belong to one of the following sets: distribution centre node, pickup node (Supplier), or delivery node (End user) [11].
- All the requests for the delivery must be satisfied by either direct shipments or transportation from distribution centres.
- There is a limit on the capacity of the products for each supplier.
- All distribution centres must be provided by vehicles to be able to perform any transportation processes.
- For the delivery and pick up, a fleet of homogeneous vehicles must perform all the delivery processes.
- After finishing each delivery, all the vehicles that are responsible for either pick up or delivery must return to the distribution centre.
- Vehicles can visit pick up nodes more than one time, but delivery nodes are not allowed to be visited more than one time.

The proposal of the mid-route shipment consolidation concept depends on the idea of the synchronisation between the delivery of the product and the availability of the vehicles, as these actions takes place simultaneously. A focus group study was made with the carrier companies to see their opinion about this concept in real-life applications. The feedback described this method as a potential way to reduce costs and to improve vehicle utilisation. On the other hand, it might just need contract adjustments and some extra resources to be implemented. Mid-route shipment consolidation sheds light on the possibility of simple consolidation that can take place by exchanging shipments between vehicles.

In this paper, a transportation model is formulated and then discussed based on a comparison between two scenarios; the first model is a proposed transportation model that emphasises the importance of consolidation by adding multiple distribution centres (DCs) or warehouses between the nodes of the supply (plants) and the demand (hypermarkets). Consolidation takes places at the distribution centres so that the fleet will not go all the way from the factory to the retail store with less than the full truck capacity, as the distribution centres will allow the utilisation of most of the truck capacity, this will also divide the route of the fleet into two phases. The first phase will be from the plant to the distribution centre, while the second phase will be from the distribution centres to the hypermarkets. This consolidated transportation model should save some of the transportation costs, in addition to saving the environment from the pollutants that the fleet will produce if the number of trucks is not reduced. Moreover, the distribution centres will offer extra storage space for the hypermarkets, supplying the needed demand all while eliminating the wasted time and the delay that takes place when ordering from the plant directly. The second model is the current model used in a real dairy supply chain that uses direct shipment delivery from the plants to the hypermarkets. Comparison between the consolidated model and the non-consolidated model is performed to show if there is a significant reduction in cost and emissions between the two models. Dairy products were selected as they are essential and the demand on them is increasing [32].

3.3. Linear Programming Transportation Model

The objective function of the model minimises the cost by reducing the handling of the product from the shipper (Plants) to the consolidation points, which are the distribution centres offering the fewest amount of touch points. Additionally, the speed to the market as the strategy of consolidation models depend on delivering the shipments on time, which means that no late deliveries are accepted, since fast moving consumer goods (FMCG) are addressed. In general, there are two types of transportation models, classified into balanced problems and unbalanced problems. The balanced problems are when the demand does not exceed the supply while the unbalanced problems are when the demand exceeds the supply. Since this model deals with hypermarkets as the final destinations, it will be more realistic to deal with balanced transportation problem model to avoid any shortage in the products, as this will cause losses for the hypermarkets. Hence, the model seeks achieving the maximum utilisation of the truck available capacity and providing a faster transportation process. The transportation model can be formulated as the following linear programming model with m origins nodes and n destinations nodes.

$$\textbf{Minimise} \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}x_{ij} \tag{1}$$

$$\sum_{j=1}^{n} x_{ij} \leq a_i \qquad i = 1,\ 2,\ \ldots\ldots\ldots\ldots m \tag{2}$$

$$\sum_{i=1}^{m} x_{ij} \geq b_j \qquad j = 1,\ 2,\ \ldots\ldots\ldots\ldots n \tag{3}$$

$$\sum_{j=1}^{n} x_{ij} + \sum_{i=1}^{m} x_{ij} \leq \ a_i + b_j \tag{4}$$

$$x_{ij} \geq 0 \tag{5}$$

The objective is to obtain the number of units that will be shipped from origins to destinations taking into account that transportation cost should be minimised while satisfying all the constraints mentioned above. Where x_{ij} is the number of units of shipped from the origin (plant) i to destination (demand) j, and c_{ij} is the delivery cost of one unit from the origin i to the destination j expressed in cost per kilometer multiplied by the number of trucks, which is specified as the total amount of units divided by each truck capacity divided by the total number of products. Moreover, a_i is the number of units supplied from the plant (origin) and b_j is the number of units at the destination demand locations.

3.4. Distribution Centre Locations

In the real case study, there are no actual distribution centres or warehouses. Nevertheless, the locations of the three warehouses cannot be assumed randomly. The centre of gravity method was used to determine the location of the distribution centres according to the quantity of the two products that will be supplied by the two plants. Table 1 gives the demand and location of each distribution centre with reference point in the middle between the two plants. Using these data, the exact coordinates are calculated and the locations are located on Google maps as shown in Figure 4.

Table 1. Demand and location data for each distribution centre.

DC		Plant 1	Plant 2
DC 1	Demanded quantity per week	4500 cartons	1500 cartons
	Relative location	65 Km N. West	63.37 Km S. East
DC 2	Demanded quantity per week	1000 cartons	2000 cartons
	Relative location	65 Km N. West	63.37 Km S. East
DC 3	Demanded quantity per week	1500 cartons	1500 cartons
	Relative location	65 Km N. West	63.37 Km S. East

For DC 1:

X-coordinate: $\frac{4500\ (-65\ \times\ \cos 45)\ +\ 1500\ (63.75\ \times\ \cos 45)}{6000} = -23.33\ \ Km$ (West)

Y-coordinate: $\frac{4500\ (65\ \times\ \sin 45)\ +\ 1500\ (-63.75\ \times\ \sin 45)}{6000} = 23.33\ \ Km$ (North)

For DC 2:

For X-coordinate: $\frac{1000\ (-65\ \times\ \cos 45)\ +\ 2000\ (63.75\ \times\ \cos 45)}{3000} = 14.731\ Km$ (East)

For Y-coordinate: $\frac{1000\ (65\ \times\ \sin 45)\ +\ 2000\ (-63.75\ \times\ \sin 45)}{3000} = -14.731\ \ Km$ (South)

For DC 3:

For X-coordinate: $\frac{1500\ (-65\ \times\ \cos 45)\ +\ 1500\ (63.75\ \times\ \cos 45)}{3000} = -0.4419\ \ Km$ (West)

For Y-coordinate: $\frac{1500\ (65\ \times\ \sin 45)\ +\ 1500\ (-63.75\ \times\ \sin 45)}{3000} = 0.4419\ \ Km$ (North)

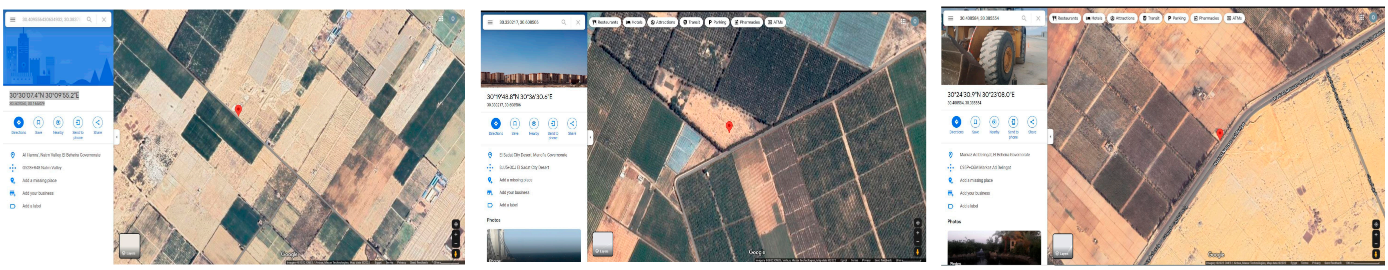


Figure 4. Locations of the three Distribution Centres.

3.5. Cost Analysis

After determining the locations of the distribution centres the cost of the transportation between the nodes could be easily calculated. However, to estimate the total cost, the number of required trucks should be determined, based on the trucks' capacities. Assuming a fleet of homogeneous tail lift trucks (shown in Figure 5), the number of required trucks is calculated as the total number of cartons to be shipped divided by the capacity of each truck. The following data were collected from the plant. The capacity of each truck is approximately 500 cartons of milk. The average fuel consumption of the tail lift truck is 11 litres per 100 km, which means that the average fuel consumption of the truck equals 0.11 litre per km. Additionally, this kind of truck operates on diesel fuel where the diesel price in Egypt as of May 2022 is EGP 6.750 per litre. Therefore, the price of fuel per km: $0.11 \times 6.750 = 0.7425$ EGP. The total transportation cost per unit is calculated by using Equation (6). As the truck route is considered a round trip, the shipper charges double the distance because the truck returns empty.

$$Total\ per\ unit\ transportation\ cost = \frac{2 \times Distance\ in\ Km \times Price\ of\ fuel\ per\ Km \times number\ of\ trucks}{number\ of\ units} \tag{6}$$

Figure 5. A tail lift truck used for transportation of milk cartons.

4. Case Study and Results

In this case study, a two-phase transportation model is proposed for a dairy products supply chain. The first phase is between two different large dairy plants (origins) that supply milk cartons to three distribution centres or warehouses (destinations), which will be located between the two suppliers according to centre of gravity method to minimise the distances between the nodes as much as possible. The second phase will be the delivery of the milk cartons from the distribution centres to seven different hypermarket branches located in Cairo. As shown in the model, the supply should always be greater than or equal to the demand to avoid shortage in stock at the hypermarket and to satisfy the condition of balanced transfer problem that was assumed in the model.

The distances between all the nodes of the model are specified after locating the distribution centres that will be elaborated in the site analysis. Data on the capacity of the trucks, the weekly production, and the forecasted demand of milk cartons were collected from the two plants. In comparison, the non-consolidated model will be a delivery model between the two plants and the end destinations without using the distribution centres. The result of the two-phase model will be compared to the non-consolidated model to observe the difference between the two delivery models.

4.1. The Consolidated Model

The consolidation model is the model that contains the distribution centers between the nodes of the origin and the end destination, it is divided into two phases (echelons). The first echelon is between the plants and the distribution centres. While the second phase is between the distribution centres and seven branches of a large hypermarket chains as shown in Figure 6 and the distances between the nodes are given in Tables 2 and 3. Figures 7 and 8 show the first and second phases, respectively. Each distribution centre is replenished from both plants; however, each demand point is replenished by a single distribution centre (based on the distance). Tolls are estimated to be EGP 200 per truck per round trip. The reason for breaking this model into two phases is to solve the objective function with fewer constraints and to be simpler while solving. Moreover, the result from the two phases will be combined to be compared with the non-consolidated model.

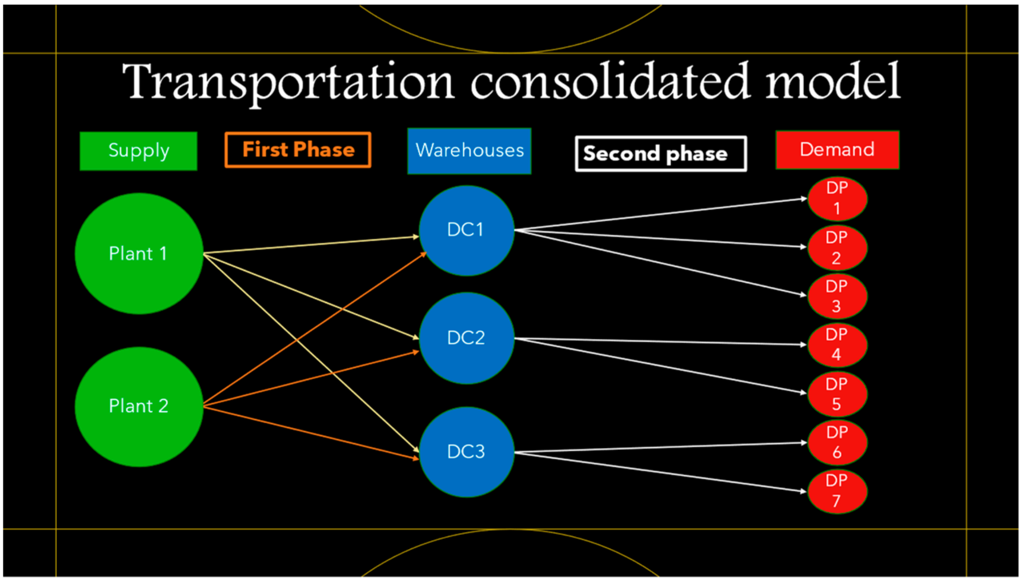


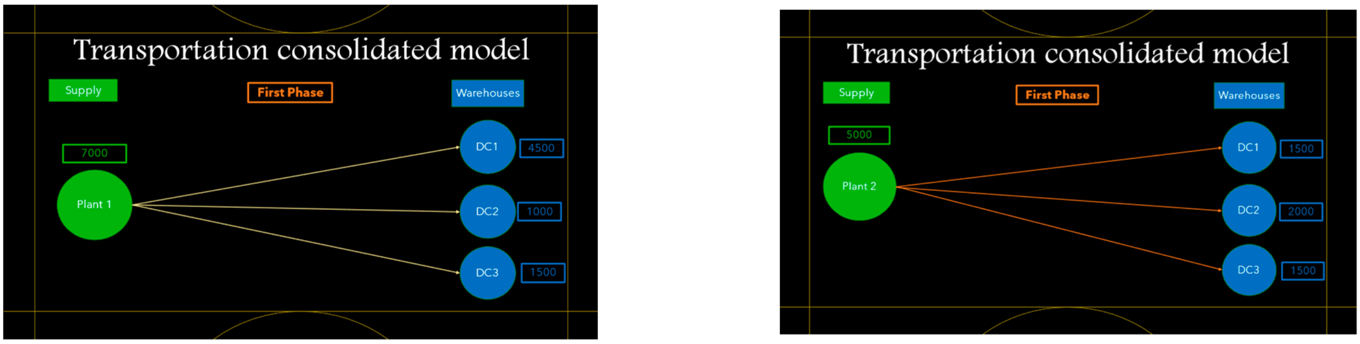
Figure 6. The transportation model with consolidation.

Table 2. Distances between plants and distribution centres (km).

DC	Plant 1	Plant 2
DC 1	125	49.6
DC 2	79	89.5
DC 3	106	74.3

Table 3. Distances between distribution centres and demand points (km).

DC	DP1	DP2	DP3	DP4	DP5	DP6	DP7
DC 1	177	165	165	-	-	-	-
DC 2	-	-	-	103	95.1	-	-
DC 3	-	-	-	-	-	124	119



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

Figure 7. Phase 1 of the transportation model with consolidation for: (**a**) Plant 1, (**b**) Plant 2.

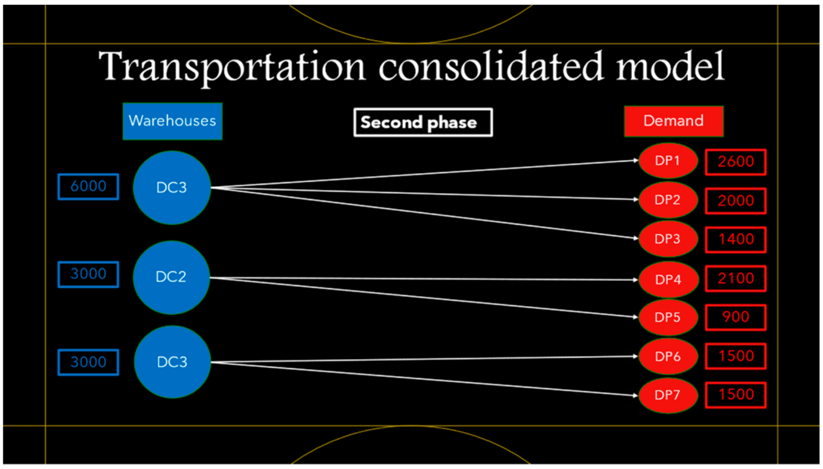


Figure 8. Phase 2 of the transportation model with consolidation.

Given that the weekly supply capacities for Plant 1 and Plant 2 are 7000 and 5000 cartons, respectively, phase 1 is modelled as follows:

$$\text{Minimise } 0.37116\ X_{11} + 0.23463\ X_{12} + 0.31482 X_{13} + 0.147312 X_{21} + 0.265815\ X_{22} + 0.220671\ X_{23}$$

Subject to

$$X_{11} + X_{12} + X_{13} \leq 7000$$
$$X_{21} + X_{22} + X_{23} \leq 5000$$
$$X_{11} + X_{21} = 8000$$
$$X_{12} + X_{22} = 2000$$
$$X_{13} + X_{23} = 2000$$
$$X_{ij} \geq 0 \quad (\text{non} - \text{negativity constraint})$$

Phase 2 is modelled as follows:

$$\text{Minimise } 1.0681\ X_{11} + 0.89005\ X_{12} + 0.953625\ X_{13} + 1.05958\ X_{24} + 0.7582 X_{25} + 0.76828 X_{36} + 0.75343 X_{37}$$

Subject to

$$X_{11} + X_{12} + X_{13} \leq 6000$$
$$X_{24} + X_{25} \leq 3000 X_{36} + X_{37} \leq 3000$$
$$X_{ij} \geq 0 \quad (\text{non} - \text{negativity constraint})$$

Excel Solver was used to solve these models, the total cost for the first phase of the consolidated model is 1823.68. In the second phase, the origins are the distribution centres and the destinations are seven branches of a large hypermarket chain, the total cost for the second phase of the consolidated model is EGP 4135.5. Hence, the total cost for the consolidated model is EGP 5959.18 per week.

4.2. The Non-Consolidated Model

The non-consolidated model is the currently used model in the studied supply chain, hence there is no distribution centre in this model as shown in Figure 9. In this model, transportation costs are calculated directly for each route by using Equation (6). The total cost for this model is EGP 9962.95 per week. Figure 10 gives the comparison between the total costs of the consolidated model and the non-consolidated model. It was found that using the consolidated model has led to a 40% reduction in costs. In addition, as the fuel consumption is reduced in the consolidation model, less emissions are produced leading to a more sustainable logistics model. Hence, the findings validate the significance of the consolidation model as it does not only help in reducing the costs, but also it is a more environmentally friendly method, which is considered one of the most important aspects in logistics management. Moreover, it reduces the CO2 and other emissions produced from the heavy-duty trucks. The results of this study agree with recent studies from the literature, and gives an opportunity to companies in Egypt to adopt shipment consolidation in their distribution strategy [31,33].

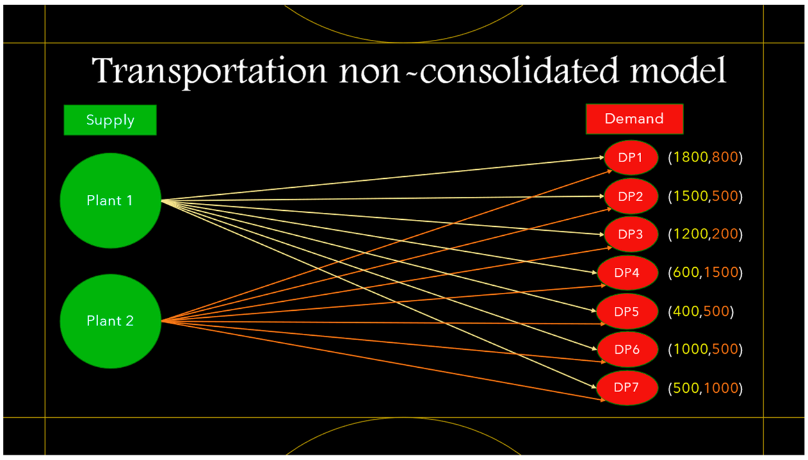


Figure 9. The transportation model with no consolidation.

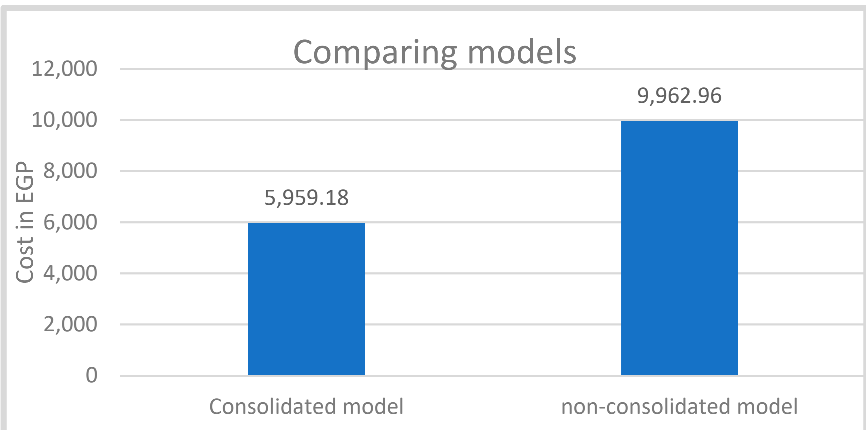


Figure 10. The total transportation costs for the two models.

The process of implementing shipment consolidation has strong implications for policy makers and top management. From cost- and service-level perspectives, shipment consolidation achieves better results; it should be included in both tactical and operational decision levels. It is implied that significant savings can be achieved by performing shipment consolidation at a small subset of customer nodes, mid-route shipment consolidation can be used for carriers with non-clustered customer networks, and highly variable demand patterns.

5. Conclusions

Consolidation is not only a cost reduction method, but also it is a more efficient and environmentally friendly solution in logistics. Moreover, consolidation can solve traffic problems by decreasing the number of heavy trucks on the roads, and hence less maintenance will be required as heavy-duty trucks are responsible for the largest share of road usage. In this paper, a practical example of the benefits of consolidation was discussed. A case study from dairy supply chain was addressed, and two scenarios were studied; the first model used consolidation by using distribution centres as midpoints between the origins (milk plants) and the destinations (hypermarkets), while the second model uses direct shipment from the origins to the destinations. By comparing the two models, it was found that the consolidation method is an efficient, reliable, and environmentally friendly strategy as it could achieve cost reduction by more than 40%.

The cost of applying this model is relatively cheap if compared to the used model, as the extra expenses will be the distribution centres. These can be well managed if the principles of choosing the locations of these distribution centres, such as the centre of gravity method, are applied in addition to proper site analysis. Limitations of this paper are the relatively low number of covered works in the literature. This is due to the novelty of the shipment consolidation concept, and consequently the body of literature on its applications is relatively small. Another limitation is working on a small-sized network; however, this is a good direction for future work by extending the supply chain network to include more echelons. The consolidation model can be applied to other industries and the best example that shows the importance of consolidation is international shipping, as the shipping costs are much higher and to ship LCL is considered a waste of money that can be solved by using consolidation. Similarly, the last three years have witnessed a recession in the world economy due to the COVID-19 virus, shipment consolidation played a lifesaving role in this crisis by combining multiple shipments, hence reducing the cargo ships around the world which helped in stopping the spread of the virus. The multi-product pickup and delivery model can be used to develop a distribution network between multiple suppliers and developing an optimised model that is designed to manage the distribution network. Other directions for future research include fleet mixing with heterogeneous vehicles, and using delivery time-windows. Additionally, more insights on the impact of shipment consolidation on different parts of the supply chain need to be measured.

Author Contributions: Conceptualization, N.A.M.; methodology, N.A.M. and O.E.; software, O.E.; validation, O.E.; formal analysis, N.A.M.; O.E., writing—original draft preparation; O.E., writing—reviewing and editing; N.A.M., visualization, O.E.; supervision, N.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

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

References

1. Gartenstein, D. What Roles Does the Finance Department Play in a Business? 2019. Available online: https://bizfluent.com/facts-5683333-role-finance-department-play-business-.html (accessed on 5 March 2022).
2. Groß, P.-O.; Ehmke, J.F.; Mattfeld, D.C. Cost-Efficient and Reliable City Logistics Vehicle Routing with Satellite Locations under Travel Time Uncertainty. *Transp. Res. Procedia* **2019**, *37*, 83–90. [CrossRef]
3. Santhi, A.R.; Muthuswamy, P. Pandemic, War, Natural Calamities, and Sustainability: Industry 4.0 Technologies to Overcome Traditional and Contemporary Supply Chain Challenges. *Logistics* **2022**, *6*, 81. [CrossRef]
4. Cortes, J.D.; Suzuki, Y. Vehicle Routing with Shipment Consolidation. *Int. J. Prod. Econ.* **2020**, *227*, 107622. [CrossRef]

5. Straube, F.; Nitsche, B. Defining the "New Normal" in International Logistics Networks: Lessons Learned and Implications of the COVID-19 Pandemic. *WiSt Wirtsch. Stud.* **2020**, *50*, 16–25. [CrossRef]
6. Bertazzi, L.; Moezi, S.D.; Maggioni, F. The value of integration of full container load, less than container load and air freight shipments in vendor–managed inventory systems. *Int. J. Prod. Econ.* **2021**, *241*, 108260. [CrossRef]
7. Srivastava, S.K. Green supply-chain management: A state-of-the-art literature review. *Int. J. Manag. Rev.* **2007**, *9*, 53–80. [CrossRef]
8. Ülkü, M.A. Dare to care: Shipment consolidation reduces not only costs, but also environmental damage. *Int. J. Prod. Econ.* **2012**, *139*, 438–446. [CrossRef]
9. Nitsche, B.; Durach, C.F. Much Discussed, Little Conceptualized: Supply Chain Volatility. *Int. J. Phys. Distrib. Logist. Manag.* **2018**, *48*, 866–886. [CrossRef]
10. Risberg, A. A systematic literature review on e-commerce logistics: Towards an e-commerce and omni-channel decision framework. *Int. Rev. Retail Distrib. Consum. Res.* **2022**, *33*, 67–91. [CrossRef]
11. Azizi, V.; Hu, G. Multi-product pickup and delivery supply chain design with location-routing and direct shipment. *Int. J. Prod. Econ.* **2020**, *226*, 107648. [CrossRef]
12. Pourakbar, M.; Sleptchenko, A.; Dekker, R. The floating stock policy in fast moving consumer goods supply chains. *Transp. Res. Part E: Logist. Transp. Rev.* **2009**, *45*, 39–49. [CrossRef]
13. Bathaee, M.; Nozari, H.; Szmelter-Jarosz, A. Designing a New Location-Allocation and Routing Model with Simultaneous Pick-Up and Delivery in a Closed-Loop Supply Chain Network under Uncertainty. *Logistics* **2023**, *7*, 3. [CrossRef]
14. Gue, K.R. *Crossdocking: Just-in-Time for Distribution, Graduate School of Business*; Public Policy Naval Postgraduate School: Monterey, CA, USA, 2001; p. 8.
15. Yildiz, H.; Ravi, R.; Fairey, W. Integrated optimization of customer and supplier logistics at Robert Bosch LLC. *Eur. J. Oper. Res.* **2010**, *207*, 456–464. [CrossRef]
16. Kinnear, E. Is there any magic in cross-docking? *Supply Chain Manag. Int. J.* **1997**, *2*, 49–52. [CrossRef]
17. Ferreira, K.M.; de Queiroz, T.A. A simulated annealing based heuristic for a location-routing problem with two-dimensional loading constraints. *Appl. Soft Comput.* **2022**, *118*, 108443. [CrossRef]
18. Liao, C.-J.; Lin, Y.; Shih, S.C. Vehicle routing with cross-docking in the supply chain. *Expert Syst. Appl.* **2010**, *37*, 6868–6873. [CrossRef]
19. Agustina, D.; Lee, C.K.M.; Piplani, R. Vehicle scheduling and routing at a cross docking center for food supply chains. *Int. J. Prod. Econ.* **2014**, *152*, 29–41. [CrossRef]
20. Santos, F.A.; Mateus, G.R.; Da Cunha, A.S. The pickup and delivery problem with cross-docking. *Comput. Oper. Res.* **2013**, *40*, 1085–1093. [CrossRef]
21. Dondo, R.; Cerdá, J. The heterogeneous vehicle routing and truck scheduling problem in a multi-door cross-dock system. *Comput. Chem. Eng.* **2015**, *76*, 42–62. [CrossRef]
22. Keshtzari, M.; Naderi, B.; Mehdizadeh, E. An improved mathematical model and a hybrid metaheuristic for truck scheduling in cross-dock problems. *Comput. Ind. Eng.* **2016**, *91*, 197–204. [CrossRef]
23. Baniamerian, A.; Bashiri, M.; Zabihi, F. Two phase genetic algorithm for vehicle routing and scheduling problem with cross-docking and time windows considering customer satisfaction. *J. Ind. Eng. Int.* **2018**, *14*, 15–30. [CrossRef]
24. Hao, H.; Geng, Y.; Tate, J.E.; Liu, F.; Chen, K.; Sun, X.; Liu, Z.; Zhao, F. Impact of transport electrification on critical metal sustainability with a focus on the heavy-duty segment. *Nat. Commun.* **2019**, *10*, 5398. [CrossRef] [PubMed]
25. Gaton, B. Electrification of the trucking fleet: Not far off, and likely to happen fast. *ReNew Technol. A Sustain. Future* **2019**, *146*, 82–85.
26. Fontaine, P.; Minner, S.; Schiffer, M. Smart and sustainable city logistics: Design, consolidation, and regulation. *Eur. J. Oper. Res.* **2023**, *307*, 1071–1084. [CrossRef]
27. Perboli, G.; Rosano, M. Parcel delivery in urban areas: Opportunities and threats for the mix of traditional and green business models. *Transp. Res. Part C: Emerg. Technol.* **2019**, *99*, 19–36. [CrossRef]
28. Muñoz-Villamizar, A.; Velázquez-Martínez, J.C.; Mejía-Argueta, C.; Gámez-Pérez, K. The impact of shipment consolidation strategies for green home delivery: A case study in a Mexican retail company. *Int. J. Prod. Res.* **2022**, *60*, 2443–2460. [CrossRef]
29. da Silva, R.M.; Frederico, G.F.; Garza-Reyes, J.A. Logistics service providers and industry 4/0: A systematic literature review. *Logistics* **2023**, *7*, 11. [CrossRef]
30. Zielske, M.; Held, T.; Kourouklis, A. A framework on the use of agile methods in logistics startups. *Logistics* **2022**, *6*, 19. [CrossRef]
31. Wang, H.; Dong, J.; Niu, B.; Xu, X. Could shipment consolidation jointly improve the economic and environmental sustainability of a maritime service supply chain? *Int. J. Logist. Res. Appl.* **2023**, 1–46. [CrossRef]
32. Malik, M.; Gahlawat, V.K.; Mor, R.S.; Dahiya, V.; Yadav, M. Application of Optimization Techniques in the Dairy Supply Chain: A Systematic Review. *Logistics* **2022**, *6*, 74. [CrossRef]
33. Zhang, J.; Lu, J.; Zhu, G. Optimal shipment consolidation and dynamic pricing policies for perishable items. *J. Oper. Res. Soc.* **2022**, 1–17. [CrossRef]

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The Impact of Digital Technologies and Sustainable Practices on Circular Supply Chain Management

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Abstract: *Background*: This study investigates how firms can enhance the functionality of their circular supply chains (CSCs) by adopting a portfolio of sustainable practices as well as digital technologies to increase performance. It analyzes the benefits that firms can obtain when investing in specific technologies to boost the impact of technologies and sustainable practices on CSCs, and further increase performance. *Methods:* We test several hypotheses by using structural equation modeling as well as multi-group analysis to verify whether CSCs can be achieved through sustainable practices and technologies and improve the firms' performance. *Results:* The empirical results partially support the research hypotheses. While the main research hypotheses are fully supported, the analysis of single digital technologies reveals that only a few solutions can contribute to both the management and the improvement of the CSC. *Conclusions:* Our findings demonstrate that the identification of green suppliers and ad hoc environmental regulations, combined with attention to the origin and provenance of raw materials, can promote a CSC. Moreover, transportation management systems (TMS) and the internet of things (IoT) are efficient technologies for managing transportation and product flow in the CSC. Furthermore, machine learning (ML) is effective in making positive green decisions, and 3D printing can extend product life.

Keywords: circular economy; circular supply chain; sustainable practices; digital technologies

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Citation: Romagnoli, S.; Tarabu', C.; Maleki Vishkaei, B.; De Giovanni, P. The Impact of Digital Technologies and Sustainable Practices on Circular Supply Chain Management. *Logistics* **2023**, *7*, 1. https://doi.org/10.3390/logistics7010001

Academic Editors: Benjamin Nitsche and Frank Straube

Received: 16 November 2022
Revised: 14 December 2022
Accepted: 16 December 2022
Published: 3 January 2023

1. Introduction

According to [1], circular supply chain can be defined as follows: "the coordinated forward and reverse supply chains via purposeful business ecosystem integration for value creation from products/services, by-products and useful waste flows through prolonged life cycles that improve the economic, social and environmental sustainability of organizations." In general terms, a CSC seeks to achieve zero waste through collaboration between the producer's supply chain and secondary chains, thanks to which a company can easily restore and regenerate its primary resources [2]. Moreover, following the fundaments of industrial symbiosis, a real cross-chain and cross-sector collaboration can be achieved [3]. Stakeholders can realize several benefits with a CSC, which are outcomes obtained when collaborating, negotiating, and sharing the risks and resources with long-term perspectives [4,5]. In a CSC, firms can collaborate in an international framework to maximize the value of goods, returns, and materials, achieve efficiency and profitability while diminishing negative environmental, social, and economic impacts [3].

Different from linear supply chains, a CSC improves the firms' performance by collecting goods and packaging to recover their materials and use lower natural resources [4]. Although the CSC is—in principle—very appealing, it raises several operational issues and challenges due to the management of international forward and reverse flows. For example, CSCs collect a substantial amount of waste, which can result in being unrecyclable or non-reusable. In fact, the CSC implementation and management are followed by several barriers and constraints. Working in this direction, [5] discovered that circular systems face important technical and structural barriers, which are directly related to the core activities of CE models, specifically, the absence of collecting, sorting, and recycling. Missing these activities translates into a negligible capacity to implement CSCs. Furthermore, firms can be reluctant in accepting the CE models as well as be afraid of the lack of the returns' homogeneity and standardization [5]; these are important barriers in determining the firms' capacity to create a CSC, especially when linked to the uncertainty of the international backward flows. Similarly, the literature provided a comprehensive list of barriers and risks connected to the adoption of CSC, which deter its adoption and limit its functionality [3,6]. Considering the difficult balance existing between positive and negative aspects linked to CSC, a few questions still need to be answered: how can firms enable CSC? How can firms increase the CSC functionality? Does CSC contribute to business performance? How can the effect of CSC on business performance be leveraged?

This paper contributes to these directions by focusing on two main enablers, that are sustainable practices and digital technologies. In principle, the adoption of sustainable practices renders CSCs more effective [7] since the companies undertake a set of environmental management practices to enhance the value of circular activities. In fact, the implementation of non-sustainable practices could simply harm the effectiveness of any CSC system. Furthermore, digital technologies can surely enable CSC activities by connecting the ecosystem to the companies and supporting the decision-making process [8] and reduce the volatility of the whole supply chain system [9]. Specifically, digital technologies allow companies to obtain high-value information, which can then be used to improve the strategies around the circular systems [10]. Afterwards, the effects of both sustainable practices and digital technologies on CSC are also verified against the business performance to estimate the amplitude of the direct and the indirect benefits that these three strategic drivers offer to the firms' business economic sustainability. Finally, we test whether these relationships could be improved by focusing on some specific digital technologies and, consequently, appreciating their sole effects. To estimate all these effects, we test several research hypotheses using structural equation modeling and multi-group analysis. All developed models are tested by using a sample of 157 firms and dividing them into groups to run the multi-group analysis.

Our findings reveal that both the sustainable practices and the digital technologies help firms in achieving high capacity to implement and manage CSCs. However, the adoption of an ad hoc portfolio of sustainable practices turns out to be more effective than the implementation of digital technologies. Therefore, firms should first focus on supporting the CSC systems through sustainable practices and then through digital technologies. This result is corroborated by the indirect effect on business performance, for which sustainable practices offer a contribution, along with CSC. Hence, firms can improve their business performance by enhancing the CSC as well as by exploiting the benefits of sustainable practices. Furthermore, the direct effects that we estimated can be boosted when firms implement ad hoc digital technologies; specifically, we demonstrate that the adoption of some technologies can activate some positive effects by digitalization on CSC and business performance, informing on the directions that firms should undertake when allocating their budgets as well as on how to adjust their estimations.

Our research provides some new insights in the field, as it offers two additional strategic keys to boost the impact of CSC on performance. While this relationship has been investigated by other research works (e.g., [11,12]), none of them verifies the links between both the sustainable practices and the technologies, which are—de facto—two important antecedents for pursuing CSC. Furthermore, we extrapolate more insights from these relationships by testing both direct (short term) effects as well as the indirect (long term) effects of the antecedents on performance through CSC. Finally, we also verify whether the adoption of some specific digital technologies helps in increasing the value of some relationships, resulting in being extremely useful in deriving managerial insights and prescriptions on how companies can increase the functionality of CSC.

This paper is organized as follows. Section 2 introduces the literature review on the topics and helps to develop the research questions. Section 3 provides the details on the methodology, while Section 4 reports the findings. Section 5 displays the managerial implication, while Section 6 concludes.

2. Literature Review

In this section, the relevant literature is reviewed to clarify the research gap and devise hypotheses.

2.1. Sustainable Practices

When it comes to how the sustainability and greenness of a supply chain should be measured, different components should be considered. Being environmentally sustainable requires a company to be cautious about waste and pollution, which must be minimized [7]. CE implementation requires huge investments and cultural/organizational changes and offers economic benefits that are not always easily predictable and quantifiable. Therefore, there is a need for a clear company vision, shared between company owners and top management [13]. Thanks to the increasing awareness concerning ecological and social matters, companies are on the verge of finding effective and urgent alternative solutions, not only inside their specific organizations, but also across their entire logistic networks. At the same time, firms require a comprehensive analysis of the logistic networks that are composed of transport, geopolitical, regulatory, internal, and informational barriers [14]. Considering the guidelines elaborated by the Ellen MacArthur Foundation, it has become clear that in order to implement a CSC, firms should focus on three main targets.

The first aspect pertains to the rethinking of product design, given that it is essential in maximizing both its lifespan and its potential utilization. The aim is to increase the value extracted from items received from international networks before they are discarded. A real-life application of this wise approach may be seen in the fashion industry with the Service Shirt example, brilliantly described by [15]. With this new garment concept, it has been demonstrated that a simple shirt can be developed and adapted through a long sequence of redesign exchanges among the original purchasers and their friends. In fact, the Eco-Design or Design for the Environment is a kind of layout that focuses on minimizing the ecological impact of an article during its entire life cycle. It is indeed a design concept that is gaining increasing attention, especially in the packaging sector, due to the constant interest in strong, hygienic, and respectful solutions. Thanks to Eco-Design, businesses have begun to replace the usage of petrochemicals with mineral fillers and recycled materials, maintaining the same technical feasibility while reducing production expenditures.

The second perspective in deciding to create a CSC is the establishment of a reverse network. Planning this method along the entire production line renders it feasible to exploit many benefits through the recycling and upcycling of any product. The reuse, maintenance, refurbishment, and remanufacturing of products become salient elements in improving reverse capabilities, where the environmental efficiency can be achieved through a controlled return cycle [16]. They asserted that companies will even maximize their competitive advantage if they decide to address product returns through purposeful partnerships. Therefore, choosing the appropriate supplier and organizing international networks take on significant weight when circular policies must be put into place. Additionally, Ref. [17] stressed the importance of wisely screening potential suppliers by evaluating several variables, such as quality, design competency, process capability, preventive maintenance, flow distance, space, operator training, labor flexibility, and innovation of products and processes.

The third sustainable aspect is the creation of a complete pioneering business model that attentively adheres to the shift from a conventional linear system to a circular system. In recent years, alternative business structures and ad hoc strategies (such as sharing platforms and product-as-a-service (PaaS)) have enriched the extant literature.

The sharing platform is a typical business model that links product owners with potential final users. This kind of arrangement permits individuals and organizations to use an item without owning it. The integration of the sharing principle into a supply chain may create very useful commercial synergies, given that companies can collaborate by sharing human resources or physical assets to satisfy customers' needs in a timely fashion. An instructive example of this principle, practically applied, is represented by the partnership between Nestlé and Pepsi. Although they are strong competitors in the food market, they have decided to combine elements of their supply chains to produce and sell fresh and chilled products in Belgium. They have coordinated warehousing, packaging, and deliveries to fill their trucks. The outcome was a 44% reduction in transportation costs, a 55% reduction in gas emissions, and an overall greater level of customer satisfaction.

Product-as-a-service, also referred to as a product–service system, occurs when manufacturers sell products in combination with services. Goods are often sold via subscription, with pertinent options attached, such as repair or replacement contracts. This business model has been created not only to maximize the financial performance of products, but also to minimize the ecological sway of consumerism by planning precise material cycles and augmenting alternative possibilities for usage.

From the perspective of literature review, a consistent gap has emerged surrounding the identification of an extensive portfolio of practices that businesses can embrace to implement a circular economy (CE). In fact, the previous three perspectives can all be taken into consideration to build up a comprehensive portfolio of sustainable practices to support the CSC. The question that remains to be answered consists of the identification of which practices should be included in such a portfolio, knowing that the list emerging from the previous three perspectives can be extremely wide and heterogeneous. Beyond identifying such a portfolio, this research seeks to address the impact that it has on the creation of CSC systems, which will be tested by investigating the following hypothesis:

Hypothesis 1. *The adoption of an ad hoc portfolio of sustainable practices has a positive impact on the creation and management of CSC.*

2.2. Digital Technologies

The way we interact with the physical world around us is rapidly changing through advances in technology. Companies need to use the new technologies to support the achievement of economic, environmental, and social targets that are important to sustainable development and CE implementation [18]. CSC requires the application of digital technologies to successfully pursue its goals, especially when managing reverse flows linked to international frameworks. Digitalization constitutes an effective game-changing factor. In fact, as empirically proved by [19], digital protocols can ensure environmental, social, and economic benefits. Indeed, the circular approach strongly links with technology, especially when goods and their components are accurately designed to be reused and lessen waste. According to the proposed theoretical framework, modern CE systems include both hard and soft ingredients, which are clearly connected and influence each other [20]. A study by [21] has clearly identified various types of technologies and their potential application in a CSC.

The role of digital technologies is essential in obtaining information on the real value of returns. Through Industry 4.0 technologies, products communicate with consumers and send signals to firms regarding their performance, their usability, and their deterioration [22]. Certainly, one of the most relevant technologies is blockchain, because it ensures transparency and reliability. Moreover, it allows consumers to determine if sustainable production and transportation processes were used and even allows consumers to meticulously track, moment by moment, the geographical position of each article, maximizing reverse logistic operations. Finally, this advanced protocol can create real digital chains, assuming correct cooperation with other tokens and technologies [23].

Technology becomes highly effective when it complements the existing technologies used to manage the entire logistic system and integrates omnichannel solutions [24,25]. The adoption of blockchain technologies, combined with 4.0 logic, can improve the performance of different industries and sectors in terms of a circular economy [26,27]. The integration of blockchain with radio frequency identification (RFID) may be used to pinpoint material streams and strengthen a possible recovery policy, given the electromagnetic tags that identify and monitor every product [21]. Hence, RFID is another noticeable, emerging data-safety technology given its specific sensors and actuators. Logistic management very often exploits the associated benefits, such as cost cuts, process optimization, and enhanced service quality [28]. RFID represents advancements included in the internet of things (IoT) category, along with, for instance, quick response (QR) codes.

The IoT constitutes another relevant technology, especially if it is inserted into the reverse logistic management to enhance process-oriented performance while diminishing energy absorption [29]. IoT are electronic devices that are able to communicate with each other and direct the actions of objects or machines connected to a unique network. IoT apparatuses are particularly useful to supply chains because they can collect data and send information to diverse stakeholders and suppliers along the same value conglomerate [30]. In fact, operators may visualize possible hindrances and monitor indefinite queues or delays with real-time adherence [31].

In a study by [32], IoT protocol was applied to the scrap metal industry. The results reveal that IoT solutions improve the competitive advantage of both waste producers and waste management firms, while minimizing energy resources and CO_2 emissions.

Inventory management has always been a concern for small and large firms alike, and these firms always strive to find a solution or an ordering model that can minimize the total warehousing and inventory costs [33,34]. The research of Varriale et al. [35] construed two alternative scenarios: the first observed is the conventional scenario, without any employment of digital technologies; the second scenario described is a framework that simultaneously incorporates the use of blockchain, IoT, and RFID. A five-year simulation is offered, with the incidence of disruptive events included in both scenarios. Having focused on the second scenario, it is evident that the IoT infrastructure was successfully able to connect the brick-and-mortar warehouse with the virtual one in real time, that the inventory was managed second by second, and that when a disruptive event occurred, products were instantly withdrawn, reducing ineffectiveness by 3.2%. Additionally, using blockchain and smart contracts, operational efficiency was finally assured.

One additional, useful modern tool for the sake of this study is machine learning (ML). It utilizes programmed algorithms that can receive and examine input data to predict appropriate output data within a defined range. In this way, a machine truly learns from data rather than instructions set by a technician. Together with artificial intelligence (AI), it is feasible to evaluate large amounts of data, permitting organizations to quickly respond to unforeseen circumstances [36]. The introduction of AI into a CSC can support the design, monitoring, and daily management of the supply network and help in forming solid relationships with green partners to advance complete logistical effectiveness [37].

As suggested by that latter research, the combination of AI and ML in a CSC provides numerous benefits, such as the following:

- Speedy and cheap international shipping.
- Construction of autonomous vehicles to achieve better freight programming.
- More sustainable and green transport solutions that could reduce global pollution.
- Lower number of products discarded.
- Aggrandizement of the reverse logistic system.

An enlightening example of the use of AI in transnational businesses is Pirelli, one of the leading tire manufacturers, which employs RFID, sensors, actuators, and AI models to track the location of wheels and calculate the exact number of new items to be produced. Through a tailored-made fabrication, Pirelli decreases toxic emissions into the atmosphere and associated waste materials.

One enhancement solution that companies can practice is the optimization of container loading plans [38]. The efficiency of the transport service could be exponentially improved thanks to correctly scheduled loads, with the aim of minimizing environmental impact and diminishing the waiting times of drivers during pick-up and delivery stages. Following this reasoning, it is also advisable to combine orders from different customers arising from diverse locations but sharing partial routes of transport [39].

From the literature review, there clearly emerges a gap in the descriptions of various potential technologies that firms can implement in the creation of a CSC. In fact, most of the previous research tested the outcome of new advancements in a unique sector that is typically the manufacturing sector. Instead, this work seeks to identify the specific effect of technologies on supply chains operating in heterogeneous domains. Thus, with the objective of identifying a portfolio of useful tools for CSC, we propose the following hypothesis:

Hypothesis 2. *The adoption of an ad hoc selection of digital technologies has a positive impact on the creation and management of CSC.*

2.3. Firm Performance

The setup of a CSC, thanks to sustainable practices and digital technologies, also has consequences on corporate performance.

In general, firms' results are tested for efficiency, profitability, and financial ratios, but recently, the extant literature has also begun to analyze the impact of specific social and environmentally friendly protocols [40]. Organizations can measure sustainability performance, observing the economic, social, and environmental dimensions.

From an economic point of view, sustainable arrangements should be related to costs, investments, and profit control. For instance, if we apply this approach to cost monitoring in the manufacturing industry, it entails critically cutting unnecessary procurement expenditures and energy and water consumption.

Focusing on the social domain, the indicators associated with social sustainability pertain to good working conditions, societal commitment, customer satisfaction, turnover rate, inclusiveness, and diversity.

The last criterion is the ecological performance of companies. Practically, this means ensuring the reduction of noxious emissions, waste materials, and toxic chemicals used in production, as well as the wise recovery of used goods. It is reasonable to assert that if organizations do not embrace environmental solutions, they will not be able to enjoy the long-term benefits [41].

Analyzing the study by [42], the maintenance of a CSC may have both negative and positive outcomes. In the short term, the improvement of a CSC increases costs (due to huge initial investments related to the purchase of novel machinery or process modifications), while in the long term, savings originating from the use of recycled or reused materials, less waste, and lower energy consumption are certain.

On the other hand, [43] claimed that despite lower production burdens, CSC is related to poor corporate financial performance. Nevertheless, from a managerial point of view, it is worthwhile to stress the operational and cost-based improvements potentially attainable. Moreover, the CSC creates numerous additional revenue flows if purposefully managed. The first concrete example is given by the product-as-a-service business model. In this case, as previously explained, customers do not own the product but, rather, rent it for a certain period. The applicable contract then generates a long-term relationship between the client and the supplier, permitting durable revenue streams and the product's lifetime extension. Such a long-term deal also represents an opportunity for companies to experiment with their products and collect meaningful statistical data.

To assess the relationship between environmental and corporate financial performance, extant studies suggest specific indicators, which are broken down into two categories: accounting-based indicators and market-based indicators. The accounting-based indicators (such as ROE and ROA) stress the past- and short-term financial results that reveal internal decision-making appropriateness and the correct plan of resource allocation [44]. The market-based indicators are more closely related to future and long-term financial outcomes. The positive aspects of these business indicators are as follows: (1) they represent an external and objective perspective and are therefore less vulnerable to company manipulation, and (2) they embrace the expectations of investors regarding corporate profitability. Some examples are Tobin's Q and share prices [45].

In evaluating the extant literature, it is essential to affirm that there is no scientific research which investigates the performance consequences caused by the implementation of a CSC in a firm. The goal of this work is to purposefully analyze the effects on business performance (especially on financial ratios) following the establishment of a CSC. Hence, the following hypothesis is offered:

Hypothesis 3. *The adoption of a CSC has a positive influence on firm performance.*

Figure 1 summarizes the conceptual model, including both the direct relationships between the sustainable practices (H_1) and the technologies to CSC (H_2,), respectively, as well as the direct and the indirect impacts on firms' performance by CSC (H_3) as well as by sustainable practice (H_{3S}) and technologies (H_{3T}). Furthermore, we verify the effect that digital technologies have on the aforementioned relationships by analyzing whether a certain relationship can be improved by implementing specific digital technologies. Therefore, we explore the impact offered by internet-of-things (IoT), transportation management systems (TMS), machine learning, robotics, and 3D printing in enhancing the value of relationships. Therefore, we use the label "a" to signify that we test whether certain technologies improve some of the established relationships. For example, H_{1a} signifies that we test whether the adoption of IoT, TMS, machine learning, robotics, and 3D printing boosts the effect that sustainable practices have on CSC.

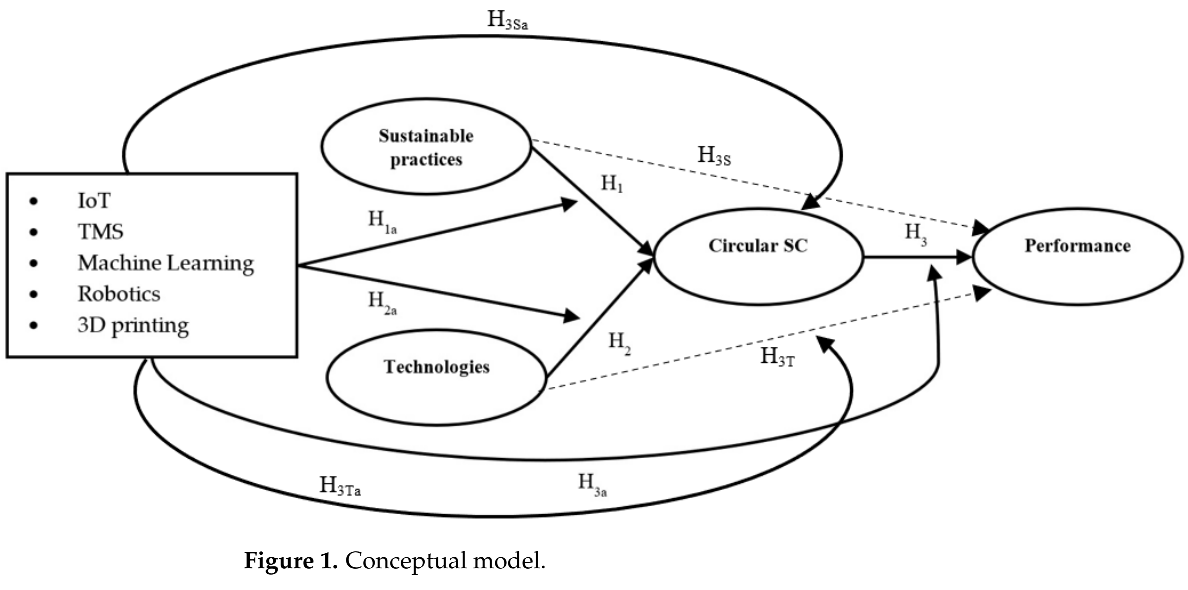

Figure 1. Conceptual model.

3. Methodology

To test our hypotheses, we designed a survey to collect information about the respondents concerning industry, company size, investments in blockchain, marketing strategies, logistic processes, and commercial performance. We then pre-tested the questionnaire conceived with a pool of experts (professors, students, professionals, and managers). We asked for feedback about wording, readability, and completeness. Finally, the survey was modified and improved accordingly.

The data-collection stage began by administering the survey to an initial sample of 120 firm managers. Obviously, for the purpose of our study, we decided to interview active experts in supply chain management. They were reached via email. Within two weeks, we received most of the responses. Meanwhile, the investigation was extended by contacting them via telephone. A total of 157 usable observations were obtained, excluding those excluded as invalid. This result represented about 12% of the entire company population we targeted (1200). The sample primarily represented large enterprises, both in terms of sales and number of employees. More than half of the organizations had an average sales turnover of more than 100 million (52%) and a workforce of more than 200 employees (53%). The data originated from European and American businesses, at 73% and 16%, respectively. Most of the interviewees were supply chain managers (52%), working primarily for manufacturers (36%) and retailers (23%). The results revealed a heterogeneous industrial panorama, with the food and beverage (22%) and the fashion (12%) sectors predominating. A more detailed representation of the distribution of interviewees and the exact composition of the sample is illustrated in Table 1. Several approaches were used to assess the non-response bias. The first approach consisted of comparing early and late respondents. A one-way analysis of variance (ANOVA) found no significant differences between the early and late answers for all items involved. Those findings supported the conclusion that non-response bias was not a significant concern. Moreover, we checked for non-response bias when evaluating the demographic variable size, number of employees, and sales. Once again, no relevant differences were discovered between the groups. All items included in the survey were measured using a 7-point Likert scale that indicates the level of accordance with a certain question (where 1 is not at all in agreement and 7 means full agreement).

To pursue the objective of this investigation, we used a technique called partial least squares path modeling (PLS-PM) and XL-Stat 2021.2.1 software. PLS-PM is a component-based estimation algorithm that calculates the links among theories by assigning scores to their original measure [46]. PLS-PM does not require any distributional postulate for the data inserted (in contrast with a maximum probability covariance-based approach). Furthermore, PLS-PM results in less biased assessments than other methods for treating equation modeling samples with fewer than 200 observations, while attaining the same effectiveness with examples above 200 observations [44]. The features of PLS-PM provided above coherently explain the usage in several business domains, such as operations management [47], supply chain management [48], sustainable supply chains [46], and closed-loop systems [49].

The first stage in our research was to identify the latent variables that are dimensions not directly observed but, rather, inferred from other variables that are instead directly measured. The latter are called manifest variables, and in our case, they were constituted by the possible choices in the survey. Conversely, the latent variables in this study were sustainable practices, technologies, circular supply chains, and performance. The final items list permits the detection of the cross-loadings associated with each construct, as displayed in Table 2, in which the bold values identify the items corresponding to the related construct.

The first relevant factors to evaluate are the composite reliability indexes, which entail an objective assessment of how much an ensemble of elements can be grouped together in the same category. In fact, if a group of elements targets the measurement of a certain construct, then the scores are expected to be similar. We focused on Chronbach's alpha and the eigenvalue. A high Chronbach's alpha value (close to 1) indicates that there is substantial reliability within the dimensions observed: the more the alpha value increases, the more the probability of error decreases. We considered a Chronbach's alpha higher than 0.8 acceptable, and to obtain this result for all of the latent variables, the challenging dimensions were reduced. Hence, it was evident that CSC and performance have a borderline Cronbach's alpha, but it is very close to 0.8, and for this reason, they were accepted. The eigenvalue indicates how many measurements of a definite concept are available. Each value that is higher than 1 represents a trustworthy dimension. As highlighted in Table 3, all of our latent variables achieved one-dimensionality. Therefore, we proceeded with the entire structural model evaluation.

Table 1. Sample description.

Sales	#	%	Employees	#	%	Country	#	%	Company Type	#	%	Professionals	#	%	Industry	Frequency	%
<10	11	7.0%	<50	14	8.9%	Europe	115	73.2%	Manufacturer	56	35.7%	SC Manager	82	52.2%	Food and Beverage	34	21.7%
10–50	38	24.2%	50–99	40	25.5%	USA	25	15.9%	Wholesaler	30	19.1%	Logistics Manager	12	7.6%	Fashion and Apparel	18	11.5%
50–100	26	16.6%	100–200	20	12.7%	Asia	4	2.5%	Distributor	14	8.9%	Operations Manager	13	8.3%	Medical and Healthcare	12	7.6%
>100	82	52.2%	>200	83	52.9%	Other	13	8.3%	Supplier	21	13.4%	Sales Manager	3	1.9%	Automobile	11	7.0%
									Retailer	36	22.9%	Production Manager	9	5.7%	Mechanic	7	4.5%
												Purchasing Manager	2	1.3%	Energy	7	4.5%
												Procurement Manager	8	5.1%	Furniture	6	3.8%
												Distribution manager	2	1.3%	E-commerce	5	3.2%
												Other	26	16.6%	Aerospace	4	2.5%
															Sport	4	2.5%
															Entertainment	4	2.5%
															Glass	3	1.9%
															Cement	3	1.9%
															Telecommunications	2	1.3%
															Luxury	2	1.3%
															Beauty and Cosmetics	2	1.3%
															Electrical and electronics	2	1.3%
															Chemical	1	0.6%
															Other	30	19.1%
Total	157	1		157	1		157	1		157	1		157	1		157	1

Table 2. Summary of the cross-loadings.

	Sustainable Practices	Technology	Performance	Circular SC
Identification of green suppliers	**0.867**	0.434	0.409	0.505
Environmental restrictions	**0.877**	0.473	0.429	0.563
Raw materials origin and provenance	**0.831**	0.486	0.460	0.541
Artificial intelligence	0.370	**0.765**	0.316	0.369
IOT sensors	0.340	**0.681**	0.458	0.444
RFID	0.368	**0.615**	0.545	0.472
Route optimization system	0.410	**0.731**	0.304	0.342
TMS	0.368	**0.721**	0.327	0.386
Mobile device monitoring of delivery people	0.402	**0.690**	0.283	0.313
Machine learning	0.396	**0.697**	0.355	0.357
Market share	0.357	0.439	**0.780**	0.454
Profits	0.420	0.393	**0.792**	0.504
ROI	0.448	0.478	**0.833**	0.463
Cost savings	0.356	0.398	**0.733**	0.477
Management of reverse logistics flows	0.492	0.414	0.447	**0.678**
Use of recycling material	0.408	0.321	0.337	**0.558**
Integration of forward and reverse logistics flows	0.269	0.373	0.280	**0.649**
Optimization of the logistics network	0.504	0.415	0.474	**0.797**
Optimization of the logistics loads	0.429	0.400	0.483	**0.757**
Logistics risks and safety	0.471	0.405	0.455	**0.720**

Table 3. Composite reliability indexes.

Latent variable	Dimensions	Cronbach's Alpha	Eigenvalues
Sustainable practices	3	0.821	2.213
Technology	7	0.828	3.476
Circular SC	6	0.786	2.927
Performance	4	0.792	2.467

4. Analysis and Results

This section provides the empirical results of the hypotheses testing by considering the complete sample; hence, no group was considered in this regard, while all the constructs were considered reflective. According to [50], the use of reflective scales allows one to verify the firms' capability on a certain field. Hereby, we wish to detect the firms' capability to make CSC function, to be technologically ahead, to be green by investing in sustainable practices, as well as to obtain business outcomes. The general outcomes showed a relative goodness-of-fit index of 0.940. All outcomes are displayed in Table 4, in which we report the result as "supported" when a research hypothesis was empirically confirmed or "not supported" in the opposite case. H1 was confirmed, because we calculated a coefficient (representing the direct effect) of 0.457, with a p-value <0.01. This impact proved that the adoption of sustainable practices positively influences the setup of a CSC. In particular, the ensemble of respective processes described in the first hypothesis were as follows:

- Correct identification of green suppliers.
- Ad hoc environmental regulations.
- Attention to the origin and provenance of raw materials.

H2 is supported because the coefficient is 0.314 and the p-value < 0.01. This empirical result shows that also the adoption of digital technologies has a favorable impact on the development of a CSC, but to a lesser extent than the adoption of sustainable practices.

H3 is also supported, given that the coefficient is 0.606 with p-value < 0.01. Therefore, the creation of a CSC has a positive impact on corporate performance, especially if the following indexes are considered: market share, profits, ROI, and cost savings.

Table 4. Results of the research hypotheses.

Research Hypotheses	Coefficients	Results	R^2	F Statistics	f^2
H1: The adoption of an ad hoc portfolio of sustainable practices has a positive impact on the creation and management of CSC	0.457 [1]	Supported	0.294	64.573	0.079
H2: The adoption of an ad hoc portfolio of digital technologies has a positive impact on the creation and management of CSC	0.314 [1]	Supported	0.460	65.619	0.015
H3: The adoption of CSC has a positive effect on firm's performance	0.606 [1]	Supported	0.436	39.369	0.136

[1] *p*-value < 0.01.

Overall, our findings suggest that both the adoption of a portfolio of digital technologies as well as the implementation of portfolios of sustainable practices activate the CSC and, hence, are effective drivers to leverage the potential and increase the capacity of CSC systems. However, the effect of sustainable practice is higher than the effect of digitalization, suggesting that firms should focus primarily on sustainable practices to enable CSC. Furthermore, our findings demonstrate that CSC can activate high business performance suggesting that circular systems are effective drivers to increase business sustainability. When estimating the indirect effects, it emerges that sustainable practices have a significant indirect impact on the business performance (the coefficient is 0.277 with p-value < 0.05), while digitalization is not statistically significant (the indirect coefficient is 0.190 with p-value < 0.1). Therefore, sustainable practices also exert a positive effect on business performance, being then a valid driver to enhance both the environmental and the economic sustainability of companies.

To improve upon this research and its methodology, a multigroup analysis was chosen, particularly focused on the digital technologies previously described. The multigroup analysis allows us to verify if predefined data groups show substantial dissimilarities in their group-specific criteria evaluations, and if this also allows for the collection of information pertaining to indirect effects. The multigroup analysis compared two groups: 1 and 0. Group 1 represents the set of companies that adopt a specific technology, while group 0 illustrates firms that do not use the same technology. To deploy the assessment, the results of which are summarized in Table 5, we measured the difference between the two groups, and subsequently, through standard deviation, we calculated the *p*-value and the level of significance.

Table 5. Results of the multigroup analysis.

Technology- > CSC	Technology- > Performance	Sustainable Practices- > CSC	Sustainable Practices- > Performance	Technology- > Sustainable Practices	Technology- > CSC
IoT	0.014 [2]	0.039 [2]			
TMS	0.004 [1]		0.024 [2]	0.041 [2]	
Machine Learning	0.005 [1]	0.033 [2]			
Robotics	0.037 [2]	0.031 [2]			
3D printing					0.030 [2]

[1] *p*-value < 0.01; [2] *p*-value < 0.05.

4.1. Internet of Things (IoT)

The first technological advancement tested was IoT, and, by using the data collection from the survey, 81 firms were counted in group 0 and 76 firms were counted in group 1. The empirical investigation demonstrates that technology has a positive effect on CSC. Therefore, if an enhancement of this relationship is required, businesses can invest in IoT to obtain superior outcomes (p-value = 0.014). As argued in the first section of this work, IoT unlocks the potentialities of CSC. In fact, via the usage of sensors and actuators, electronic devices can monitor and support the logistic system of products. It is also important to stress the indirect effect of the identified protocol on performance, given that the development of an IoT network has a strong impact (*p*-value = 0.039) on this variable. Thus, it is possible to conclude that IoT strongly leads to improvements, not only in the environmental aspect of supply chain, but also in its financial administration. Those benefits derive from an overall betterment of operational management (a benefit generally brought about by all of the technologies examined herein), but with IoT, firms gain real-time information from each operating unit concerning inventory, material flows, and customer demand. Following this approach, it is achievable to establish a more productive system that is able to better address clients' needs (and adjust production accordingly) and, at the same time, diminish waste, pollution, and resources employed.

4.2. Transportation Management System (TMS)

The results of the survey reveal that TMS was adopted by 88 companies, while 69 were not interested in this technology. TMS is one of the highest-performing technologies among those analyzed. It is a logistic platform that applies several protocols to a supply chain, with the objective of optimizing physical streams of products. It also strengthens the power of sustainable practices thanks to a controlled shipment, and without the typical issues related to transport, such as pollution and poor route scheduling. Moreover, it boosts warehouse efficiency and the degree of productivity; incoming and outgoing goods are constantly tracked, even in sectors where depositories are usually filled with products that tend to quickly deteriorate. In this way, assets are protected, and financial losses are wisely avoided. The meaningful performance enhancement is demonstrated in the analysis, with a *p*-value of 0.041.

4.3. Machine Learning (ML) and Robotics

The multigroup assessment, applied to ML and robotics, demonstrated similar influences. Both technologies lead to a positive impact on CSC, which means that their application in businesses depends on their ability to improve quality, find unusual solutions, and reduce operating costs. Notably, ML can anticipate the uncertain effects of various processes and detect flaws in circular systems, whereas robotics can facilitate the exchange of goods and carry out concurrent checks during subsequent stages of the production process.

4.4. 3D Printing

Three-dimensional printing is the only machinery studied that showed a substantial indirect outcome on sustainable practices, with a *p*-value of 0.30. Undoubtedly, 3D printers cut waste materials. In effect, with their usage, it is possible to take advantage of a close-to-demand arrangement, which reduces ordering and delivery times and lowers inventory costs.

5. Discussion and Managerial Insights

When considering the entire sample (Analysis 1), our findings indicate that the adoption of a portfolio of specific sustainable practices and technologies has a positive influence on the setup of a CSC. As explained above, the estimation found three protocols that usually promote CSC: correct identification of green suppliers, ad hoc environmental regulations, and significant attention to the origin and provenance of raw materials. As [51] affirmed, a central element of CSC is the prudent choice of suppliers since pollution depends on the production phases, and also on the logistic assemblage of final goods and their successive delivery to clients. In this matter, choosing a green operator diminishes environmental damage and fosters a more ecological logistic system, from procurement to final product sales. Furthermore, an essential feature of ensuring circularity is the attentive selection of raw resources through the criteria of durability and restoring possibility.

Finally, when public authorities potentiate ecofriendly collaborations through appropriate incentives, respectful manufacturing processes are strongly facilitated [2]. Undoubtedly, from a managerial point of view, the sustainable practices described in this study are not the only actions available to ensure the creation of a CSC; they reflect only the possibility for companies to create a new and fruitful business model. Other alternative options may be adopted according to companies' actual needs and problems. Green suppliers and raw materials selection may represent a starting point for subsequent actions that better fit the organization involved. By examining the results of Analysis 2, we identified the technologies capable of amplifying the benefits claimed by Analysis 1. The critical appraisal of indirect effects in turn made it clearly understandable as to which technologies simultaneously optimize corporate performance and sustainable practices.

From the combining of the two assessments, it emerged that the most effective technological development is TMS. In fact, TMS can achieve efficiency in logistics and international transport because it combines several novel enhancements. To reinforce this notion, our study found that TMS had effects on all three latent variables. We learned that TMS platforms, thanks to IoT networks, simultaneously ensure logistic improvements by removing queues and obstacles and support environment compliance by providing options for CO_2 reduction. To maximize their achievements, companies could combine TMS with other tools, such as ML and 3D printers. As illustrated in Table 5, those two latter developments act by strengthening the outcomes on CSC, business performance, and sustainable practices, because on the one hand, through ML, companies can train systems to take positive and green decisions, while on the other hand, 3D printers are able to extend the life cycle of products.

For the resolution of this study, it is fundamental to observe that both of the analyses conducted converge in one result: the adoption of CSC has a positive effect on companies' economic results. This appears to be in opposition to [43], which found that CSC is linked to poor financial achievements. This study's findings are notably evident in Table 5, whereby all of the technologies described, albeit indirectly, cause a substantial boost in business results, without overlooking the usual benefits originating from CSC on the last variable, as emerged from analysis 1. In our study, the following ratios were taken as economic indicators: market share, profits, ROI, and cost savings. They are the most used indexes in daily business management to measure company growth and the quality of investments. It has been elucidated that the indexes mentioned frequently do not yield considerable enrichments in the short run [42] due to high expenditures, although in subsequent stages, those indicators reveal progressive evolutions thanks to circularity, which is practically inserted into the business model.

6. Conclusions

This paper investigates how CSC functionality can be improved by adopting the portfolios of two main drivers, which are given by sustainable practices and digital technologies. The companies that implement sustainable practices acquire an important capacity to be sustainable from a social, an environmental, and an economic perspective, increasing the overall capacity to implement CSC systems in a responsible way. In fact, the capacity to be sustainable represents a considerable antecedent to create a CSC system. At the same time, the digital technologies play an important role in defining the connections between the companies and the related ecosystem, especially when organizing the logistics in an international framework; using digital technologies, the companies are able to gain high value of information and use them to improve their overall decision-making process at all levels of the companies and at all tiers of global supply chains. Therefore, the capacity to implement a CSC system increases thanks to the enabling technologies. When CSC systems are supported by sustainable practices and digital technologies, their capacity to be circular enables higher business performance, which contributes to making the overall business model economically sustainable. Inspired by this framework, we explore the impact that both sustainable practices and technologies have on increasing the CSC functionality, which impacts on the firms' performance. Afterwards, we verify whether such relationships can be improved when digital technologies are surely adopted by firms. We tested several hypotheses to verify the empirical association between sustainable practices and digital technologies with circular systems, along with the impact on business performance. At the same time, we analyzed if companies should focus on the same digital technologies with more details in order to improve the business performance even more.

Our empirical results show that both sustainable practices and digital technologies help companies in implementing circular supply chain systems; therefore, both of them represent effective drivers to pursue such types of circular systems. However, our empirical analysis demonstrates that sustainable practices are more effective than portfolios of digital technologies in enabling CSC systems. Therefore, companies should concentrate first on the creation of ad hoc portfolios of sustainable practices when aiming at implementing circular supply chain systems and then looking at digital technologies as a second investment opportunity. The creation of good circular economy systems allows companies to increase the business performance, leading to the results that the CSC system is sustainable not only from an environmental point of view, but also from an economic perspective. Furthermore, we discover that the sustainable practices have also an indirect and positive effect on their business performance, reinforcing the idea that the implementation of green practices can lead to improved economic results in the medium and long run.

Afterward, we complemented our empirical analysis with a deep analysis on the digital technologies to verify which of the technologies included in the portfolio gives a better contribution to the creation of circular economy systems and to the business performance. Our results show that companies can improve the impact that technologies have on performance as well as the links existing between sustainable practices and circular supply chain systems by implementing IoT, machine learning, and robotics. Similarly, transportation management systems, which optimize the international logistics networks, allow firms to improve the business performance with digitalization and sustainable practices while also reinforcing the links between technology and sustainable practices. Finally, 3D printing has a positive effect on the relationship between digital technologies and circular supply chain systems. These results help managers and practitioners to better drive their decisions and the allocation of their budget through investments in digital technologies, sustainable practices, and CSC systems.

This study has limitations that could be employed in subsequent avenues of research. For instance, only a small number of ecological practices and technologies were explored. This means that additional elements with an impact on the three latent variables could be identified in future research. For example, this research does not consider the digital supply chain twin technology to assess CSC. This technology is a digital representation of the physical supply chain relationships and flows, which allows supply chain managers to mimic the supply chain network and evaluate the operational and economic feasibility [52]. During the initial pre-testing of the questionnaire, digital supply chain twin emerged as not being currently used by experts; we imagine that this technology can be helpful in the future for better analyzing CSC. Finally, in forthcoming investigations, it may be useful to emphasize the opportunity for generous incentives, with the aim of encouraging the insertion of circularity within firms, as well as the possibility of exploiting the last mile concept to minimize the movement of goods and pursuing economic, environmental, and social outcomes. Moreover, disruptive events, such as the COVID-19 pandemic and the Russia–Ukraine war, could be taken into consideration to evaluate further challenges in the creation of CSC systems.

Author Contributions: Conceptualization, S.R.; methodology, P.D.G.; software, P.D.G.; validation, P.D.G. and B.M.V.; formal analysis, P.D.G. and B.M.V.; investigation, P.D.G. and B.M.V.; resources, P.D.G.; data curation, P.D.G. and B.M.V.; writing—original draft preparation, S.R.; writing—review and editing, C.T.; visualization, C.T.; supervision, P.D.G. and B.M.V.; project administration, P.D.G. and B.M.V.; funding acquisition, P.D.G. All authors have read and agreed to the published version of the manuscript.

Funding: This contribution is a part of a project that has received funding from the Lazio region ESF operational program 2014–2020, Axis III- Education and Training, Investment Priority 10.ii)—Specific Objective 10.5, Pivotal Action 21—Call for proposals "Contributi per la permanenza nel mondo accademico delle eccellenze"—Project Title: "Implementazione di progetti di digitalizzazione responsabile nelle supply chain"—CUP (Unified Project Code): F86J20002710009.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No data availability.

Acknowledgments: We would like to thank the three anonymous Reviewers for the wonderful feedback we received from them during the review process.

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

References

1. Batista, L.; Bourlakis, M.; Smart, P.; Maull, R. Business models in the circular economy and the enabling role of supply chains. In Proceedings of the 23rd European Operations Management Association (EurOMA) Conference, Trondheim, Norway, 17–22 June 2016.
2. Seuring, S.; Müller, M. From a literature review to a conceptual framework for sustainable supply chain management. *J. Clean. Prod.* **2008**, *16*, 1699–1710. [CrossRef]
3. Luthra, S.; Sharma, M.; Kumar, A.; Joshi, S.; Collins, E.; Mangla, S. Overcoming barriers to cross-sector collaboration in circular supply chain management: A multi-method approach. *Transp. Res. Part E Logist. Transp. Rev.* **2022**, *157*, 102582. [CrossRef]
4. Farooque, M.; Zhang, A.; Thürer, M.; Qu, T.; Huisingh, D. Circular supply chain management: A definition and structured literature review. *J. Clean. Prod.* **2019**, *228*, 882–900. [CrossRef]
5. Zwiers, J.; Jaeger-Erben, M.; Hofmann, F. Circular literacy. A knowledge-based approach to the circular economy. *Cult. Organ.* **2020**, *26*, 121–141. [CrossRef]
6. Kazancoglu, I.; Kazancoglu, Y.; Kahraman, A.; Yarimoglu, E.; Soni, G. Investigating barriers to circular supply chain in the textile industry from Stakeholders' perspective. *Int. J. Logist. Res. Appl.* **2022**, *25*, 521–548. [CrossRef]
7. Maranesi, C.; De Giovanni, P. Modern Circular Economy: Corporate Strategy, Supply Chain, and Industrial Symbiosis. *Sustainability* **2020**, *12*, 9383. [CrossRef]
8. de Lima, F.A.; Seuring, S.; Sauer, P.C. A systematic literature review exploring uncertainty management and sustainability outcomes in circular supply chains. *Int. J. Prod. Res.* **2022**, *60*, 6013–6046. [CrossRef]
9. Nitsche, B.; Durach, C.F. Much Discussed, Little Conceptualized: Supply Chain Volatility. *Int. J. Phys. Distrib. Logist. Manag.* **2018**, *48*, 866–886. [CrossRef]
10. Khan, S.A.R.; Zia-Ul-Haq, H.M.; Umar, M.; Yu, Z. Digital technology and circular economy practices: An strategy to improve organizational performance. *Bus. Strat. Dev.* **2021**, *4*, 482–490. [CrossRef]
11. Savita, K.S.; Dominic, P.D.D.; Ramayah, T. The drivers, practices and outcomes of green supply chain management: Insights from ISO14001 manufacturing firms in Malaysia. *Int. J. Inf. Syst. Supply Chain. Manag.* **2016**, *9*, 35–60. [CrossRef]
12. De Giovanni, P.; Folgiero, P. *Strategies for the Circular Economy: Circular District and Networks*; Routledge-Giappichelli Studies in Business and Management: New York, NY, USA, 2022; pp. 1–160.
13. Gotschol, A.; De Giovanni, P.; Vinzi, V.E. Is environmental management an economically sustainable business? *J. Environ. Manag.* **2014**, *144*, 73–82. [CrossRef] [PubMed]
14. Nitsche, B. Decrypting the Belt and Road Initiative: Barriers and Development Paths for Global Logistics Networks. *Sustainability* **2020**, *12*, 9110. [CrossRef]
15. Foss, N.J.; Minbaeva, D.B.; Pedersen, T.; Reinholt, M. Encouraging knowledge sharing among employees: How job design matters. *Hum. Resour. Manag.* **2009**, *48*, 871–893. [CrossRef]
16. Fernando, Y.; Shaharudin, M.S.; Abideen, A.Z. Circular economy-based reverse logistics: Dynamic interplay between sustainable resource commitment and financial performance. *Eur. J. Manag. Bus. Econ.* **2022**. [CrossRef]
17. Talluri, S.; Sarkis, J. A model for performance monitoring of suppliers. *Int. J. Prod. Res.* **2022**, *40*, 4257–4269. [CrossRef]
18. Vishkaei, B.M. Metaverse: A New Platform for Circular Smart Cities. In *Cases on Circular Economy in Practice*; IGI Global: Hershey, PA, USA, 2022; pp. 51–69.
19. Wu, K.-J.; Liao, C.-J.; Tseng, M.-L.; Lim, M.K.; Hu, J.; Tan, K. Toward sustainability: Using big data to explore the decisive attributes of supply chain risks and uncertainties. *J. Clean. Prod.* **2017**, *142*, 663–676. [CrossRef]
20. De Giovanni, P. Leveraging the circular economy with a closed-loop supply chain and a reverse omnichannel using blockchain technology and incentives. *Int. J. Oper. Prod. Manag.* **2022**, *42*, 959–994. [CrossRef]
21. Pagoropoulos, A.; Pigosso, D.C.; McAloone, T.C. The Emergent Role of Digital Technologies in the Circular Economy: A Review. *Procedia CIRP* **2017**, *64*, 19–24. [CrossRef]

22. De Giovanni, P. A feature fatigue supply chain game with cooperative programs and ad-hoc facilitators. *Int. J. Prod. Res.* **2019**, *57*, 4166–4186. [CrossRef]
23. Ruzza, D.; Bernasconi, G.; De Giovanni, P. *Blockchain Technology Applications in Businesses and Organizations*; IGI Global: Hershey, PA, USA, 2022; pp. 1–18.
24. Naclerio, A.G.; De Giovanni, P. Blockchain, logistics and omnichannel for last mile and performance. *Int. J. Logist. Manag.* **2022**, *33*, 663–686. [CrossRef]
25. Sammarco, G.; Ruzza, D.; Vishkaei, B.M.; De Giovanni, P. The Impact of Digital Technologies on Company Restoration Time Following the COVID-19 Pandemic. *Sustainability* **2022**, *14*, 15266. [CrossRef]
26. Arangiaro, V.; Vishkaei, B.M.; De Giovanni, P. Blockchain for Circular Economy in the Furniture Sector: The Case of Cubo Design Srl. In *Cases on Circular Economy in Practice*; IGI Global: Hershey, PA, USA, 2022; pp. 238–275.
27. Prencipe, M.P.; Vishkaei, B.M.; De Giovanni, P. Blockchain Adoption in the Winery Industry: The Case of Cantina Placido-Volpone. In *Blockchain Technology Applications in Businesses and Organizations*; IGI Global: Hershey, PA, USA, 2022; pp. 43–72.
28. Chanchaichujit, J.; Balasubramanian, S.; Charmaine, N.S.M. A systematic literature review on the benefit-drivers of RFID implementation in supply chains and its impact on organizational competitive advantage. *Cogent Bus. Manag.* **2020**, *7*, 1818408. [CrossRef]
29. Garrido-Hidalgo, C.; Ramirez, F.J.; Olivares, T.; Roda-Sanchez, L. The adoption of internet of things in a circular supply chain framework for the recovery of WEEE: The case of lithium-ion electric vehicle battery packs. *Waste Manag.* **2020**, *103*, 32–44. [CrossRef] [PubMed]
30. Xu, X.; Wu, X.; Guo, W. Applications of IoT to reverse supply chain. In Proceedings of the 7th International Conference on Wireless Communications, Networking and Mobile Computing, Wuhan, China, 23–25 September 2011.
31. Abideen, A.Z.; Mohamad, F.B.; Fernando, Y. Lean simulations in production and operations management—A systematic literature review and bibliometric analysis. *J. Model. Manag.* **2020**, *16*, 623–650. [CrossRef]
32. Mastos, T.D.; Nizamis, A.; Vafeiadis, T.; Alexopoulos, N.; Ntinas, C.; Gkortzis, D.; Papadopoulos, A.; Ioannidis, D.; Tzovaras, D. Industry 4.0 sustainable supply chains: An application of an IoT enabled scrap metal management solution. *J. Clean. Prod.* **2020**, *269*, 122377. [CrossRef]
33. Farhangi, M.; Niaki, S.T.A.; Maleki Vishkaei, B. Closed-form equations for optimal lot sizing in deterministic EOQ models with exchangeable imperfect ACquality items. *Sci. Iran.* **2015**, *22*, 2621–2633.
34. Maleki Vishkaei, B.; Pasandideh, S.H.R.; Farhangi, M. The% 1 100 screening Economic Order Quantity model under shortage and delay in payment. *Sci. Iran.* **2014**, *21*, 2429–2435.
35. Varriale, V.; Cammarano, A.; Michelino, F.; Caputo, M. Sustainable Supply Chains with Blockchain, IoT and RFID: A Simulation on Order Management. *Sustainability* **2021**, *13*, 6372. [CrossRef]
36. Wojtusiak, J.; Warden, T.; Herzog, O. Machine learning in agent-based stochastic simulation: Inferential theory and evaluation in transportation logistics. *Comput. Math. Appl.* **2012**, *64*, 3658–3665. [CrossRef]
37. Lacy, P.; Rutqvist, J. The Sharing Platform Business Model: Sweating Idle Assets. In *Waste to Wealth*; Palgrave Macmillan: London, UK, 2015; pp. 84–98. [CrossRef]
38. Alharbi, A.; Wang, S.; Davy, P. Schedule design for sustainable container supply chain networks with port time windows. *Adv. Eng. Inform.* **2015**, *29*, 322–331. [CrossRef]
39. Caracciolo, F.; Amani, P.; Cavallo, C.; Cembalo, L.; D'Amico, M.; Del Giudice, T.; Freda, R.; Fritz, M.; Lombardi, P.; Mennella, L.; et al. The environmental benefits of changing logistics structures for fresh vegetables. *Int. J. Sustain. Transp.* **2018**, *12*, 233–240. [CrossRef]
40. Govindan, K.; Rajeev, A.; Padhi, S.S.; Pati, R.K. Supply chain sustainability and performance of firms: A meta-analysis of the literature. *Transp. Res. Part E Logist. Transp. Rev.* **2020**, *137*, 101923. [CrossRef]
41. Ağan, Y.; Kuzey, C.; Acar, M.F.; Açıkgöz, A. The relationships between corporate social responsibility, environmental supplier development, and firm performance. *J. Clean. Prod.* **2016**, *112*, 1872–1881. [CrossRef]
42. Zhu, Q.; Sarkis, J. Relationships between operational practices and performance among early adopters of green supply chain management practices in Chinese manufacturing enterprises. *J. Oper. Manag.* **2004**, *22*, 265–289. [CrossRef]
43. King, A.A.; Lenox, M.J. Does It Really Pay to Be Green? An Empirical Study of Firm Environmental and Financial Performance: An Empirical Study of Firm Environmental and Financial Performance. *J. Ind. Ecol.* **2001**, *5*, 105–116. [CrossRef]
44. Albertini, E. Does Environmental Management Improve Financial Performance? A Meta-Analytical Review. *Organ. Environ.* **2013**, *26*, 431–457. [CrossRef]
45. Gentry, R.J.; Shen, W. The relationship between accounting and market measures of firm financial performance: How strong is it? *J. Manag. Issues* **2010**, *22*, 514–530.
46. Agyabeng-Mensah, Y.; Ahenkorah, E.; Afum, E.; Dacosta, E.; Tian, Z. Green warehousing, logistics optimization, social values and ethics and economic performance: The role of supply chain sustainability. *Int. J. Logist. Manag.* **2020**, *31*, 549–574. [CrossRef]
47. Peng, D.X.; Lai, F. Using partial least squares in operations management research: A practical guideline and summary of past research. *J. Oper. Manag.* **2012**, *30*, 467–480. [CrossRef]
48. Colicev, A.; De Giovanni, P.; Vinzi, V.E. An empirical investigation of the antecedents of partnering capability. *Int. J. Prod. Econ.* **2016**, *178*, 144–153. [CrossRef]

49. Bhatia, M.S.; Srivastava, R.K. Antecedents of implementation success in closed-loop supply chain: An empirical investigation. *Int. J. Prod. Res.* **2019**, *57*, 7344–7360. [CrossRef]
50. De Giovanni, P.; Vinzi, V.E. The benefits of the emissions trading mechanism for Italian firms: A multi-group analysis. *Int. J. Phys. Distrib. Logist. Manag.* **2014**, *44*, 305–324. [CrossRef]
51. Mirzaee, H.; Naderi, B.; Pasandideh, S. A preemptive fuzzy goal programming model for generalized supplier selection and order allocation with incremental discount. *Comput. Ind. Eng.* **2018**, *122*, 292–302. [CrossRef]
52. Gerlach, B.; Zarnitz, S.; Nitsche, B.; Straube, F. Digital Supply Chain Twins—Conceptual Clarification, Use Cases and Benefits. *Logistics* **2021**, *5*, 86. [CrossRef]

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Article

Blockchain Technology and Sustainability in Supply Chains and a Closer Look at Different Industries: A Mixed Method Approach

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Abstract: *Background*: This study presents a comprehensive review of blockchain technology with a sustainability orientation in supply chains and logistics. *Methods*: The publications are extracted from the Scopus and Web of Science databases, comprising 552 publications between 2017 and 2022. Several bibliometric laws and techniques, namely three-field analysis, Bradford's Law, Lotka's Law, and thematic maps, are applied in R with the bibliometrix package. Content analysis is also carried out based on 185 publications to appreciate the industry-based view of the field. *Results*: The bibliometric results indicate that this field is on the rise. Authors, sources, affiliations, countries, keywords, and their relationships are also addressed. The findings of the content analysis and thematic maps reveal that some of the most highlighted themes in the literature include traceability, COVID-19, the internet of things, and Industry 4.0. The most popular industry in this field is discovered to be food and agriculture. *Conclusions*: This paper contributes to the still relatively scarce literature on how blockchain technology fosters sustainable supply chains and logistics, providing a closer look at blockchain use, methodologies, and future directions for different industries concerning food, agriculture, fashion, textile and apparel, manufacturing, automotive, maritime and shipping, healthcare and pharmaceutical, mining and mineral, and energy.

Keywords: blockchain; sustainability; supply chains; logistics; bibliometric analysis; biblioshiny; three-field analysis; Bradford's law; Lotka's law; thematic map; content analysis

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Citation: Ayan, B.; Güner, E.; Son-Turan, S. Blockchain Technology and Sustainability in Supply Chains and a Closer Look at Different Industries: A Mixed Method Approach. *Logistics* **2022**, *6*, 85. https://doi.org/10.3390/logistics6040085

Academic Editors: Benjamin Nitsche and Frank Straube

Received: 5 November 2022
Accepted: 6 December 2022
Published: 8 December 2022

1. Introduction

Blockchain technology (BT) has been used frequently in many industries such as healthcare systems, logistics, maritime, education, finance, education, cloud and edge computing, smart-contract transactions, governance, emissions trading, and business information [1–4]. In addition to all these industries, the importance of BT is also growing in the supply chain industry, which is the focus of our study.

Several business units, such as suppliers, manufacturers, distributors, and retailers, collaborate in the supply chain to source raw materials, convert them into finished products, or deliver products to retailers [5]. Supply chains are getting longer and more complicated as they become more global [6,7]. One of the challenges that modern supply chains typically face is sustainability, and BT is seen as essential to a company's ability to achieve supply chain sustainability [8,9]. Since the last two decades, research on supply chain management (SCM) has increasingly focused on the issue of sustainability [10]. SCM is described by Seuring and Müller [11] as the management of material and information flows, as well as the collaboration between businesses throughout the supply chain, while aiming to achieve all three facets of sustainable development: societal, environmental, and economic [12]. The main objective of sustainable supply chains is to create and maintain long-term economic, social, and environmental value for all parties involved in supplying goods and services to markets [9].

How to incorporate the sustainability idea into SCM has been a heated topic of debate in academia and practice [13]. There are still issues to be researched that academicians have called for future researchers, including how to use BT to prevent supply chain disruptions, determine the system's resilience and traceability, and ensure its sustainability [2,3]. Additionally, logistics in many industries have undergone a significant transition, particularly in light of the COVID-19 pandemic. Nitsche and Straube [14] proposed development scenarios for future logistics networks. Among these scenarios are the presence of the globalization trend, increased investment in transparency and related technologies, and increased flexibility and resilience in various logistics networks. BT is regarded as one of the key exciting technologies that will help to realize this vision. To address these calls and suggestions, this study examines the use of BT in sustainable supply chains with a mixed approach that includes bibliometric and content analysis.

To take an up-to-date picture of publications in a field in the literature, there are a variety of methods used, such as bibliometric analysis, systematic literature review, and meta-analysis. The term "bibliometrics" was first used by Pritchard [15] as a replacement for "statistical bibliography". Bibliometric analysis provides a quantitative examination of publications in the literature, and it has mainly two methods in the form of performance analysis and science mapping [16–18]. Science mapping focuses on the connections between research components, whereas performance analysis mostly provides descriptive statistics on research components [18].

Content analysis is frequently used along with bibliometric analysis in literature reviews to assess current knowledge and comprehend intellectual frameworks [19]. It is a common technique in empirical social sciences for qualitative and quantitative analysis [19,20]. According to Drisko and Maschi [21] (p. 7), content analysis is "*a family of research techniques for making systematic, credible, or valid and replicable inferences from texts and other forms of communication*". The principal aim is to derive valid conclusions about the contexts wherein texts (or other significant material) were used [22]. Content analysis is a manual or automated technique which can be explored in three ways: human-scored schema, individual word counting systems (mostly automated), and artificial intelligence-based computer systems [23,24]. Insights, topics, research diversification, research trends, and research gaps from papers grouped into clusters can be identified with the aid of content analysis [25].

For the present study, the subject of BT and sustainability in supply chains and logistics was chosen for two main reasons: (1) This study answers a call for additional research into the dynamics of the adoption of BT in sustainable supply chains and logistics. It has been suggested that the sustainability issue in the blockchain-integrated supply chain should receive more attention in future studies [3,26]. (2) To date, there is only one study [27] that provides a review of BT for sustainable supply chains using bibliometric analysis and content analysis. In comparison, the database and publications are handled more comprehensively in this study. While 146 publications between 2018 and October 2021 obtained from Scopus are discussed in [27], Web of Science (WoS) and Scopus are considered together in this study and a total of 552 studies between 2017 and September 2022 are investigated. Analyses, namely three-field analysis, Bradford's Law, Lotka's Law, and thematic maps, not covered in [27], are examined within the bibliometric analysis. Apart from the industries (food, healthcare, manufacturing, infrastructure) covered in the content analysis by Sahoo et al. [27], many more different industries, including food, agriculture, fashion, textile and apparel, manufacturing, automotive, maritime and shipping, healthcare and pharmaceutical, mining and mineral, and energy, are also identified and examined in the present study.

By carrying out a comprehensive bibliometric and content analysis of blockchain and sustainability research in supply chain and logistics, it is aimed at providing valuable insights into this emerging research field. The current study answers the following research questions (all being posed within the context of supply chains and logistics):

RQ1. *What is the status of the research on blockchain and sustainability?*

1. What is the distribution of publications over the years?
2. What are the top research components (sources, authors, affiliations, countries, keywords) in terms of production and how they are interrelated?
3. Does the research collection confirm the bibliometric laws (Bradford's Law and Lotka's Law) based on source and author productivity?
4. What are the topmost cited publications?
5. What themes have been discovered in the literature thus far and how have they changed over the years?

RQ2. *What are the industry-based insights of the research on blockchain and sustainability?*

6. What are the benefits, challenges, and uses of BT in different industries?
7. What methods and theories are used in the studies?
8. What are the open research questions for different industries?

The remainder of the current study is organized as follows: the next section includes the background of the study field. In the methodology section, information about the analyses used and the search protocol (databases, search criteria, search strings, and preparation of the collection for the analysis) are provided in detail. The results of both bibliometric and content analyses are presented in the findings section and, finally, the study is discussed and concluded in the last section.

2. Background

BT was first conceptualized in 2008 by a person (or group) named Satoshi Nakamoto, in an article titled "Bitcoin: Peer-to-Peer Electronic Cash System" [28] (p. 9). It can be characterized as a decentralized shared ledger where verified and synchronized data is stored in a peer-to-peer network using chronological, encrypted, chained blocks [29] to generate permanent and tamper-proof records [30,31]. By enabling a distributed consensus that allows every online transaction to be confirmed at any moment in the future, this technology has the potential to change the digital world [28].

The blockchain system has an accurate and verifiable record of every transaction that has ever taken place. Therefore, blockchain has the potential to improve data security, transparency, and integrity [28,32,33]. It is built on a few fundamental concepts, including decentralization, verifiability, immutability [7,34], security, chronological data, collective maintenance, and programmability [35]. Decentralization describes a network structure with a trust-based architecture that functions independently of any authority. Verifiability indicates that every participant encrypts their data using their private-public keys. Immutability means that each new block to be added to the chain carries the hash value of the preceding block and that this new block can be added to the system with consensus thanks to the consensus-based algorithm of the BT [34]. Due to the system's robust encryption, it offers security. Chronological data is ensured with blockchain. The system not only saves the data permanently, but also connects the different blocks in chronological order. The maintenance of the system is primarily carried out by collective decisions because of the distributed database nature of blockchain. Last but not least, since blocks can both store and encode data, blockchain also enables programmability [35].

It is widely acknowledged that BT is a significant advancement that, in the not-too-distant future, will fundamentally alter how organizations are organized, managed, and operated [36]. As a matter of fact, many companies have started to show great interest in this technology today. BT can be used in many areas [36], and it has gained a global attention due to its many advantages in supply chains [1,2,4].

The movement of materials cannot be done directly through a single organization. Most products pass through a number of organizations as they move between original suppliers and end customers [37]. Today, it is not possible for organizations to exist on their own, and their ultimate success is based on their ability to manage their integration and coordination abilities with other members of the supply chain [38]. In today's world, uncertainties in customer expectations, big leaps in technology, and fast internet connections have forced businesses to cross local and national borders. Therefore, with the impact of the changing environment, businesses are faced with sophisticated customers who demand greater product variety, lower cost, better quality, and faster responses. For such reasons, businesses adopt supply chain management to compete successfully [39]. SCM is an integrated system management that purchases raw materials, converts them into finished products, and distributes these products to both retailers and customers [40] while facilitating information sharing between various business units. A successful SCM depends on full-time and accurate access and sharing of information by all members [38]. Furthermore, it is influenced by customer expectations, globalization, information technologies, regulations, competition, and environment [40]. Supply chain management connects suppliers, manufacturers, distributors, and customers by using information technology to meet customer expectations efficiently and effectively [39]. The use of communication and information technology is crucial to achieving the goal of maximizing every party's overall and long-term benefits through SCM cooperation and information sharing [41]. Digitalization, particularly BT, may transform supply chain management [42]. One of the most crucial tools of Industry 4.0 is thought to be BT. Today's complicated and multi-tier supply chains can benefit from using blockchain due to its many advantages, including smart contracts, decentralization, transparency, traceability, immutability of data, and data privacy [43].

BT integration into the supply chain enables product tracking, flexibility, sustainability, traceability, and increased quality. Blockchain allows supply chains to operate more efficiently and quickly [4]. From the standpoint of sustainable supply chains, using blockchain has many advantages for businesses including cost savings, operational efficiency, transparency, and traceability [1]. Different stages of the supply chain can be tracked thanks to the blockchain system. Data recorded on a blockchain can verify that products are protected according to their specifications. For example, real-time location information is shared when the goods being transported pass through customs and ports. Supply chains can be dynamically optimized using such recorded data [6]. In addition, recently, environmental concerns, new regulations, and competitive, complex environmental regulations have led companies towards sustainable supply chain management (SSCM).

SSCM is the process of planning, organizing, coordinating, and managing supply chain to make them sustainable [10]. The sustainability of supply chains is a top issue for most businesses [9]. There has been a change from a one-dimensional view of sustainable development to a three-dimensional understanding of sustainability that incorporates environmental, social, and economic responsibilities [13,44]. The creation and preservation of long-term economic, social, and environmental value is the main objective of sustainable supply chains for all parties involved in providing goods and services to markets [9]. BT is strongly linked to the three dimensions of sustainability in the supply chain, and it has advantages for sustainability [43]. Businesses will be able to increase their social vitality, sustainable use of energy and natural resources, and environmentally friendly operations by using blockchain [7]. By effectively tracing items and keeping track of environmental compliance along the whole supply chain, BT can significantly contribute to the reduction of carbon emissions, air pollution, resource usage, and waste of energy [7,9].

3. Methodology

3.1. Analysis and Tool

This study conducts a bibliometric analysis of publications on integrating BT into sustainability-oriented supply chains and logistics. After giving a comprehensive review with bibliometric indicators, the current study also provides a closer look at different industries by conducting content analysis.

The following are the justifications for utilizing bibliometric analysis in this study, as stated in [45]:

- Unlike other methods (e.g., content analysis), bibliometric analysis is more reliable and scalable.
- Bibliometric methods can offer valuable and detailed information by providing an in-depth and thorough analysis of the numerous relationships (such as citations, keywords, and co-citations) associated with the publications under review.
- Using bibliometric approaches, researchers may easily and intuitively visualize key research areas.

Content analysis is carried out for the following reasons: first, while bibliometric analysis offers a substantial data set and enables researchers to see the overall pattern of publications for a specific subject, it is unable to provide comprehensive details about the content of the focal subject [46]. Second, combining various analysis techniques also increases the validity and strength of the findings of the study [47]. Numerous studies in the literature use mixed methods consisting of bibliometric and content analysis [27,46,48]. In this way, both quantitative and qualitative methods are used together to provide broader insights into the field. Therefore, after conducting bibliometric analysis, content analysis is carried out to appreciate the industry-based view and to provide a holistic view of the findings and gaps of the research collection.

The results of the bibliometric analysis are provided in the first section of the findings. To address the first research question (RQ1), the distribution of publications by years (RQ1.1), top research components and their relationship (three-field analysis) (RQ1.2), bibliometric laws (Bradford's and Lotka's Laws) (RQ1.3), most cited publications (RQ1.4), and thematic evolutions over the years (thematic maps) (RQ1.5) were presented under bibliometric analysis. To answer the second research question (RQ2), the results of the content analysis are provided with a closer look the benefits, challenges, and uses of BT (RQ2.1), the methods and theorems used (RQ2.2), and future directions (RQ2.3) in the reviewed studies concerning different industries.

The bibliometric analysis was conducted by using biblioshiny, a web-interface for bibliometrix package [49] in R (version 4.2.1). It is an open-source package, and it has been effectively used in various bibliometric studies so far [50–54]. Biblioshiny's menu has categories of data, filters, overview, sources, authors, documents, clustering, conceptual structure, intellectual structure, and social structure. Moral-Muñoz et al. [55] provided a comparative analysis of the software tools for the bibliometric analysis and stated that through its user interface biblioshiny, bibliometrix packages, including more extensive methods, have gained more attention recently than other tools.

3.2. Search Protocol

The information about the databases, search criteria and search terms, combining databases, and search results are provided in detail. All keyword queries were made from the databases on 21 September 2022, and the publications reached were downloaded by the authors within the same day.

3.2.1. Databases

The first step to carry out a bibliometric analysis is to select the database(s). This study considers both Scopus and WoS as databases and gives comprehensive information about merging databases, since the two top citation databases are Scopus and WoS, and they are widely used in bibliometric research [56]. Up until 2004, when the launch of Elsevier's Scopus, Amsterdam, The Netherlands, swiftly replaced WoS as the primary source of bibliometric data, WoS, owned by Clarivate Analytics, dominated the scientific community [57].

Many researchers take publications from the Scopus or/and WoS databases into consideration when performing bibliometric analysis [58]. Two independent bibliometric analyses (one from Scopus and the other from WoS) are frequently carried out when both databases are considered, and few studies merge two databases without providing information on how to perform the combination [58].

3.2.2. Search Criteria

Information on inclusion and exclusion criteria when searching is explained in this section. The language of the publications was selected as English for both databases. No exclusion was made regarding subject area, affiliation, or journal. For the document types, editorial material and book chapters were excluded and articles and conference papers were considered as in [45]. Regarding the search field, the "title, abstract, and keywords" option was selected for Scopus and "topic" corresponding to the relevant field in Scopus was chosen for WoS.

3.2.3. Search Strings

The only bibliometric study about blockchain for sustainable supply chain management has been recently conducted by Sahoo et al. [27]. The keywords of the study are as follows: "(blockchain" OR "cryptographic ledger" OR "digital ledger" OR "distributed ledger" OR "public transaction ledger") AND ("sustainable" OR "sustainability" OR "green" OR "environment*" OR "social*" OR "economic*" OR "circular economy") AND ("supply chain" OR "supply chain management" OR "logistics" OR "transport*" OR "mobility"). Some of these keywords, however, were not utilized in this study because they had little impact on search results or did not accurately capture the subject matter; for instance, the keyword "mobility" by itself does not relate to the terms supply chain and logistics.

The keywords used in searches on the databases were determined by examining previous relevant bibliometric studies too. Below are the search terms in bibliometric studies in the literature on the four keywords (blockchain, sustainability, supply chain, and logistics) discussed in the current study. Literature searches were conducted for search strings of:

- *Blockchain:* "blockchain" [52,59], ("blockchain or ethereum" OR "blockchain or distributed ledger technology" OR "blockchain or smart contracts") [60];
- *Sustainability:* (sustainab* OR triple bottom line OR TBL OR ((green OR clean) AND "production") [61], ("sustainability" OR "sustainable" OR "sustainab*") [62], ("sustainab*") [45];
- *Blockchain in supply chain and logistics:* (blockchain* AND ("supply chain*" OR logistic*)) [45], (supply chain OR logistics OR transport AND (blockchain OR block chain OR distributed ledger technology)) [63];
- *Sustainability in supply chain:* ("supply chain" OR "supply chains" OR scm OR "supply chain management") AND (sustainable OR sustainability) [64].

Search strings for the current study were finalized as follows: ("blockchain*" OR "distributed ledger technolog*" OR "smart contract*") AND ("sustainab*" OR "triple bottom line" OR "TBL") AND ("supply chain*" OR "logistic*").

3.2.4. Combining Databases and Search Results

In the keyword search results, 470 publications were found for Scopus and 454 for WoS. In Scopus, the publications were extracted in BibTeX format with all information selected. The publications obtained in WoS were exported as a plain text file with the record content "Full record and cited references" selected. To merge these datasets, codes using bibliometrix package functions, namely convert2df and mergeDbSources (see Aria and Cuccurullo [65] for details), were written in RStudio (version 4.2.1), an R IDE, and then publications with missing information about authors or abstracts were manually eliminated from the dataset.

First, the separate datasets, namely scopus.bib (Scopus dataset) and savedrecs.txt (WoS dataset), were converted into bibliographic data frames with the converting function called "convert2df". Second, using the "mergeDbSources" function, the two datasets were merged into one by removing duplicated documents from the dataset ("remove.duplicated" was set to "TRUE"). As a result, 328 duplicate documents were removed from the dataset.

Finally, the dataset was manually checked and publications with missing information were excluded from the dataset. After this cleaning procedure, a total of 552 publications were considered for the bibliometric analysis.

4. Findings

4.1. Bibliometric Analysis

4.1.1. Overview

The main information regarding the collection is given in Table 1. 552 publications have been produced on 272 different sources by 1600 different authors. The field shows an annual growth rate of 152.19%.

Table 1. Main Information.

Description	Results
Period	2017–September 2022
Publications	552
Sources	272
Annual growth rate %	152.19
Average citations per publication	19
Authors	1600
Authors of single-authored publication	40
Document types:	
article	316
article; early access	47
article; proceedings paper	3
conference paper	62
proceedings paper	40
review	72
review; early access	12

As Table 2 shows, the number of publications has been increasing over the years.

Table 2. Annual Publications.

Year	Publications
2017	2
2018	8
2019	50
2020	109
2021	179
2022	204

4.1.2. Three-Field Analysis

Three-field analysis (Sankey diagram) has been used in various bibliometric studies [53,66–69]. Sankey diagrams, which have historically been used to represent the flow of energy or materials, provide quantitative data regarding flows, linkages, and transformations [70]. The larger the size of the rectangles where the research components (keyword, country, source, institution, author, etc.) are represented, the more relationships between the components [67].

First, in this study, keywords were manually checked before analysis in order to avoid the display that may occur due to the problem of representing words with the same meaning in different terms, such as "smart city" and "smart cities" or "sustainable city" and "sustainable cities", keywords represented with different rectangles in the three-field plot in [66].

In the keywords of some studies in the dataset, it was observed that words with the same meaning were represented two or more times by different keywords (e.g., "internet of things", "IoT", and "internet of things (IoT)"). All these keywords were consistently corrected with a single keyword (for this example, all keywords were converted to "IoT"). Apart from this, the same representative keywords were decided for all studies and corrections were made to ensure that the keywords of the studies were consistent (e.g., keywords represented as "block chain" in study X, "block-chain" in study Y, "blockchain" in study Z were corrected to "blockchain" for all studies).

Sankey diagrams for the study were created by using biblioshiny's "three field plot" selecting the top 20 of each research component. Figure 1 illustrates the relationships between the author's keywords (left), authors (middle), and sources (right).

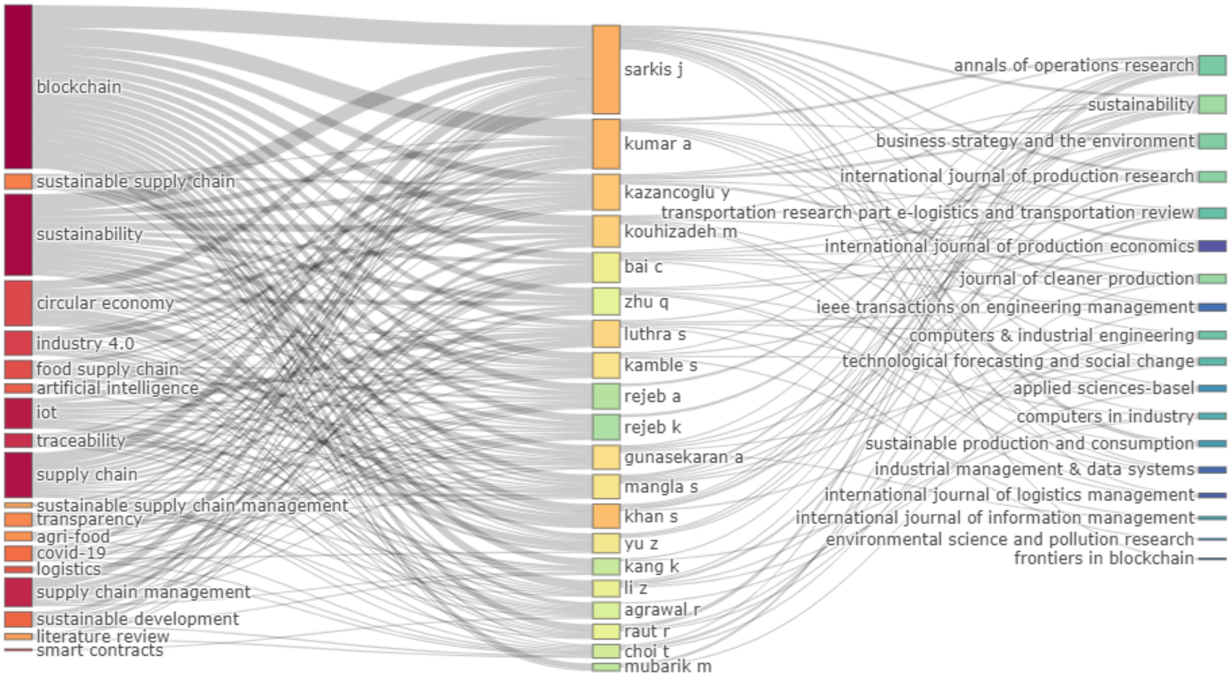


Figure 1. Three Field Plot for author's keywords, authors, and sources.

The three-field analysis of the top keywords, authors, and sources indicates that Sarkis J (Joseph Sarkis) has the most incoming (from keywords) and outgoing (to sources) flow counts. He has a strong relationship with the main research topics ("blockchain", "sustainability", and "supply chain") and many of the listed core journals. *Sustainability*, *Annals of Operations Research and Business Strategy* and *The Environment* have the most relationships in terms of incoming flow counts, demonstrating that many top authors have published their studies in these journals. Apart from the main topics, there are other top keywords that indicate relationships with top authors, such as IoT, circular economy, Industry 4.0, COVID-19, and agri-food.

The second diagram was generated for the top countries (left), affiliations (middle), and authors (right), and is given in Figure 2. Most relationships between a country and its top affiliations belong to China, followed by India. It is evident that there are many collaborations between research components. For instance, Yasar University is in Turkey and receives incoming flows from not just Turkey but also China, France, the UK, and India. The Hanken School of Economics is in Finland and has relationships with Finland, the USA, Denmark, China, and France.

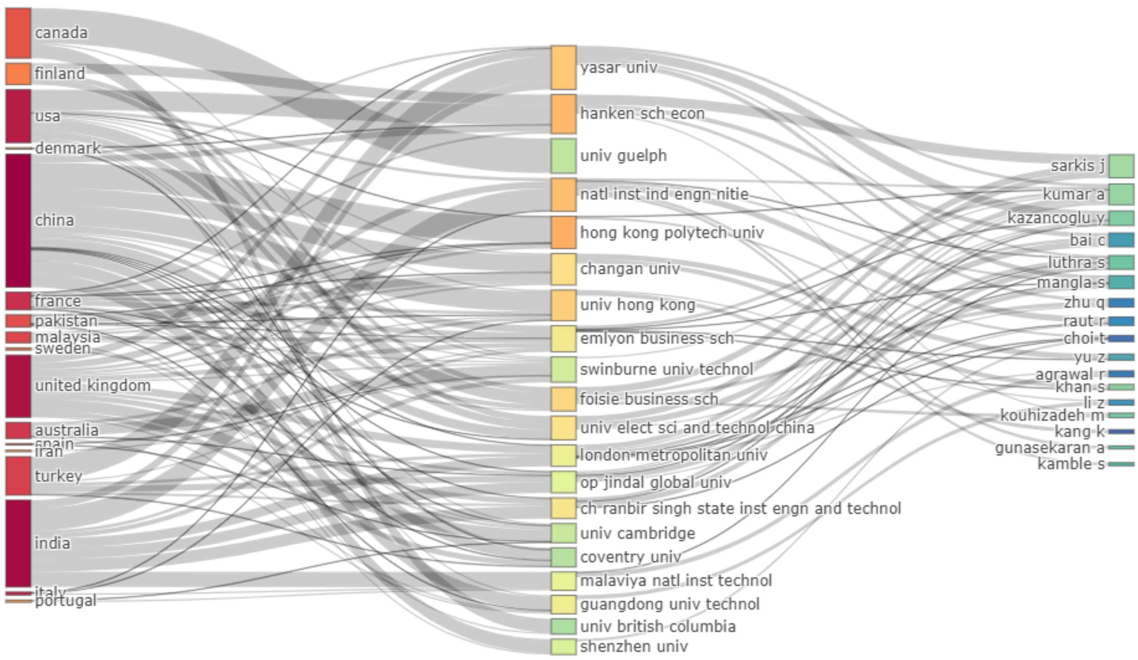


Figure 2. Three Field Plot for countries, affiliations, and authors.

4.1.3. Bradford's Law

According to Bradford's Law [71], there are few journals that publish numerous articles and many journals that publish few articles on a particular topic. To observe the core journals or to cluster the journals, Bradford's Law has been used in different bibliometric studies [69,72–74].

The distribution of the sources according to the amount of publication is shown in Figure 3 (the sources whose names are written belong to the first group). According to the results, there are 187 publications in 13 sources in the first cluster, 183 publications in 77 sources assigned to the second cluster, and 182 publications in 182 sources in the third cluster. While all the sources in the third cluster had a single publication, 14% of the articles (76 out of 552 publications) were published in a single journal (i.e., *Sustainability*).

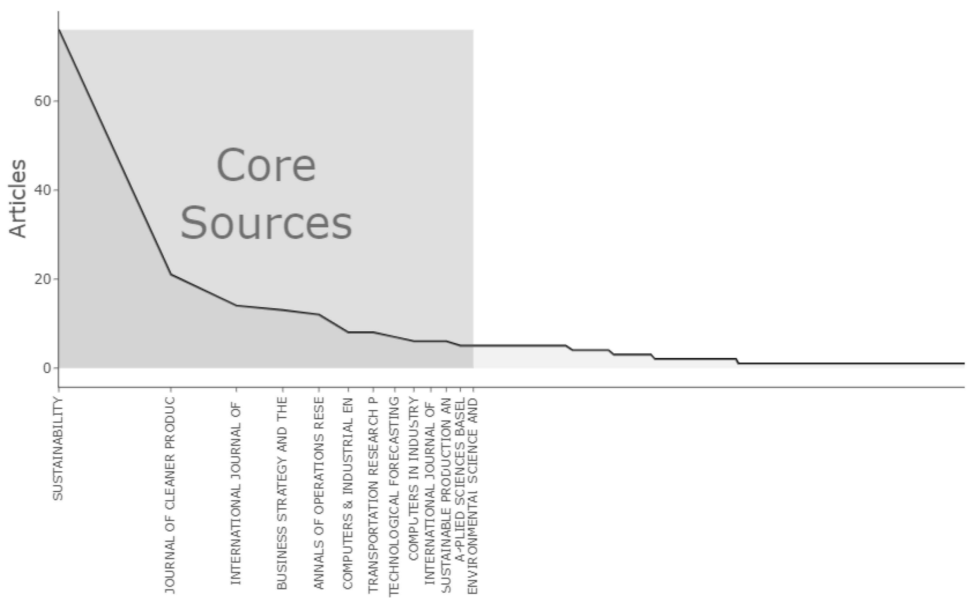


Figure 3. Source clustering through Bradford's Law.

Mathematical compliance with the rule was calculated according to Kumar and Mohindra [72]. The calculation was made for the 1:n:n^2 rule and the error rate was found. By this rule, the relationship of each cluster in the study is 13:77:182 (272 sources in total) and the mean Bradford multiplier is 4.14 (average (77/13, 182/77)). The error calculation is as follows:

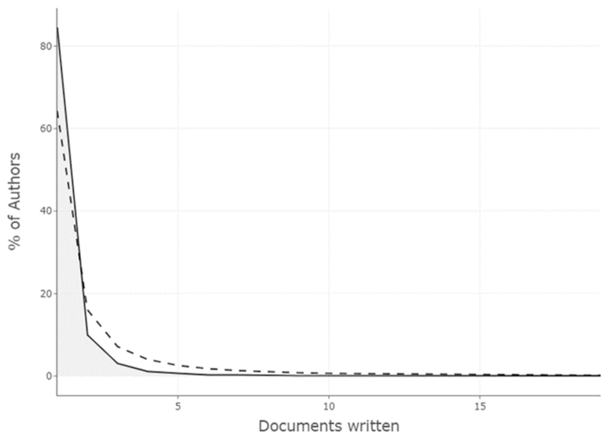
$$13:13 \times 4.14:13 \times 4.14^2 = 13:53.86:223.18 \quad (1)$$

$$\%\ \text{error} = ((13 + 53.86 + 223.18) - 272)/272 \times 100 = 6.63\% \quad (2)$$

The data confirms Bradford's Law as the percentage of error is not too high [72].

4.1.4. Lotka's Law

Lotka's Law is one of the laws that have been applied in bibliometric studies, just like Bradford's Law [72,74]. Lotka's Law (the inverse square law of scientific productivity) [75] seeks to identify researchers who produce more frequently in a certain field of expertise. Authors' productivity is illustrated in Figure 4a. 84.5% of the authors published just one article, whereas the most productive author (Joseph Sarkis) had 19 publications (0.1%).



(**a**)

Publications (X)	Authors (Y)	Authors (Expected, n = 3.088)
1	1352	1352
2	159	159
3	48	45.46
4	17	18.70
5	10	9.39
6	4	5.35
7	4	3.32
8	2	2.20
9	1	1.53
10	1	1.10
17	1	0.21
19	1	0.15

(**b**)

Figure 4. Author Productivity through Lotka's Law (**a**) The number of publications and the number of authors in the collection are illustrated; (**b**) The number of publications (X), the number of authors (Y), and the expected number of authors calculated through the law are given.

All calculations were made according to Kumar and Mohindra [72] and the data is given in Figure 4b. The formula for Lotka's Law is given by the expression:

$$X^n Y = C \quad (3)$$

The values of 1 for X and 1352 for Y were given, and C was found to be 1352. Then, by giving the values X = 2, Y = 159, and C = 1352, n was calculated as 3.088. The number of authors was calculated using the n = 3.088 value. According to the results, it is seen that the expected number of authors was consistent with the number of authors (Y). Therefore, Lotka's Law applies to this study.

4.1.5. Most Impactful Publications

The top five most cited studies are given in Table 3. The most cited publication belongs to Saberi et al. [76]. In the study, an overview of BT, its use in the supply chain, and the challenges it faces were discussed. The second most cited study [77] examined how blockchain can impact key supply chain management goals such as sustainability, cost, and speed. While underlining the potential future direction of blockchain application and technology, Hughes et al. [78] emphasized the numerous obstacles to blockchain adoption. Included in addition were several instances of supply chain and logistics businesses that stand to gain a lot from BT. Kamble et al. [79] discovered the drivers of blockchain adoption in agriculture supply chains and explored their relationships. Traceability, auditability, immutability, and provenance were found to be the top four drivers of BT adoption. In another study, Kamble et al. [80] conducted a literature review and suggested a framework that recognizes supply chain resources and visibility as the primary driving forces behind building data analytics capabilities and attaining sustainable performance in agri-food supply chains.

Table 3. Top Five Most Cited Publications.

Author	Title	Total Citations
Saberi et al. [76]	Blockchain technology and its relationships to sustainable supply chain management	988 (Scopus) 829 (WoS)
Kshetri [77]	Blockchain's roles in meeting key supply chain management objectives	732 (Scopus)
Hughes et al. [78]	Blockchain research, practice and policy: Applications, benefits, limitations, emerging research themes and research agenda	287 (Scopus)
Kamble et al. [79]	Modeling the blockchain enabled traceability in agriculture supply chain	270 (Scopus)
Kamble et al. [80]	Achieving sustainable performance in a data-driven agriculture supply chain: A review for research and applications	255 (Scopus)

4.1.6. Thematic Evolution

A group of keywords can be treated as a concise summary of a particular research theme and two parameters, density and centrality, apply to any research topic [81]. The degree of interconnection between all keywords is determined by density, while the degree of interconnection with other themes is measured by centrality [81]. A thematic map (strategic diagram) is illustrated as divided into four areas based on the themes' density and centrality [82]. The four quadrants have different aspects [81–83]:

- *Niche themes (upper-left quadrant; high density and low centrality):* They are often referred to as "highly developed and isolated themes". The connections between themes are strong internally but weak outside. They are just marginally relevant to the field.
- *Motor themes (upper-right quadrant; high density and high centrality):* This quadrant addresses well-developed themes crucial to the structure of a research area.
- *Emerging or declining themes (lower-left quadrant; low density and low centrality):* This quadrant demonstrates weakly developed and peripheral themes.
- *Basic themes (lower-right quadrant; low density and high centrality):* Although they are poorly developed, the themes in the lower-right quadrant are crucial for a research topic. Therefore, this quadrant gathers "general, basic, and transversal" themes.

There isn't a single, conclusive response to the problem of what themes could persist in the future. Cahlik [81] stated that themes that were prevalent in earlier periods have a good likelihood of remaining in later ones. In addition, engaging development of a theme may provide a greater chance of permanence than simple dynamics, and if they are not considered to be interesting by researchers, many of the themes from the fourth quadrant may disappear from the field in the next period [81].

Thematic maps or thematic evolutions of different years have been applied in many bibliometric studies [48,68,69,84]. For the analysis, first, some text preprocessing methods were applied by preparing and using a dictionary in the "Text Editing" area of the biblioshiny program to eliminate keywords about search strings, such as blockchain, smart contracts, sustainability, sustainable supply chain, supply chain, and logistics, as these keywords stand out in the analysis as expected and provide no useful information and insights about the themes.

To understand the evolution of the themes in the corpus, the author's keywords were used to generate the thematic maps. To maintain the readability of the maps and give insightful information, the following parameters were selected (number of words = 200, minimum cluster frequency = 5, number of labels for each cluster = 2, and the other parameters were default) [68]. The time zones were set for 2020 and 2021. This is due to several factors, including the recent sharp rise in article production in the last two years, the goal to maintain a constant quantity of articles over time, and the need to highlight recent trends.

Evolutions of the themes for the years 2017–2022 and their relationships are shown in Figure 5. The themes are given for the years 2017 to 2020 on the left, the year 2021 in the middle, and the year 2022 on the right. It is observed that *IoT*, *traceability*, and *Industry 4.0* have been studied for all time periods. Other themes that have been developed in 2022, are, for instance, circular economy and multi-tier supply chain. It is observed that the *food supply chain* theme has a connection with *COVID-19*, and *circular economy* has relationships with *digital technologies*, *COVID-19*, and *Industry 4.0*. Themes for each period are illustrated as thematic maps to deepen the analysis.

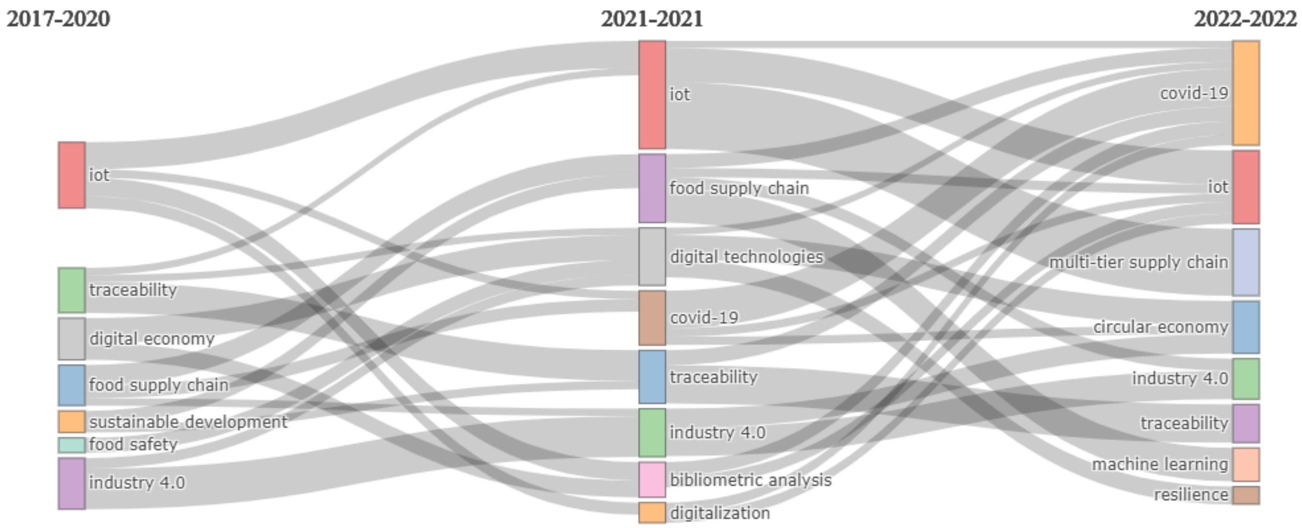


Figure 5. Thematic Evolution Map (2017–2022).

The thematic map for 2017 and 2020 (Figure 6) has twelve thematic clusters, namely, food safety, cost saving, food supply chain, traceability, sustainable development, environmental sustainability, data science, IoT, Industry 4.0, supply chain performance, digital economy, and peer-to-peer. The food safety cluster, labelled by food safety, China, and Evoo (Extra Virgin Olive Oil) and the cost saving cluster are in the niche themes quadrant, indicating marginal relevance to the field. The well-developed and crucial topics of the research field, motor themes, consist of three clusters: food supply chain, traceability, and sustainable development. Basic themes have three clusters as IoT (IoT, artificial intelligence, smart city), Industry 4.0 (Industry 4.0, circular economy, fashion), and supply chain performance (supply chain performance, supply chain visibility, and information transparency). Digital economy appears to be an emerging theme, whereas the peer-to-peer topic seems to be a declining theme. Environmental sustainability and data science are sandwiched between niche and emerging themes.

The next period's map, the thematic map for 2021 (Figure 7), has nine thematic clusters, namely, *digital technologies*, *bibliometric analysis*, *food supply chain*, *digitalization*, *IoT*, *Industry 4.0*, *traceability*, *COVID-19*, and *Tradelens* (developed jointly by IBM and GTD Solution, TradeLens is an open supply chain platform powered by blockchain technology (www.tradelens.com (accessed on 5 November 2022)). *Tradelens* seems to be a declining theme, whereas *COVID-19* can be an emerging theme with higher centrality. Although *traceability* is a motor theme for the 2017–2020 period, it is placed between quadrants 3 and 4, namely basic and emerging themes for the 2021 map. *IoT* and *Industry 4.0* are basic themes that almost become motor themes with more development. *Digitalization* and *food supply chain* are motor themes; both the number of studies in these domains are substantial and there are close internal relationships with thematic areas. *Digital technologies* and *bibliometric analysis* are located in the second quadrant (niche themes).

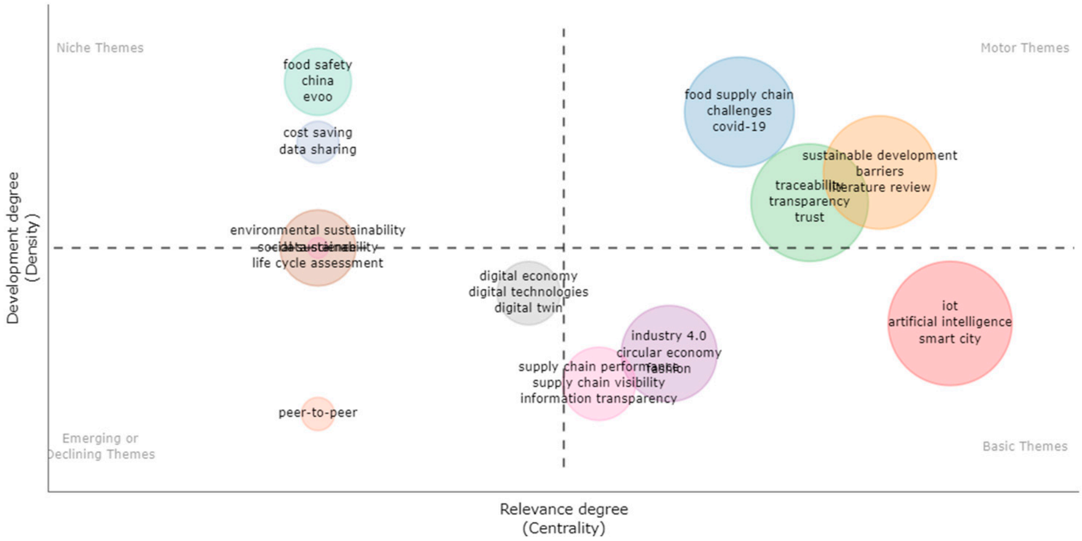


Figure 6. Thematic Map (2017–2020).

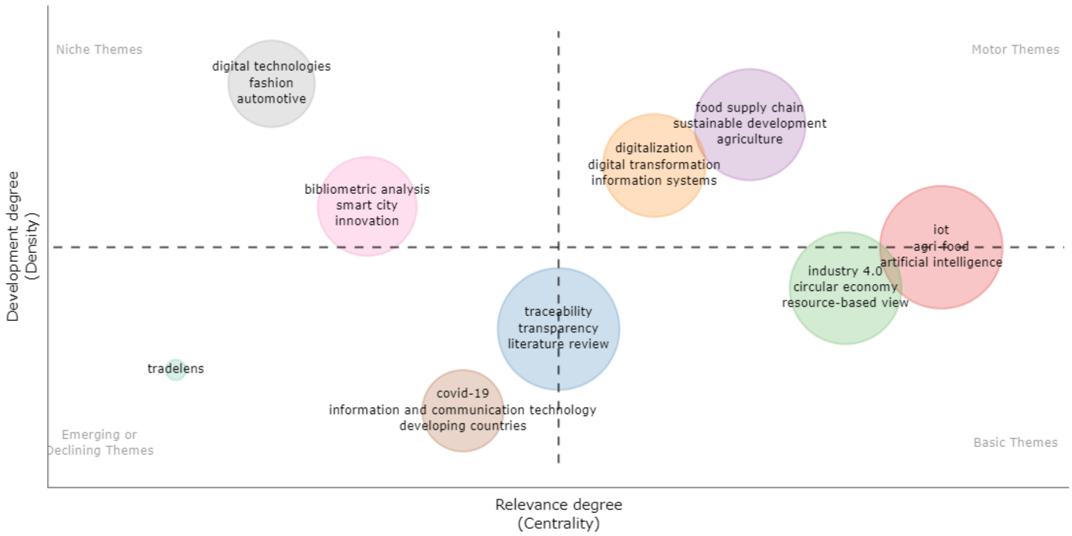


Figure 7. Thematic Map (2021).

The current year's map, the thematic map for 2021 (Figure 8), has ten thematic clusters, namely IoT, circular economy, Industry 4.0, traceability, COVID-19, resilience, carbon emission, environmental, machine learning, multi-tier supply chain, and game theory. Machine learning and environmental are located as niche themes. Traceability is sandwiched between niche and motor themes, indicating that it has gained density and move upward compared to the 2021 map. It is seen that new themes have emerged, such as multi-tier supply chain, game theory, and carbon emission. COVID-19 and Industry 4.0 have gained more centrality and density, as a result, they have become motor themes. IoT, circular economy, and resilience are in basic themes.

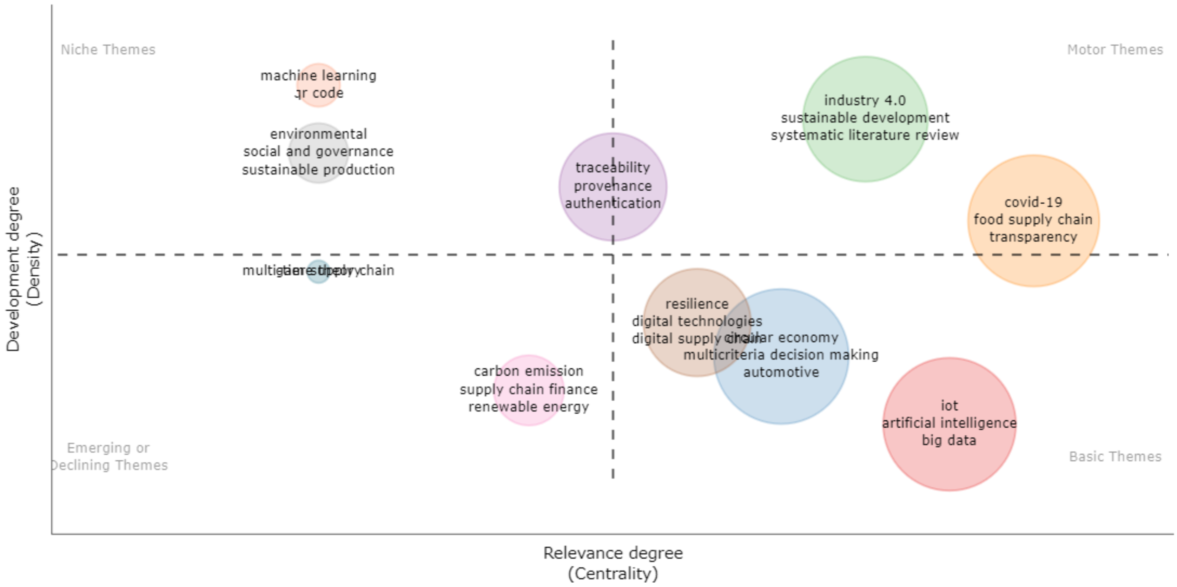


Figure 8. Thematic Map (2022).

4.2. Content Analysis

The literature review team, consisting of two Ph.D. candidates, rigorously reviewed the abstracts, findings, discussions, and conclusions of the 552 publications and manually clustered them by industry, considering some inclusion and exclusion criteria. The article was supposed to be about blockchain adoption in industries within sustainable supply chain systems to meet the initial inclusion requirement. As an exclusion criterion, some publications that did not mention a specific industry for blockchain adoption in the supply chain were not included in the sample. This led to 185 publications and eight industry clusters examining the benefits, challenges, and use of BT in a sustainable supply chain system based on specific industries as well as discussing methods and theories used, and future directions in the reviewed studies.

The industry with the most publications is found to be *food and agriculture* when the distribution of publications by industries is examined (Table 4). The three industries with the least number of publications are *energy, mining and mineral,* and *healthcare and pharmaceutical*.

Table 4. Distribution of Publications by Industries.

Industry	Number of Publications
Food and Agriculture	115
Fashion, Textile, and Apparel	18
Manufacturing	12
Maritime and Shipping	10
Automotive	9
Healthcare and Pharmaceutical	8
Mining and Mineral	7
Energy	6
Total	**185**

Other than these industries, there are niche applications in different supply chains based on blockchain use, such as oil and gas [85], aircraft [86], airports [87], autonomous vehicle [88], defence [89,90], forestry [91], trucking [92], tourism [93], and telecom [94]. Due to the low number of studies related to these industries, they were not evaluated under content analysis.

4.2.1. The Uses, Benefits and Challenges of Blockchain Technology

Food and Agriculture Industries

Agriculture and food supply chains (FSCs) are essential for the sustainability of human activities [77,95,96]. Major changes are now needed in the agrifood industry to encourage sustainability, reduce waste, and motivate a shift toward sustainable, healthy diets [97]. Traditional agricultural business models endured a tremendous transformation during the preceding three industrial revolutions [98,99] after facing several challenges such as counterparty and financing risk, low customer confidence [100], lack of a strong method for integrating various information systems, lack of prompt and clear information regarding temperature and status of the products, controlling high communication costs [101], inconsistent product quality, lost data [102], and a surplus of manually processed papers [101,103].

The fourth industrial revolution has significantly accelerated the development of agricultural sustainability [98,104–106]. Nowadays, agriculture businesses have no option but to adapt to the new system in the practices of the increasingly digitalized and globalized world [107,108]. To assure economic, social, and environmental sustainability, modern agriculture needs to incorporate technologies like machine learning, big data analytics, cloud computing, the IoT, blockchain, and other developments (e.g., smart sensors, robotics, digital twins, and cyber-physical systems) more synergistically [99,109,110]. With less human participation and more accurate data, these cutting-edge digital technologies enable the development of interconnected, data-driven, intelligent, agile, and autonomous systems for entire supply chain processes [98,101,104,105,111,112]. Blockchain has also started to be used in sustainable e-agriculture applications [113] and it fosters cooperation in the e-agriculture supply chains [31,106,114].

Food supply chain systems also share the same characteristics as agriculture supply chains. Flour milling, milk processing, meat processing, the canning industry and the production of dried and canned fruit, vegetables, and seeds, fishing, manufacturing of sugar and confectionery, chocolate and desserts, and production of spices are the traditional industries that make up the food industry [115]. Consumers and stakeholders are becoming increasingly concerned about the reliability, safety, quality, and distribution—which must adhere to sustainability standards—of food information due to the lack of transparency and traceability in FSCs [116,117]. For FSCs to address societal, economic, and environmental demands, managing sustainability is a critical strategy [118,119]. FSCs are quickly getting more and more complex in today's globalizing environment [96,110,118,120]. Recently, due to several terrible events such as environmental deterioration, climate change, population growth, resource scarcity, and food waste caused by the COVID-19 pandemic have further increased the problems in sustainable FSCs on a global scale [99,110,121–127]. These problems have a lot to gain from blockchain technology's distributed ledger, transparency, traceability, and other aspects [128,129]. To ensure food safety and reduce harmful environmental impacts, it is necessary to move towards resilient and sustainable food systems [126,130] with the help of BT.

BT can offer many benefits for agriculture and FSCs. Real-time farm management, high levels of automation, and data-driven intelligent decision-making in an industrial agriculture ecosystem will dramatically increase agri-food supply chain efficiency, food safety, and resource utilization [98]. Numerous rules, governmental laws, and specifications can be handled easily to create food security through the blockchain [131–133].

BT has the potential to increase supply chain transparency, allowing to produce high-quality food with minimal negative social and environmental effects particularly in the agri-food industry [134,135]. In this way, high-quality products can be discovered and marketed to the rest of the world [101]. In addition, blockchain-based food monitoring systems aid in preventing inflated price increases [125]. Once customers' trust is gained through blockchain, their satisfaction level can be positively impacted [136] and, in the long run, they can be loyal to the company [137,138].

BT has the potential to increase existing food production in a cost-effective and sustainable manner [126,139]. It can provide shorter transit distances, quicker payment settlements [102], and the avoidance of food waste [102,103,105,140]. Through the realization of information's traceability, security, and non-manipulation, which are particularly helpful in the agri-food sector, BT can promote sustainability [31,141,142]. Environmental preservation, pollution control [143], water conservation, the health of the soil and plant insurance [110] are other benefits of BT.

Blockchain offers chances to find and utilize synergies between various actors [144]. It improves supply chain coordination by giving warehouse managers more information [145], and combines many sources of information for more effective logistical management [145,146]. Blockchain implies novel business models [147] where each agricultural step will be automatically linked into the supply chain up to the final customer [80,104]. Furthermore, blockchain offers the potential for guaranteeing equitable value distribution and fair supply chain procedures, which can be helpful for organizations like social enterprises, NGOs, and fair trade agencies that wish to demonstrate to their clients that they are committed to sustainability [148].

With the help of data integration, suppliers and buyers can communicate directly without the need for intermediaries [128,149], and, through the elimination of intermediaries in the agri-food supply chain [122,150], farmer income may be increased. By tracking the source of food, blockchain helps build trust between producers and consumers [151,152], forecast demand [135], increase awareness, and help the transition to a more sustainable food system [126].

Improved visibility and traceability, as well as the immutability of records, are also recognized as advantages of BT [98,126,129,153–156] that may be helpful for regulators in assisting with the identification and reduction of possible food fraud cases [110,123,149,157,158], and counterfeiting [102,135,159] especially for society in less developed nations and rural areas [108,149]. One of the basic human rights is a healthy diet. However, as a result of increasing population and urbanization, the land allocated for agriculture has decreased [160]. In traditional supply chains, it has become challenging to obtain healthy foods and consume foods devoid of toxic chemicals. For example, daily reports of numerous instances of food fraud, contamination, and adulteration from various regions of India point to the urgent requirement for an improved decentralized supply chain paradigm [102]. Therefore, it is necessary to take advantage of BT in modern supply chains to prevent potential food fraud. With the help of BT, bacterial contamination or inferior food can be identified quickly [122,161]. For preventing fraud efforts, several businesses have begun to adopt blockchain in the real world. For example, IBM and Walmart have established a partnership by creating a blockchain-based platform to determine whether food fraud incidents may be identified or diminished [110]. Similarly, Alibaba's Food Trust frameworks have also tried to integrate BT into the food cold chain for perishable foods to boost food safety [142]. In addition, Walmart and Kroger were among the first businesses to integrate BT into their supply chains, and the outcomes of this implementation have demonstrated that this technology also saves time in terms of routing and sourcing [162].

In conclusion, the "farm to fork" concept is highlighted using BT [105,109,163–166]. Namely, BT has made it possible to track the crop through every stage, from production to harvest. For instance, during the production stage, data from the blockchain system will be used to protect product details such as production area, planting and harvest dates, fertilizer status, chemicals and pesticides used [80], agricultural permits, and food safety certificates [146]. After all, before the product reaches the fork, it is put through several inspections. Governmental agencies and food safety inspectors schedule field visits to farms and facilities. If specifications are met, products can be digitally signed by relevant organizations and governmental bodies following an inspection [146].

On the other hand, in some cases, various obstacles may be encountered that may prevent the use of BT. The biggest barriers preventing food businesses from implementing BT are the lack of the necessary technical skills, education, and training resources [99,167], regulatory and governmental issues [168], low technological readiness levels [169], high investment cost, technological immaturity, lack of awareness and customer acceptance, resistance from old business models, and a lack of common frameworks architecture [118]. In terms of technical problems, BT has scalability issues [98,170,171] due to the heavy computing required. Ethereum can only process 15 transactions per second, which is a very low rate when compared to other financial authorities, demonstrating the scalability concerns with blockchain [172]. Although one of the most cutting-edge methods in the food sector is BT, the design and development of the suggested systems take a lot of time and effort [95]. BT depends on internet availability and infrastructure capacity, so especially for small and medium-sized enterprises, lack of internet connectivity makes it difficult to integrate into their business [122,173,174]. Since the adoption of blockchain is frequently extremely expensive [175], the investment costs to be incurred in the integration process may be more challenging [176]. The importance of infrastructure improvement that enables better and more efficient physical connectivity between related parties [177]. Moreover, there are still issues with security, technical, legislative, infrastructural, institutional, and other crucial factors and developing appropriate IoT solutions to address complex and unique issues in the agriculture sector is suggested [79,178,179]. In terms of regulative issues, the implementation of BT reduces stakeholder control over agricultural production processes and operations. Therefore, the adoption of BT finds significant resistance from managers and decision-makers, especially on sustainability-related issues [31].

While researching agriculture and FSCs, some industries have been studied in detail in the literature. As such, cocoa [180], cheese [154], cotton [145], wine [181,182], halal food [131], organic tea [149,183], crystal sugar [130], smart honey [158], perishable foods [133,142], dairy products [102,154,184], seafood [117,185,186], and olive oil [187,188] are among the main industries studied.

It is necessary to specify the integration of BT into the system. In the reviewed studies, the use of BT is generally explained by developing a model architecture [102,153,174,187,189–191]. Mostly, there are various layers in the developed architectures. For example, according to Vo et al. [189], there are four layers in the BT-based structure that make up their architecture: the business layer, the traceability layer, the blockchain layer, and the application layer. Each layer serves a different purpose, and smart contracts can be useful in these layers. The blockchain smart contract allows for the real-time capture of feedback data regarding different ties, which can further optimize the control of agricultural production and provide the basis for maximizing its benefits [128,141,192]. In the proposed architectures, the blockchain-based supply chain system is generally integrated with the IoT technology. IoT and blockchain-enabled systems are essential for FSCs to adopt cost-effective methods [163,190,193]. Combining specific technologies, such as using IoT devices or RFID tags to smart contracts, can enhance the benefits of blockchains [103,153]. Platforms built on BT and IoT enhance supply chain visibility, improve contract execution, and boost the authenticity of product source data [96,100,103,194]. With the help of the IoT devices placed on the objects in the chain, the humidity and temperature of the crops can be measured, and the location of the products can be easily monitored using the QR codes placed [101,125,188,195], and fine-grained sensing can be available throughout the whole supply chain [98]. In this way, the consumer can view the whole life cycle of the product, and they may see how the price is handled in each of the transactions [125]. Another framework suggests smart packaging. With the help of blockchain and radio-frequency identification tags, during the whole chain foods' information can be tracked and smart packages' color change once the food spoils [196]. Among the blockchain systems used in research projects, the Ethereum platform is the most widely used alternative [95].

Fashion, Textile and Apparel Industries

The increased production of goods that directly cause environmental or societal issues is considered a significant problem in fast fashion [197]. In addition, as in other industries, COVID-19 has had a significant impact on the fashion industry, both in terms of supply and demand dynamics, as store closures or revenues decrease [198]. The fashion industry should drive digital innovation such as BT and create smart solutions, as part of the United Nations' Sustainable Development Goals [199].

Similar and related to the fashion industry, social, environmental, and sustainability concerns are common in the textile and apparel industry, which emphasizes the need for efficient traceability solutions [200]. The following benefits of using BT in the textile and apparel industry's supply chain are particularly noteworthy: transparency, tracking, sustainability, combating slavery, and brand protection [201]. Blockchain traceability data can also improve the life cycle assessment of textile products. Data from blockchain traceability might help characterize and understand a product's impacts, and also inform product eco-design and boost transparency regarding the effects of a product's life cycle [202].

The integration of technologies, such as smart contracts, 3D printing, QR-codes and AI with BT in the fashion industry can assist in achieving all objectives linked to maintaining the required ethical, social, and environmental standards [198,203]. As information about the fashion product, including the brand, the ingredients, the producer, and even the customer, is verified and stored, the items' usage history can be readily followed and validated, and with the help of BT, these used products can be cleaned and sterilized, then sold, rented, or donated to extending their useful life [197]. With no geographical restrictions, BT records every transaction involving clothing along the value chain. There is no requirement for third-party operators since value chain participants may decentralize access and disseminate information from any place [203].

Using blockchain in the global fashion industry can also affect the triple bottom line, which includes the planet, people, and profit [203]. Since the fashion industry depends on global supply chains for its operations, which are highly fragmented and have serious transparency and traceability issues, more and more businesses in these industries are being asked to demonstrate their commitment to sustainability in order to combat these issues [204]. Blockchain's significance in sustainability is evident [205] and the success of sustainable supply chains can be attained by using BT [198]. This technology can also promote sustainability from a consumer perspective. Accessing product information that might support ethical purchasing habits or guarantee product originality is challenging for customers [206]. Consumers are more encouraged and more likely to purchase sustainable goods and fashion brands when they have access to more reliable and clear guidance about the social and environmental effects of the clothing [202,207,208]. Using blockchain in supply chains can also help prevent inappropriate use of labor, as all information is open and cannot be covered up, and consumers become aware of the working conditions workers are exposed to [201]. All parties might make use of the special chance, flexibility, and power to track back their supplier networks and build an open and sustainable supply chain using the blockchain-based traceability system [206].

Blockchain's role in fostering responsible management as well as how companies' messages of responsible management contribute to sustainability in luxury fashion supply chains were also explored [209]. Most executives have a positive opinion of blockchain's ability to enhance responsible management in the supply chain for luxury fashion. BT can help managers increase consumer engagement and avoid greenwashing in the supply chain and stop the counterfeiting of goods sold by third parties that do not own a certain brand [201].

Three sustainability goals that companies focus their efforts on while using BT investigated in the fashion supply chain and product safety, brand authenticity and strategic positioning are found [210]. It is advised that supply chain companies take the blockchain into account as a significant strategic resource that may be used with other digital technologies to provide them with an advantage over rivals. Considering the blockchain implementation intentions of the supplier companies, "relative advantage, compatibility, perceived trust, top management considerations, absorptive capacity, information sharing and collaborative culture, and trading partners' influence" were found to have an impact [211].

With all these benefits, there are some obstacles to the acceptance and use of BT in the fashion sector, such as a bottleneck of digitization, a lack of industry knowledge, immutability, the network's poor scalability, interoperability, transaction speed, some security and privacy issues, block capacity, and power consumption [203,204]. Companies with a highly fragmented supply chain will need greater organizational efforts and bear higher expenses since specific data is needed for blockchain traceability. Government incentives and knowledgeable customers who ask for its features might both have an impact on the environment and the adoption of BT [205]. The role that governments can play is also highlighted in other studies [203,212]. If the value propositions are emphasized for various stakeholders in the supply chain as an incentivization mechanism, the obstacles to the adoption and deployment of BT can be removed [203].

Manufacturing Industry

Traditional supply chains are being upended by the pandemic [213] and technological spillovers, which is resulting in a sustainable digital economy powered by modern manufacturing breakthroughs and business models [214]. Manufacturing industries are increasingly conscious that chasing only financial gains would not enable them to compete successfully [215]. Sustainable supply chains, which are created by utilizing technologies such as blockchain, attract more and more attention every day and are considered necessary to maintain competitive advantage and long-term existence [216–219], and increase manufacturing firms' profits [216]. The positive impact of blockchain on green supply chain practices including green manufacturing, green design, green distribution, and green procurement has been confirmed by Mubarik et al. [217].

The supply chain integration can be exceptional in the manufacturing industry if the transactions are sufficiently transparent and can be traced [220]. Due to its real-time transparency, eliminating the need for intermediaries, and cost-saving advantages, BT has been suggested for sustainable supply chain management in the manufacturing industry [216,218]. By reducing redundant paperwork, enabling businesses to estimate demand and supply in real-time, and, as a result, preventing unnecessary extra production, blockchain strengthens the supply chain's resilience and integration [217].

BT is also recommended in different applications to support sustainability, such as plastic recycling, steel manufacturing, additive manufacturing, and cloud manufacturing. The usage of blockchain as smart contracts is advised to separate plastics and increase the accuracy of data on recycled plastics [221]. These technologies are useful for effectively sorting plastics and can be relied upon in the plastic circular economy. With the use of these technologies, data can be safely shared between parties including segregators, recyclers, and manufacturers. Similarly, for steel manufacturing supply chains, BT has been suggested to make a resilient supply chain possible [213]. Concerning additive manufacturing, as there is less energy wasted during additive manufacturing, it is a more environmentally friendly method of production. If blockchain and additive manufacturing technologies are combined, the manufacturing industry can gain a great deal [222]. In addition, a blockchain-based cloud manufacturing system can conduct real-time analytics and traceability for better quality control, inventory management, and audit reliability [214]. Moreover, real-time analytics can reduce carbon footprint as audit reliability is carried out in real time and in-person travel to verify papers and inventory stock are avoided [214]. It is also stated that when the government offers incentives, businesses will embrace BT to track their carbon emission activity [219].

Han and Rani [223] have recently investigated the barriers to BT adoption in sustainable supply chain management in the manufacturing industry and identified 25 barriers including "fear of change", "the infancy of the technology", "organizational culture", "cyber security concerns", "lack of awareness", "possible fear of data misuse", "regulations for blockchain development", "massive financial investment", etc. Lack of awareness was determined to be the main obstacle to the BT adoption. Another study looked at common barriers to the use of BT in remanufacturing. It showed that "scaling of technology," "operational challenges," and "lack of awareness on blockchain risk" were the three main obstacles [215]. In addition, elimination of these barriers can also have impacts on Sustainable Development Goals. For example, by eliminating the "lack of awareness of blockchain risk", the industry can train its employees with BT and promote learning opportunities (its associated goal is SDG 4-quality education) [215].

Maritime and Shipping Industries

The shipping industry, which has been impacted by the long-term instability of global trade, has recently gone from having excess transportation capacity to lacking it, and both situations seriously impair the shipping industry's ability to grow sustainably [224]. Blockchain supports sustainable business models and promotes sustainable practices in these industries by enabling greater knowledge cycling and relational actions among supply chain operators [225]. For example, Korean shipping firms integrate BT into their operations to generate sustainable profit [226]. In addition, machine learning on the cloud inside BT was recommended by Wong et al. [227] to achieve technological sustainability, as it can fulfill the increasing blockchain needs and learn from the blockchain's big data.

Moreover, maritime and shipping supply chains can be made traceable using the blockchain platform for distributed data and information storage and sharing, smart contracts to perform transactions automatically, and many supporting technologies (such as IoT devices, GPS, and sensors) [228]. The two crucial stages in the lifespan of a transaction within the blockchain network are transparency and security [229]. To provide more security and transparency, smart contracts can be put up at key locations along the shipping route [229] and it might help many parties by cutting back on workloads, the amount of inspection, and time-wasting [230].

Increased visibility, transparency, and real-time information across routes, decreased paperwork, data and information authenticity, enhanced collaboration and cooperation, decreased rework and recall, decreased risk of document loss, improved job performance [231], increased competitiveness and efficiency [228], and decreased need for manpower which can cause a lot of mishaps aboard ships [230] are some of the positive effects of BT in the maritime industry. In addition, a blockchain-based approach and identification mechanism may raise people's awareness of the need to control marine plastic debris, which is a problem that affects both the environment and human life [232]. On the contrary, some of the risks that come with using BT can be summed up as follows [233]:

- It is possible for smart contracts to be misunderstood, and smart contracts frequently need to be updated to account for shifting circumstances in the real world. As a result, there may be discrepancies between what is expected of them and what really happens.
- There can be cyberattacks against elements of the blockchain, such as ledger and blockchain maintenance nodes.
- Failures of the hardware or infrastructure upon which the blockchain system is based can happen.
- There may be unintentional exposure or leakage of private company information.
- This technology may result in infrastructure failures, smart contract hazards, delays in payment processing, and bottlenecks throughout the supply chain.

Automotive Industry

The automotive industry is the most affected and challenging sector, especially after COVID-19 pandemic [234]. BT provides great advantages in automobile industry [235], particularly for internet-connected or autonomous automobiles [236]. In many global supply chains, there is a lack of information transparency, which may lead to product quality uncertainties. For this reason, information flows should be developed for automotive products from supply chain raw material to sales distribution [235]. BT can be utilized to build a trustworthy peer-to-peer network [236] and is also guaranteed to make solving environmental problems and challenges with the global supply chain easier [237].

The problem of sustainability is more significant nowadays due to growing environmental concerns, pressure on businesses from customers, communities, as well as national and international government representatives [237], and the circular economy's integration with Industry 4.0 components like BT [238]. Supply chains can be more sustainable and flexible by using the latest technologies [234,239]. For example, through the influence on the adoption of green supply chain practices in the automotive industry, Industry 4.0 technologies have an influence on the performance of the supply chain [240].

Integrating blockchain increases item traceability and decreases waiting times, increasing supply chain operating efficiency [241]. For example, Daimler created a blockchain-based platform to record all financial and transaction information about the lifecycle of a vehicle. This will be the basis for all subsequent information, including vehicle delivery, registration, maintenance, and last kilometer. Since each vehicle will have a separate digital identity, users can monitor and examine the whole traffic history [235].

In terms of raw material traceability, information monitoring, immutability, and cost savings, BT has paved the way for the sustainable growth of the automotive supply chain [235]. For these reasons, it is now important to research how BT promotes supply chain sustainability [237]. Xu et al. [235] conducted a case study examining the supply chains of some automotive companies such as Daimler, Wolkswagen. Research results show that recycling and remanufacturing procedures significantly increase the efficiency of car components. For instance, the system should incorporate procedures like the usage of batteries with sustainable qualities in the electric vehicle industry [237]. About a century later, due to existing technological developments, electrical automobiles seem to have a multi-faceted development compared to traditional cars. To reduce global CO_2 emissions, the automobile industry is switched to electric motors from internal combustion engines. The need for more flexible, cost-effective, and high-quality mobility solutions directs the industry to increase expenditures on smart and sustainable technologies [242]. To obtain long-term cost savings without decreasing the quality of their goods, it is advised that automakers invest more in recycling technologies [237].

In addition, there are also some obstacles that have been emphasized, such as lack of internal and external cooperation, lack of technical infrastructure, uncertainty of high return on investment, lack of digitization in the supply chain, security issues, difficulty in combining existing software, and procedures with the blockchain structure [235].

Healthcare and Pharmaceutical Industries

BT has generated interest from all over the world because it has the potential to revolutionize sustainable supply chain management in the healthcare industry [243]. In particular, the COVID-19 pandemic has had a huge impact on the healthcare industry on a global scale, resulting in serious difficulties for multi-layered supply chain management [244] and raised questions about the long-term viability of the healthcare system [245,246]. These concerns have accelerated the adoption of digital technology, and one of these emerging digital technologies is blockchain, which stands out for a variety of reasons [243]. The benefits of using blockchain in the healthcare industry include increased performance efficiency, higher patient satisfaction, openness, and traceability [243,247].

The existing pharmaceutical supply chains have issues as well; for instance, it restricts manufacturers and regulatory bodies insight into and control over the distribution of pharmaceuticals; cannot resolve the issue with cyber security [248]. To avoid medicine shortages or waste in any healthcare facility, an effective system of supply management should be put in place. The efficacy of pharmaceutical supply chains can be affected by the adoption of blockchain, which will also have an impact on the organization's supply chain sustainability [248]. In addition, by tracking and monitoring in near-real time just the medical deliveries that need refrigeration for temperature changes along their supply chain path, blockchain with RFID tags and other intelligent IoT technologies might help lower transportation-related costs [249].

Drug counterfeiting is a global problem with significant risks to consumers and the public in general, as well as threatening the reputation of the pharmaceutical industry [249,250]. The implementation of BT in pharmaceutical supply chains to support traceability is recommended in reviewed studies [248–250]. Controlling illegal actions, promoting sustainability performance, boosting operational efficiency, improving supply-chain coordination, and detecting market trends are identified to be the business requirements for traceability systems [249]. Companies' expertise, teamwork, technical maturity, supply chain practices, leadership, and governance of the traceability activities are crucial success elements for implementation [249].

The reviewed publications in the healthcare industry focused on medical and personal protective equipment (PPE) and the use of blockchain in the blood bank supply chain [244,245,247]. It is suggested that BT can be integrated into the system by utilizing IoT and other technologies [244,247]. In most studies, model proposals have been developed in which the blockchain is integrated into the health system. By exchanging real-time supply-demand data between each blood bank and hospital using BT, for instance, there will not be any issues such as maintaining more blood inventory than necessary, according to a research model for a blood bank proposed in [247]. Patient satisfaction can also be increased as the required blood will be swiftly called through the system and delivered to the patient.

Mining and Mineral Industries

There are various abuses or damages caused by many mining and mineral applications. Cobalt, for example, is used for many different purposes including the production of lithium-ion batteries for electronic devices but mining practices associated with cobalt are notorious for violations of human rights, such as child and slave labor [249,251].

To maintain sustainability, ethical practices in the mining and mineral industries have been recommended emphasizing the role of blockchain [251–253]. Industry initiatives are being made to increase the sustainability of mineral supply chains by using digital certification and traceability [254]. Blockchain-based systems are currently placing a lot of attention on the chain of custody governance and traceability in the cobalt supply chain, such as providing secure information about the circumstances of raw material extraction and processing and transmitting this information to businesses along the supply chain and all the way down to the brand user [249,251,253]. Blockchain technologies make guarantees that information is communicated in a way that cannot be altered and is available to the relevant actors, making it easy to track items between several supply chain levels [252].

For example, the Congolese cobalt industry uses BT to store and transport data using distributed ledger technology. The information traces the evolution of the minerals from their original state to that of hydroxide, sulfate, cathode, and ultimately batteries. Even though there are hundreds of suppliers in this intricate supply chain, data on child labor, poor working conditions, and other dangers is kept up to date and available to the user [253]. Significant technologies other than blockchain are a crucial component; for example, IBM conducts chemical analysis research using AI technology to determine the origin of cobalt [252].

The minerals in which BT is used vary in terms of the processes involved. Compared to minerals like cobalt, diamond-tracking blockchain technologies are easier to use. For instance, while one company preserves the distinct identities of diamonds generated from more than 40 attributes, minerals like cobalt tracked by other companies go through challenging steps like smelting and refining, making it challenging to adopt a perfect approach [252].

BT can effectively build the chain of trust between enterprises in the coal industry (e.g., realizing data encryption, information sharing and credit transmission of enterprises, reducing human intervention and operational risks with the help of smart contracts) and greatly enhance the growth of supply chain finance in the coal industry [255].

The interaction between the blockchain and trust is investigated in the metal industry, focusing on steel and copper supply chains [256], and BT is viewed as a very promising technology regarding trust in the supply chain partner, particularly in the context of sustainability. When technology trust is investigated, there is a lot of dependence on records that have previously undergone authentication testing (such as "eco-labels" that track the sustainability qualities of items). However, there is still a lot of reliance on third-party certificates in the metal industry, since there is less confidence in the data's reliability or accuracy [256]. In addition, blockchain-enabled traceability solutions can fall short of challenging the access and resource usage disparities that already exist [254].

Energy Industry

Decarbonization, digitization, and decentralization are the three "Ds" of the energy transition [257]. According to the International Energy Agency's key benchmarks for monitoring development in the energy sector, transport emissions must be decreased by 43% by 2030 [258]. Incorporating BT is crucial for enhancing the trust, accountability, transparency, cooperation, and information sharing in supply chains for sustainable energy [259]. Blockchain can uncover the enormous potential of linking decentralized grid-end nodes and offer a common network for peer-to-peer energy transactions between parties by eliminating the restrictions imposed by a centralized supply chain [257].

BT has mostly focused on sustainable energy. Consumers increasingly desire a smarter, cleaner, and more sustainable energy source than in the past due to technological advancements and the declining cost of renewable energy [260]. In addition, energy-efficient smart homes are getting more and more attention. Every prosumer aspires to create a more cost- and energy-efficient, sustainable house [261]. BT encourages the adoption of renewable energy sources. The global energy industry is becoming smarter as a result of the advent of smart devices and supporting software, as well as the declining cost of renewable energy [260].

Applications for blockchain have the power to significantly improve and change current energy networks. Schletz et al. [262] created a pilot model to investigate blockchain application in energy supply systems. This architecture uses IoT devices to gather and assess real-time energy production and demand data. When a generator produces more energy than it needs, the extra is delivered to the local grid and sold to a different nearby generator in the blockchain-based marketplace. When a manufacturer requires energy, IoT devices automatically purchase it from the blockchain market, or they turn the devices off to reduce energy use. When energy prices are low, IoT devices use more energy, and when energy prices are high, they use less. This process makes flexible pricing possible and eliminates a monopolistic market structure.

BT benefits the energy industry in several ways, enabling both small and large businesses to operate in an energy efficient manner, and thus offering an advantage for the emergence of new business models that can increase energy efficiency in developing countries [262]. Ensuring the entry of small renewable energy producers into the energy market, the elimination of uncertainties in product supply and price through smart contracts, and helping regulators to document energy transactions (transparency in carbon emissions, etc.) can also be counted among these benefits [260]. Moreover, decentralized and distributed trading systems are made possible by BT, which also creates a more reliable, secure, and transparent trading environment [261]. Adoption of BT is, however, hampered by the main obstacle, which is regulatory uncertainties as current regulatory frameworks do not support blockchain as a possible technology or allow energy trade from prosumers to consumers [262]. In addition, the other significant obstacle to the use of blockchain in sustainable energy supply chains is determined to be "high investment cost" [259].

4.2.2. The Methodology-Based Evaluations

The methods and theories included in the studies examined are given in Table 5.

Table 5. Methods and Theories Used in the Publications.

Industry	Categories	F	Publications
Food and Agriculture	**Methods**		
	Quantitative	31	[31,43,79,97,109,114,118,123,125,129,136,142,151,160,161,165,167,175,176,179–181,183,188,191,194,263–266]
	Qualitative	8	[109,121,129,148,182,195,267,268]
	Proposal (model, architecture, etc.)	24	[79,100,102,103,112,125,128,130,135,146,147,158,159,162,166,172–174,187,189–191,193,269]
	Case Study	28	[42,77,101,110,111,115,126,131–133,137–139,141,144,146,149,152–154,156,177,181,184,185,187,192,267]
	Literature Review	47	[42,43,79,95,96,98,99,104–108,110,113,115–117,119,120,122,127,129,132–134,137,138,140,143,145,146,150,155,157,163,164,168–171,177,178,186,190,196,267,270]
	Theories		
	Critical Success Factors Theory	1	[263]
	Cumulative Prospect Theory	1	[31]
	Game Theory	2	[161,175]
	Technology, Organization, Environment Theory	2	[176,180]
	Unified Theory of Acceptance and Use of Technology	1	[176]
	E-CAOS Model	1	[141]
	System Theory and System Dynamics Modelling	1	[184]
	Innovation Resistance Theory	1	[148]
	Information Processing Theory	1	[194]
	Dynamic Capability Theory	1	[194]
Fashion, Textile, and Apparel	**Methods**		
	Quantitative	4	[202,208,211,212]
	Qualitative	1	[209]
	Proposal (model, architecture, etc.)	3	[197,206,271]
	Case Study	8	[198,200,203,205–207,210,272]
	Literature Review	4	[198,201,204,271]
	Theories		
	Social Capital and Resource Based Theory	1	[210]
	Diffusion of Innovation Theory	1	[211]
Manufacturing	**Methods**		
	Quantitative	9	[215–221,223,273]
	Qualitative	1	[273]
	Proposal (model, architecture, etc.)	1	[223]
	Case Study	4	[213–215,223]
	Literature Review	2	[213,222]
	Theories		
	Resource Based Theory and Network Theory	1	[218]
	Technology, Organization, Environment Theory	1	[219]
	Unified Theory of Acceptance and Use of Technology	1	[220]
Maritime and Shipping	**Methods**		
	Quantitative	1	[226,233]
	Qualitative	1	[228,233]
	Proposal (model, architecture, etc.)	3	[224,225,227]
	Case Study	5	[225,227–229,232]
	Literature Review	3	[227,230,231]
	Theories		
	Technology Acceptance Model Theory	1	[229]

Table 5. *Cont.*

Industry	Categories	F	Publications
Automotive	**Methods**		
	Quantitative	5	[234,236–238,240]
	Proposal (model, architecture, etc.)	3	[239,241,242]
	Case Study	2	[234,235]
	Theories		
	Dynamic Capabilities Theory	1	[236]
	Technology, Organization, Environment Theory	1	[235]
Healthcare and Pharmaceutical	**Methods**		
	Quantitative	2	[243,247]
	Qualitative	1	[249]
	Proposal (model, architecture, etc.)	3	[245,248,250]
	Case Study	1	[246]
	Literature Review	1	[244]
	Theories		
	Technology Adoption Models Theory and Task-Technology Fit	1	[247]
	Graph Theory and Matrix Approach Theory	1	[246]
	Unified Theory of Acceptance and Use of Technology	1	[250]
Mining and Mineral	**Methods**		
	Qualitative	3	[249,254,256]
	Proposal (model, architecture, etc.)	2	[251,255]
	Case Study	2	[252,256]
	Literature Review	2	[251,253]
Energy	**Methods**		
	Qualitative	2	[258,259]
	Proposal (model, architecture, etc.)	1	[261]
	Case Study	3	[259,260,262]
	Literature Review	1	[257]

4.2.3. Future Directions

There are general directions that are independent of the industry and industry-based suggestions when the future directions of the studies are considered. After the general directions are given below, the industry-specific directions are given next to the industry name.

The application of BT in different industries is recommend in studies [197,205,209]. Many companies offer BT solutions with a limited scope (only with the pilot projects) but on the other hand, they need a ready-made solution. To take full benefits of BT, suitable systems should be developed in the future that includes required infrastructure, standard operating procedures, strict quality norms and skilled human resources [135]. It will be beneficial to create complex socio-technical systems that call for multidisciplinary skills from a variety of fields, including computer science, the social sciences, and business [157]. Future studies can also investigate how engineers, operational professionals, and the academic community can work together to improve the reliability of the blockchain system [229], to create standards and offer useful performance metrics for the use of BT [223].

In addition, as certification firms are crucial to the supply chain participants' compliance, certification organizations' roles in supply chains may be further investigated and operationalized [206]. Future research might also focus on the elements influencing the success or failure of blockchain after adoption [223]. The employees must also receive the necessary training in order to handle and utilize this cutting-edge technology [273]. Analyzing the return on investment or performing the cost-benefit analysis of the proposed architecture for adoption and scaling up can also be an important area of future work [191].

New ideas have emerged that connect BT with various Industry 5.0 technologies such as big data, the IoT, radio frequency identification (RFID), near-field communication (NFC) [96], artificial intelligence, augmented reality, autonomous robot, digital twin, virtual reality and, 3D printing that can be taken into account in future studies [270].

Research on implementing BT in sustainable supply chain management is still in its early stages. More study is required to fully explore the potential of BT in various industries considering various nations [232]. Future work intends to use parameters like finance, policy, pollution, and energy to evaluate sustainable/smart BT [263]. Furthermore, other highlighted challenges, such as regulatory, technical, and interoperability issues, should be addressed in more detail [116]. As studies have concentrated more on the economic aspect of sustainability, it is necessary to look into the social sustainability of access rights and privacy concerns of the BT integration [227] and environmental aspects [236].

- *Food and Agriculture Industries:* Despite its many benefits, the real implementation of blockchain in the agricultural food supply chain is still in its infancy [79,153,180,264]. Much research should be done to use it to create reliable and secure decentralized apps [172]. Unvalidated sustainable e-agriculture implementation and non-informalized sustainable analysis are still understudied as developing themes [106]. The biggest issue with this is that there are not many incidents of it happening, and the direct and indirect social and environmental benefits of the technologies have not been properly tracked down or measured yet. Longitudinal studies could be very helpful to detect the direct and indirect social and environmental benefits of the technologies in the long run [153,268]. It would also be helpful to compare the effects on different supply chains, including long and short FSCs [153].
- *Fashion, Textile and Apparel Industries:* Since the implementation of BT is complicated, future research can focus more on to examine the challenges related to implementation in these industries [197], and the interaction and integration of diverse blockchain systems [206]. Considering the methodological point of view, case studies are based on a small sample in the reviewed studies, as very few brands and suppliers in the fashion, textile, and apparel industries are starting to adopt the use of blockchain. Therefore, future studies may include more brands and suppliers [203]. Additionally, other than qualitative case studies, it is advised to use quantitative techniques to create robust inferences in cases [205,210].
- *Manufacturing Industry:* Future research is suggested to focus on the creation of an integrated technological application framework to combine blockchain and artificial intelligence in the manufacturing sector [213]. In addition, the multi-cloud seamless method for collaborative enterprise management, wherein corporate information systems based on various clouds are capable of handling synchronous workloads, can be the focus of future research [214]. Future research should involve more companies and larger sample of areas or countries [218]. For instance, the reviewed studies focused on Malaysian [218], Danish [215], and Chinese [220] manufacturing companies. More research is also needed to compare BT uses in both traditional manufacturing and remanufacturing [215]. It is advised that the government enact necessary regulations to encourage the use of BT throughout the nation or industry (manufacturing) [273]. Although the concept of combining BT with additive manufacturing is recommended, in practice it is considerably more complicated, and more research should be conducted [222]. A blockchain-based additive manufacturing system will need to work in harmony with a variety of stakeholders [222].
- *Maritime and Shipping Industries:* On various maritime information infrastructures, cross-sectional and longitudinal case studies can be carried out [225] as more case studies needed to generalize the findings [227]. Regarding the many aspects, including environmental, business internal, and technological, a study on the collaboration between shipping companies and shippers is suggested [226]. By creating an end-to-end blockchain network combining smart contracts with machine learning features for the global process of exporting and importing, future research can further utilize the

shipping sector [229]. In addition to a risk-focused strategy, examining the difficulties and suggested adaptive techniques in implementing a blockchain integrated system may provide a more thorough understanding of blockchain's potential in the maritime shipping industry [233]. Moreover, future studies can concentrate on examining the unique characteristics of maritime industry in comparison to other industries in terms of blockchain acceptability, as well as the role of government authorities in terms of the adoption and usage of the technology [231].

- *Automotive Industry:* Since research generally is based on the data taken from the automobile industry of a particular country (for example, India), it would not be correct to generalize the results of the studies in this sector to the whole world. The results will likely be different for less developed countries with limited organizational skills and access to information resources [236]. Future researchers can extend the models used by using complex mathematical modeling and simulations to reveal the underlying phenomena between variables [237].
- *Healthcare and Pharmaceutical Industries:* The examined publications' recommendations for future research emphasized the need for governments to assist the use of BT by enterprises for innovative solutions [247]. It is also crucial to consider other aspects of the healthcare industry and the various types of equipment that are used [244]. In addition, many methods can be used, including real case studies and additional mathematical and empirical modeling tools for these industries BT applications [245].
- *Mining and Mineral Industries:* Like other industries, more case studies and quantitative analysis are required for mining and mineral industries in future studies [256]. Future studies might compare blockchain versus non-blockchain solutions more thoroughly in terms of costs and other factors, and look at the relationship between consumers' traits and how they respond to BT-based items [252]. It is also important to carefully consider how mandatory and optional frameworks of blockchain implementations differ from one another [253].
- *Energy Industry:* Blockchain adoption in energy research is still in its early stages [257,260,262]. Future research needs to obtain empirical data from pilot studies [262]. The findings in [260] stressed the significance of incentives for the energy industry. The establishment of research platforms and the study of BT should be supported by several institutions, such as companies, institutions, and universities. In addition, governments should streamline management processes and increase management levels and efficiency to safeguard energy blockchain innovation. In future studies, a blockchain-based energy transaction platform can be implemented in a smart home environment. In addition, long-term comparisons can be made by calculating the energy costs between a normal home and a smart home using the recommended platform [261].

5. Discussion and Conclusions

The use of BT in increasingly digitalized and globalized supply chains and logistics has been explored in the context of sustainability using a mixed-method approach. This study includes 552 studies published between 2017 and September 2022 in the Scopus and WoS databases on blockchain and sustainability in supply chains and logistics for bibliometric analysis. Studies focusing on certain industries were assessed among the publications collected in the bibliometric study, and a total of 185 articles were reached for content analysis. The study provides the current state of the research components with bibliometric indicators as well as appreciates the industry-based view of the field using content analysis.

To address the first research question (RQ1), the status of the research on blockchain and sustainability, various bibliometric analyses and rules have been applied. The results of the distribution of publications over the years (RQ1.1) show that this field is on the rise as stated in [3,26], and the field has attracted more attention since 2019, showing an annual growth rate of 152.19%. To identify top research components (sources, authors, affiliations, countries, keywords) and how they relate (RQ1.2), three-field analysis is used. Joseph Sarkis [1,2,40,76,180] is the most productive author with more relationships with the main research field and many of the listed core journals. Many top-productive authors have published their studies in *Sustainability*, *Annals of Operations Research and Business Strategy*, and *The Environment* journals. For the top keywords, other than search strings, IoT, circular economy, Industry 4.0, COVID-19, and agri-food keywords indicate relationships with top authors. For the top countries, China and India have more relationships with top affiliations. Many collaborations between countries, affiliations, and authors are also detected, such as, The Hanken School of Economics (Finland) has relationships with Finland, the USA, Denmark, China, and France and many top authors.

It is also investigated whether the research collection complies with Bradford's Law and Lotka's Law (RQ1.3), and it was found to confirm. Source clustering and author productivity calculations with bibliometric laws highlight that there are a few journals (e.g., *Sustainability*, *Journal of Cleaner Production*, and *International Journal of Production Research*) that publish many articles and many journals that publish few articles. Similarly, 84.5% of authors publish only one article in the research field. The top cited publications are investigated (RQ1.4), and it is found that Saberi et al. [76], providing an overview of BT, its use in supply chains, and the challenges it faces, have the most citations in the field.

When the discovered themes are examined (RQ1.5), in accordance with the statements about the themes' persistency in [81], it can be concluded that since IoT, traceability, and Industry 4.0 have been studied for all time periods, these themes have a greater likelihood of remaining in the next periods. In addition, COVID-19 with food industry themes can also be prevalent and popular in later periods because they appear as motor themes in this year's map, and the effects of COVID-19 have been studied by researchers in recent years (e.g., Galanakis et al. [164] discuss potential innovations (internet and communication technologies, blockchain, etc.) for the food industry affected by the pandemic). Since carbon emission, supply chain finance, and renewable energy themes are located in emerging themes, the development of these themes can gain popularity if they receive interest from researchers.

The themes highlighted by the bibliometric study, such as COVID-19 and traceability, were expanded upon by industry-specific content analysis. Food and agriculture are the most popular industry in this discipline, followed by fashion, textile, and apparel, while energy is the least popular industry. To appreciate the industry-based insights of the research on blockchain and sustainability in supply chains (RQ2), the benefits, challenges, and uses of BT (RQ2.1), the methods and theories (RQ2.2), and future directions (RQ2.3) in the research collection are investigated.

One of the most significant benefits of using blockchain in supply chains, according to findings, is its potential strength in enabling the development of a more sustainable system for all industries. The other benefits are as follows: transparency, traceability [128,129,134,201,202,231,243,247–250,259], fewer negative environmental effects [143], quality assurance, resilient and more efficient supply chain systems, [97,125,129,216], real-time management, utilization of resources [98], cost efficiency [126,139,216,218], increased synergy between supply chain actors [156], improved visibility and the immutability of records [98,126,129,153–156], and reduced fraud and counterfeiting attempts [102,110,123,135,149,157–159]. On the other hand, there are challenges, such as the lack of resources for technical expertise, education, and training [99,167,235], lack of awareness and knowledge [118,203,204,215,223], high investment costs [175,176,259], regulatory, governmental [168,237,262], operational [215], scalability [98,170–172,203,204,215], and security and privacy [79,178,179,203,204,235] issues.

Usage areas of blockchain-based sustainable supply chains include e-farming applications [31,106,113,114], open to trace food tracking systems from farm to fork [80,105,109,146,163–166], detection of counterfeiting in fashion products (e.g., luxury bags, dresses) [201,209], plastic recycling, steel manufacturing, additive manufacturing, and cloud manufacturing [213,221], determining routes and destinations in shipping [226,229], customs procedures [229], processes between blood banks and hospitals [244,245,247], renewable energy systems [260], and the journey of precious minerals and metals [252,253,256]. It has been suggested that expanding the use of BT across all industries can provide more fruitful outcomes such as the development of global, data-driven, intelligent, agile, and autonomous systems in supply chains [98,101,104,105,111,112], and advance the realization of sustainability in all its forms: economic, social, and environmental. IoT, digital twins, AI, machine learning, cloud computing, and RFID are some of these technologies [99,109,110].

When the methods used are examined, it is seen that quantitative, qualitative, proposal (model, architecture, etc.), case study and literature review studies are carried out. Considering industries, literature reviews for food and agriculture, case studies for fashion, textile, and apparel, maritime and shipping, and energy, quantitative studies for manufacturing and automotive, proposal studies for healthcare and pharmaceuticals, qualitative studies for mining and minerals are the most used. When theory usage is evaluated, it has been observed that theories are employed very rarely in studies overall and not at all in studies of the mining, mineral, and energy industries. The Technology, Organization, Environment Theory is used in the food and agriculture [176,180], manufacturing [219], and automotive [235] industries. The Unified Theory of Acceptance and Use of Technology is also utilized in different industries: food and agriculture [176], manufacturing [220], and healthcare and pharmaceutical [250].

When the directions for future research are considered, it is highlighted that more research should be done and that various institutions should collaborate to work in this area, increase incentives (for instance, by governments), and diversify the use of BT with innovations like IoT, RFID, digital twins, big data, and artificial intelligence.

Author Contributions: Conceptualization, S.S.-T., B.A. and E.G.; Methodology, B.A.; Software, B.A.; Formal analysis, B.A. and E.G.; Investigation, B.A. and E.G.; Resources, B.A. and E.G.; Data curation, B.A.; Writing—original draft preparation, B.A and E.G.; Writing—review and editing, S.S.-T., B.A. and E.G.; Visualization, B.A.; Supervision, S.S.-T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

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

References

1. Kouhizadeh, M.; Saberi, S.; Sarkis, J. Blockchain Technology and the Sustainable Supply Chain: Theoretically Exploring Adoption Barriers. *Int. J. Prod. Econ.* **2021**, *231*, 107831. [CrossRef]
2. Saberi, S.; Kouhizadeh, M.; Sarkis, J. Blockchains and the Supply Chain: Findings from a Broad Study of Practitioners. *IEEE Eng. Manag. Rev.* **2019**, *47*, 95–103. [CrossRef]
3. Lim, M.K.; Li, Y.; Wang, C.; Tseng, M.-L. A Literature Review of Blockchain Technology Applications in Supply Chains: A Comprehensive Analysis of Themes, Methodologies and Industries. *Comput. Ind. Eng.* **2021**, *154*, 107133. [CrossRef]
4. Gad, A.G.; Mosa, D.T.; Abualigah, L.; Abohany, A.A. Emerging Trends in Blockchain Technology and Applications: A Review and Outlook. *J. King Saud Univ.-Comput. Inf. Sci.* **2022**, *34*, 6719–6742. [CrossRef]
5. Beamon, B.M. Supply Chain Design and Analysis: Models and Methods. *Int. J. Prod. Econ.* **1998**, *55*, 281–294. [CrossRef]
6. Breese, J.L.; Park, S.-J.; Vaidyanathan, G. Blockchain Technology Adoption in Supply Change Management: Two Theoretical Perspectives. *Issues Inf. Syst.* **2019**, *20*, 140–150. [CrossRef]
7. Munir, M.A.; Habib, M.S.; Hussain, A.; Shahbaz, M.A.; Qamar, A.; Masood, T.; Sultan, M.; Mujtaba, M.A.; Imran, S.; Hasan, M.; et al. Blockchain Adoption for Sustainable Supply Chain Management: Economic, Environmental, and Social Perspectives. *Front. Energy Res.* **2022**, *10*, 899632. [CrossRef]
8. Khan, S.A.; Mubarik, M.S.; Kusi-Sarpong, S.; Gupta, H.; Zaman, S.I.; Mubarik, M. Blockchain Technologies as Enablers of Supply Chain Mapping for Sustainable Supply Chains. *Bus. Strategy Environ.* **2022**, *31*, 3742–3756. [CrossRef]
9. Rejeb, A.; Rejeb, K. Blockchain and supply chain sustainability. *Logforum* **2020**, *16*, 363–372. [CrossRef]
10. Pagell, M.; Shevchenko, A. Why Research in Sustainable Supply Chain Management Should Have No Future. *J. Supply Chain Manag.* **2014**, *50*, 44–55. [CrossRef]
11. Seuring, S.; Müller, M. From a Literature Review to a Conceptual Framework for Sustainable Supply Chain Management. *J. Clean. Prod.* **2008**, *16*, 1699–1710. [CrossRef]

12. Rajeev, A.; Pati, R.K.; Padhi, S.S.; Govindan, K. Evolution of Sustainability in Supply Chain Management: A Literature Review. *J. Clean. Prod.* **2017**, *162*, 299–314. [CrossRef]
13. Saeed, M.A.; Kersten, W. Drivers of Sustainable Supply Chain Management: Identification and Classification. *Sustainability* **2019**, *11*, 1137. [CrossRef]
14. Nitsche, B.; Straube, F. Defining the "New Normal" in International Logistics Networks: Lessons Learned and Implications of the COVID-19 Pandemic. *WiSt—Wirtsch Stud.* **2021**, *50*, 16–25. [CrossRef]
15. Pritchard, A. Statistical Bibliography or Bibliometrics. *J. Doc.* **1969**, *25*, 348.
16. Noyons, E.C.; Moed, H.F.; Luwel, M. Combining Mapping and Citation Analysis for Evaluative Bibliometric Purposes: A Bibliometric Study. *J. Am. Soc. Inf. Sci.* **1999**, *50*, 115–131. [CrossRef]
17. Noyons, E.; Moed, H.; Van Raan, A. Integrating Research Performance Analysis and Science Mapping. *Scientometrics* **1999**, *46*, 591–604. [CrossRef]
18. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to Conduct a Bibliometric Analysis: An Overview and Guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
19. Gaur, A.; Kumar, M. A Systematic Approach to Conducting Review Studies: An Assessment of Content Analysis in 25 Years of IB Research. *J. World Bus.* **2018**, *53*, 280–289. [CrossRef]
20. Seuring, S.; Gold, S. Conducting Content-Analysis Based Literature Reviews in Supply Chain Management. *Supply Chain Manag. Int. J.* **2012**, *17*, 544–555. [CrossRef]
21. Drisko, J.W.; Maschi, T. Content Analysis. In *Pocket Guide to Social Work Re*; Oxford University Press: Oxford, UK, 2016.
22. Krippendorff, K. Content Analysis. In *An Introduction to Its Methodology*; Sage Publications: Thousand Oaks, CA, USA, 2018.
23. Morris, R. Computerized Content Analysis in Management Research: A Demonstration of Advantages&Limitations. *J. Manag.* **1994**, *20*, 903–931.
24. Mody, M.A.; Hanks, L.; Cheng, M. Sharing Economy Research in Hospitality and Tourism: A Critical Review Using Bibliometric Analysis, Content Analysis and a Quantitative Systematic Literature Review. *Int. J. Contemp. Hosp. Manag.* **2021**, *33*, 1711–1745. [CrossRef]
25. Nagariya, R.; Kumar, D.; Kumar, I. Service Supply Chain: From Bibliometric Analysis to Content Analysis, Current Research Trends and Future Research Directions. *Benchmarking Int. J.* **2020**, *28*, 333–369. [CrossRef]
26. Fallahpour, A.; Wong, K.Y.; Rajoo, S.; Fathollahi-Fard, A.M.; Antucheviciene, J.; Nayeri, S. An Integrated Approach for a Sustainable Supplier Selection Based on Industry 4.0 Concept. *Environ. Sci. Pollut. Res.* **2021**, 1–19. [CrossRef] [PubMed]
27. Sahoo, S.; Kumar, S.; Sivarajah, U.; Lim, W.M.; Westland, J.C.; Kumar, A. Blockchain for Sustainable Supply Chain Management: Trends and Ways Forward. *Electron. Commer. Res.* **2022**, 1–56. [CrossRef]
28. Crosby, M.; Pattanayak, P.; Verma, S.; Kalyanaraman, V. Blockchain Technology: Beyond Bitcoin. *Appl. Innov.* **2016**, *2*, 71.
29. Yuan, Y.; Wang, F.-Y. Towards Blockchain-Based Intelligent Transportation Systems. In Proceedings of the 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), Rio de Janeiro, Brazil, 1–4 November 2016; pp. 2663–2668. [CrossRef]
30. Treiblmaier, H. The Impact of the Blockchain on the Supply Chain: A Theory-Based Research Framework and a Call for Action. *Supply Chain Manag. Int. J.* **2018**, *23*, 545–559. [CrossRef]
31. Zkik, K.; Belhadi, A.; Khan, S.A.R.; Kamble, S.S.; Oudani, M.; Touriki, F.E. Exploration of Barriers and Enablers of Blockchain Adoption for Sustainable Performance: Implications for e-Enabled Agriculture Supply Chains. *Int. J. Logist. Res. Appl.* **2022**, 1–38. [CrossRef]
32. Zhao, J.L.; Fan, S.; Yan, J. Overview of Business Innovations and Research Opportunities in Blockchain and Introduction to the Special Issue. *Financ. Innov.* **2016**, *2*, 28. [CrossRef]
33. Kshetri, N. Can Blockchain Strengthen the Internet of Things? *IT Prof.* **2017**, *19*, 68–72. [CrossRef]
34. Hackius, N.; Petersen, M. Blockchain in Logistics and Supply Chain: Trick or Treat? In *Digitalization in Supply Chain Management and Logistics: Smart and Digital Solutions for an Industry 4.0 Environment, Proceedings of the Hamburg International Conference of Logistics (HICL), Hamburg, Germany, 12–14 October 2017*; Epubli GmbH: Berlin, Germany, 2017; Volume 23, pp. 3–18. [CrossRef]
35. Schlegel, M.; Zavolokina, L.; Schwabe, G. Blockchain Technologies from the Consumers' Perspective: What Is There and Why Should Who Care? In Proceedings of the Proceedings of the 51st Hawaii International Conference on System Sciences, Hilton Waikoloa Village, Hawaii, USA, 3–6 January 2018.
36. Coita, D.C.; Abrudan, M.M.; Matei, M.C. Effects of the Blockchain Technology on Human Resources and Marketing: An Exploratory Study. In *Strategic Innovative Marketing and Tourism*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 683–691.
37. Waters, D. Logistics. In *Supply Chain Management. M.: UNITI-DANA.*; Kogan Page: London, UK, 2003.
38. Min, H.; Zhou, G. Supply Chain Modeling: Past, Present and Future. *Comput. Ind. Eng.* **2002**, *43*, 231–249. [CrossRef]
39. Vonderembse, M.A.; Uppal, M.; Huang, S.H.; Dismukes, J.P. Designing Supply Chains: Towards Theory Development. *Int. J. Prod. Econ.* **2006**, *100*, 223–238. [CrossRef]
40. Hervani, A.A.; Helms, M.M.; Sarkis, J. Performance Measurement for Green Supply Chain Management. *Benchmarking Int. J.* **2005**, *12*, 330–353. [CrossRef]
41. Gunasekaran, A.; Ngai, E.W. Information Systems in Supply Chain Integration and Management. *Eur. J. Oper. Res.* **2004**, *159*, 269–295. [CrossRef]

42. Park, A.; Li, H. The Effect of Blockchain Technology on Supply Chain Sustainability Performances. *Sustainability* **2021**, *13*, 1726. [CrossRef]
43. Mukherjee, A.A.; Singh, R.K.; Mishra, R.; Bag, S. Application of Blockchain Technology for Sustainability Development in Agricultural Supply Chain: Justification Framework. *Oper. Manag. Res.* **2021**, *15*, 46–61. [CrossRef]
44. Carter, C.R.; Rogers, D.S. A Framework of Sustainable Supply Chain Management: Moving toward New Theory. *Int. J. Phys. Distrib. Logist. Manag.* **2008**, *38*, 360–387. [CrossRef]
45. Rejeb, A.; Rejeb, K.; Simske, S.; Treiblmaier, H. Blockchain Technologies in Logistics and Supply Chain Management: A Bibliometric Review. *Logist.-Basel* **2021**, *5*, 72. [CrossRef]
46. Esen, M.; Bellibas, M.S.; Gumus, S. The Evolution of Leadership Research in Higher Education for Two Decades (1995–2014): A Bibliometric and Content Analysis. *Int. J. Leadersh. Educ.* **2020**, *23*, 259–273. [CrossRef]
47. Calabuig-Moreno, F.; Gonzalez-Serrano, M.H.; Alonso-Dos-Santos, M.; Gómez-Tafalla, A. Entrepreneurial Ecosystems, Knowledge Spillovers, and Their Embeddedness in the Sport Field: A Bibliometric and Content Analysis. *Knowl. Manag. Res. Pract.* **2021**, *19*, 65–83. [CrossRef]
48. Bretas, V.P.; Alon, I. Franchising Research on Emerging Markets: Bibliometric and Content Analyses. *J. Bus. Res.* **2021**, *133*, 51–65. [CrossRef]
49. Aria, M.; Cuccurullo, C. Bibliometrix: An R-Tool for Comprehensive Science Mapping Analysis. *J. Informetr.* **2017**, *11*, 959–975. [CrossRef]
50. Nafade, V.; Nash, M.; Huddart, S.; Pande, T.; Gebreselassie, N.; Lienhardt, C.; Pai, M. A Bibliometric Analysis of Tuberculosis Research, 2007–2016. *PLoS ONE* **2018**, *13*, e0199706. [CrossRef]
51. Derviş, H. Bibliometric Analysis Using Bibliometrix an R Package. *J. Scientometr. Res.* **2019**, *8*, 156–160. [CrossRef]
52. Firdaus, A.; Razak, M.F.A.; Feizollah, A.; Hashem, I.A.T.; Hazim, M.; Anuar, N.B. The Rise of "Blockchain": Bibliometric Analysis of Blockchain Study. *Scientometrics* **2019**, *120*, 1289–1331. [CrossRef]
53. Munim, Z.H.; Dushenko, M.; Jimenez, V.J.; Shakil, M.H.; Imset, M. Big Data and Artificial Intelligence in the Maritime Industry: A Bibliometric Review and Future Research Directions. *Marit. Policy Manag.* **2020**, *47*, 577–597. [CrossRef]
54. Rodríguez-Soler, R.; Uribe-Toril, J.; Valenciano, J.D.P. Worldwide Trends in the Scientific Production on Rural Depopulation, a Bibliometric Analysis Using Bibliometrix R-Tool. *Land Use Policy* **2020**, *97*, 104787. [CrossRef]
55. Moral-Muñoz, J.A.; Herrera-Viedma, E.; Santisteban-Espejo, A.; Cobo, M.J. Software Tools for Conducting Bibliometric Analysis in Science: An up-to-Date Review. *Prof. Inf.* **2020**, *29*, e290103. [CrossRef]
56. Zhu, J.; Liu, W. A Tale of Two Databases: The Use of Web of Science and Scopus in Academic Papers. *Scientometrics* **2020**, *123*, 321–335. [CrossRef]
57. Caputo, A.; Kargina, M. A User-Friendly Method to Merge Scopus and Web of Science Data during Bibliometric Analysis. *J. Mark. Anal.* **2022**, *10*, 82–88. [CrossRef]
58. Echchakoui, S. Why and How to Merge Scopus and Web of Science during Bibliometric Analysis: The Case of Sales Force Literature from 1912 to 2019. *J. Mark. Anal.* **2020**, *8*, 165–184. [CrossRef]
59. Dabbagh, M.; Sookhak, M.; Safa, N.S. The Evolution of Blockchain: A Bibliometric Study. *IEEE Access* **2019**, *7*, 19212–19221. [CrossRef]
60. Tandon, A.; Kaur, P.; Mäntymäki, M.; Dhir, A. Blockchain Applications in Management: A Bibliometric Analysis and Literature Review. *Technol. Forecast. Soc. Chang.* **2021**, *166*, 120649. [CrossRef]
61. Ejsmont, K.; Gladysz, B.; Kluczek, A. Impact of Industry 4.0 on Sustainability—Bibliometric Literature Review. *Sustainability* **2020**, *12*, 5650. [CrossRef]
62. Furstenau, L.B.; Sott, M.K.; Kipper, L.M.; Machado, E.L.; Lopez-Robles, J.R.; Dohan, M.S.; Cobo, M.J.; Zahid, A.; Abbasi, Q.H.; Imran, M.A. Link between Sustainability and Industry 4.0: Trends, Challenges and New Perspectives. *IEEE Access* **2020**, *8*, 140079–140096. [CrossRef]
63. Muessigmann, B.; von der Gracht, H.; Hartmann, E. Blockchain Technology in Logistics and Supply Chain Management—A Bibliometric Literature Review from 2016 to January 2020. *IEEE Trans. Eng. Manag.* **2020**, *67*, 988–1007. [CrossRef]
64. Muñoz-Villamizar, A.; Solano, E.; Quintero-Araujo, C.; Santos, J. Sustainability and Digitalization in Supply Chains: A Bibliometric Analysis. *Uncertain Supply Chain Manag.* **2019**, *7*, 703–712. [CrossRef]
65. Aria, M.; Cuccurullo, C. Package 'Bibliometrix'. *J. Informetr.* **2020**, *11*, 959–975. [CrossRef]
66. Janik, A.; Ryszko, A.; Szafraniec, M. Scientific Landscape of Smart and Sustainable Cities Literature: A Bibliometric Analysis. *Sustainability* **2020**, *12*, 779. [CrossRef]
67. Kumar, R.; Singh, S.; Sidhu, A.S.; Pruncu, C.I. Bibliometric Analysis of Specific Energy Consumption (SEC) in Machining Operations: A Sustainable Response. *Sustainability* **2021**, *13*, 5617. [CrossRef]
68. Mühl, D.D.; de Oliveira, L. A Bibliometric and Thematic Approach to Agriculture 4.0. *Heliyon* **2022**, *8*, e09369. [CrossRef] [PubMed]
69. Wang, J.; Li, X.; Wang, P.; Liu, Q. Bibliometric Analysis of Digital Twin Literature: A Review of Influencing Factors and Conceptual Structure. *Technol. Anal. Strateg. Manag.* **2022**, 1–15. [CrossRef]
70. Riehmann, P.; Hanfler, M.; Froehlich, B. Interactive Sankey Diagrams. In *Proceedings of the IEEE Symposium on Information Visualization, 2005. INFOVIS 200*; IEEE: Piscataway, NJ, USA, 2005; pp. 233–240.
71. Bradford, S.C. Sources of Information on Specific Subjects. *Engineering* **1934**, *137*, 85–86.

72. Kumar, A.; Mohindra, R. Bibliometric Analysis on Knowledge Management Research. *Int. J. Inf. Dissem. Technol.* **2015**, *5*, 106.
73. Tsay, M.; Li, C. Bibliometric Analysis of the Journal Literature on Women's Studies. *Scientometrics* **2017**, *113*, 705–734. [CrossRef]
74. Su, Y.-S.; Lin, C.-L.; Chen, S.-Y.; Lai, C.-F. Bibliometric Study of Social Network Analysis Literature. *Libr. Hi Technol.* **2020**, *38*, 420–433. [CrossRef]
75. Lotka, A.J. The Frequency Distribution of Scientific Productivity. *J. Wash. Acad. Sci.* **1926**, *16*, 317–323.
76. Saberi, S.; Kouhizadeh, M.; Sarkis, J.; Shen, L. Blockchain Technology and Its Relationships to Sustainable Supply Chain Management. *Int. J. Prod. Res.* **2019**, *57*, 2117–2135. [CrossRef]
77. Kshetri, N. 1 Blockchain's Roles in Meeting Key Supply Chain Management Objectives. *Int. J. Inf. Manag.* **2018**, *39*, 80–89. [CrossRef]
78. Hughes, L.; Dwivedi, Y.K.; Misra, S.K.; Rana, N.P.; Raghavan, V.; Akella, V. Blockchain Research, Practice and Policy: Applications, Benefits, Limitations, Emerging Research Themes and Research Agenda. *Int. J. Inf. Manag.* **2019**, *49*, 114–129. [CrossRef]
79. Kamble, S.S.; Gunasekaran, A.; Sharma, R. Modeling the Blockchain Enabled Traceability in Agriculture Supply Chain. *Int. J. Inf. Manag.* **2020**, *52*, 101967. [CrossRef]
80. Kamble, S.S.; Gunasekaran, A.; Gawankar, S.A. Achieving Sustainable Performance in a Data-Driven Agriculture Supply Chain: A Review for Research and Applications. *Int. J. Prod. Econ.* **2020**, *219*, 179–194. [CrossRef]
81. Cahlik, T. Search for Fundamental Articles in Economics. *Scientometrics* **2000**, *49*, 389–402. [CrossRef]
82. Cobo, M.J.; López-Herrera, A.G.; Herrera-Viedma, E.; Herrera, F. An Approach for Detecting, Quantifying, and Visualizing the Evolution of a Research Field: A Practical Application to the Fuzzy Sets Theory Field. *J. Informetr.* **2011**, *5*, 146–166. [CrossRef]
83. Aria, M.; Misuraca, M.; Spano, M. Mapping the Evolution of Social Research and Data Science on 30 Years of Social Indicators Research. *Soc. Indic. Res.* **2020**, *149*, 803–831. [CrossRef]
84. Zhang, J.Z.; Srivastava, P.R.; Sharma, D.; Eachempati, P. Big Data Analytics and Machine Learning: A Retrospective Overview and Bibliometric Analysis. *Expert Syst. Appl.* **2021**, *184*, 115561. [CrossRef]
85. Munim, Z.H.; Balasubramaniyan, S.; Kouhizadeh, M.; Hossain, N.U.I. Assessing Blockchain Technology Adoption in the Norwegian Oil and Gas Industry Using Bayesian Best Worst Method. *J. Ind. Inf. Integr.* **2022**, *28*, 100346. [CrossRef]
86. Mandolla, C.; Petruzzelli, A.M.; Percoco, G.; Urbinati, A. Building a Digital Twin for Additive Manufacturing through the Exploitation of Blockchain: A Case Analysis of the Aircraft Industry. *Comput. Ind.* **2019**, *109*, 134–152. [CrossRef]
87. Di Vaio, A.; Varriale, L. Blockchain Technology in Supply Chain Management for Sustainable Performance: Evidence from the Airport Industry. *Int. J. Inf. Manag.* **2020**, *52*, 102014. [CrossRef]
88. Arunmozhi, M.; Venkatesh, V.G.; Arisian, S.; Shi, Y.; Sreedharan, V.R. Application of Blockchain and Smart Contracts in Autonomous Vehicle Supply Chains: An Experimental Design. *Transp. Res. Part E Logist. Transp. Rev.* **2022**, *165*, 102864. [CrossRef]
89. Sudhan, A.; Nene, M.J. Employability of Blockchain Technology in Defence Applications. In Proceedings of the Proceedings of the International Conference on Intelligent Sustainable Systems (ICISS 2017), Palladam, India, 7–8 December 2017; IEEE: New York, NY, USA, 2017; pp. 630–637. [CrossRef]
90. Tran-Dang, H.; Kim, D.-S. Physical Internet for Military Logistics: Perspectives. In *Proceedings of the 2019 10th International Conference on Information and Communication Technology Convergence (ICTC), Jeju, Korea, 16–18 October 2019*; Ict Convergence Leading the Autonomous Future; IEEE: New York, NY, USA, 2019; pp. 755–757. [CrossRef]
91. Munoz, M.F.; Zhang, K.; Shahzad, A.; Ouhimmou, M. LogLog: A Blockchain Solution for Tracking and Certifying Wood Volumes. In Proceedings of the 2021 IEEE International Conference on Blockchain and Cryptocurrency (ICBC), Sydney, Australia, 3–6 May 2021; IEEE: New York, NY, USA, 2021. [CrossRef]
92. Alacam, S.; Sencer, A. Using Blockchain Technology to Foster Collaboration among Shippers and Carriers in the Trucking Industry: A Design Science Research Approach. *Logist.-Basel* **2021**, *5*, 37. [CrossRef]
93. Arbatskaya, E.; Khoreva, L. Blockchain as an Innovative Digitalization Achievement in Logistics of Eco-Tourism. In Proceedings of the E3S Web of Conferences, Chelyabinsk, Russia, 17–19 February 2021; Kankhva, V., Ed. [CrossRef]
94. Zhang, N.; Xu, Y. Environmental Study on Cooperation System of Cross-Border Tracking Economic Crimes Based on Block Chain-Take Telecommunication Fraud as an Example. *Ekoloji* **2019**, *28*, 4437–4446.
95. Tsoukas, V.; Gkogkidis, A.; Kampa, A.; Spathoulas, G.; Kakarountas, A. Blockchain Technology in Food Supply Chain: A State of the Art. In Proceedings of the 2021 6th South-East Europe Design Automation, Computer Engineering, Computer Networks and Social Media Conference (SEEDA-CECNSM), Preveza, Greece, 24–26 September 2021; pp. 1–8. [CrossRef]
96. Bhat, S.A.; Huang, N.-F.; Sofi, I.B.; Sultan, M. Agriculture-Food Supply Chain Management Based on Blockchain and IoT: A Narrative on Enterprise Blockchain Interoperability. *Agric.-Basel* **2021**, *12*, 40. [CrossRef]
97. Agnusdei, G.P.; Coluccia, B. Sustainable Agrifood Supply Chains: Bibliometric, Network and Content Analyses. *Sci. Total Environ.* **2022**, *824*, 153704. [CrossRef] [PubMed]
98. Liu, Y.; Ma, X.; Shu, L.; Hancke, G.P.; Abu-Mahfouz, A.M. From Industry 4.0 to Agriculture 4.0: Current Status, Enabling Technologies, and Research Challenges. *IEEE Trans. Ind. Inform.* **2020**, *17*, 4322–4334. [CrossRef]
99. Hassoun, A.; Ait-Kaddour, A.; Abu-Mahfouz, A.M.; Rathod, N.B.; Bader, F.; Barba, F.J.; Biancolillo, A.; Cropotova, J.; Galanakis, C.M.; Jambrak, A.R.; et al. The Fourth Industrial Revolution in the Food Industry-Part I: Industry 4.0 Technologies. *Crit. Rev. Food Sci. Nutr.* **2022**, 1–17. [CrossRef]

100. Cao, Y.; Yi, C.; Wan, G.; Hu, H.; Li, Q.; Wang, S. An Analysis on the Role of Blockchain-Based Platforms in Agricultural Supply Chains. *Transp. Res. Part E-Logist. Transp. Rev.* **2022**, *163*, 102731. [CrossRef]
101. Tseng, C.-T.; Shang, S.S.C. Exploring the Sustainability of the Intermediary Role in Blockchain. *Sustain. Switz.* **2021**, *13*, 1936. [CrossRef]
102. Khanna, A.; Jain, S.; Burgio, A.; Bolshev, V.; Panchenko, V. Blockchain-Enabled Supply Chain Platform for Indian Dairy Industry: Safety and Traceability. *Foods* **2022**, *11*, 2716. [CrossRef]
103. Varriale, V.; Cammarano, A.; Michelino, F.; Caputo, M. Sustainable Supply Chains with Blockchain, IoT and RFID: A Simulation on Order Management. *Sustain. Switz.* **2021**, *13*, 6372. [CrossRef]
104. Lezoche, M.; Hernandez, J.E.; Díaz, M.D.M.E.A.; Panetto, H.; Kacprzyk, J. Agri-Food 4.0: A Survey of the Supply Chains and Technologies for the Future Agriculture. *Comput. Ind.* **2020**, *117*, 103187. [CrossRef]
105. Dadi, V.; Nikla, S.R.; Moe, R.S.; Agarwal, T.; Arora, S. Agri-Food 4.0 and Innovations: Revamping the Supply Chain Operations. *Prod. Eng. Arch.* **2021**, *27*, 75–89. [CrossRef]
106. Song, L.; Wang, X.; Merveille, N. Research on Blockchain for Sustainable E-Agriculture. In Proceedings of the 2020 IEEE Technology and Engineering Management Conference, TEMSCON 2020, Novi, MI, USA, 3–6 June 2020. [CrossRef]
107. Kumar, S.; Raut, R.D.; Nayal, K.; Kraus, S.; Yadav, V.S.; Narkhede, B.E. To Identify Industry 4.0 and Circular Economy Adoption Barriers in the Agriculture Supply Chain by Using ISM-ANP. *J. Clean. Prod.* **2021**, *293*, 126023. [CrossRef]
108. Sodamin, D.; Vaněk, J.; Ulman, M.; Šimek, P. Fair Label versus Blockchain Technology from the Consumer Perspective: Towards a Comprehensive Research Agenda. *AGRIS -Line Pap. Econ. Inform.* **2022**, *14*, 111–119. [CrossRef]
109. Scuderi, A.; La Via, G.; Timpanaro, G.; Sturiale, L. The Digital Applications of "Agriculture 4.0": Strategic Opportunity for the Development of the Italian Citrus Chain. *Agric.-Basel* **2022**, *12*, 400. [CrossRef]
110. Singh, V.; Sharma, S.K. Application of Blockchain Technology in Shaping the Future of Food Industry Based on Transparency and Consumer Trust. *J. Food Sci. Technol.* **2022**, *246*, 6–17. [CrossRef]
111. Tsolakis, N.; Schumacher, R.; Dora, M.; Kumar, M. Artificial Intelligence and Blockchain Implementation in Supply Chains: A Pathway to Sustainability and Data Monetisation? *Ann. Oper. Res.* **2022**, 1–54. [CrossRef]
112. Dey, S.; Saha, S.; Singh, A.K.; McDonald-Maier, K. SmartNoshWaste: Using Blockchain, Machine Learning, Cloud Computing and QR Code to Reduce Food Waste in Decentralized Web 3.0 Enabled Smart Cities. *Smart Cities* **2022**, *5*, 162–176. [CrossRef]
113. Dong, S.; Yang, L.; Shao, X.; Zhong, Y.; Li, Y.; Qiao, P. How Can Channel Information Strategy Promote Sales by Combining ICT and Blockchain? Evidence from the Agricultural Sector. *J. Clean. Prod.* **2021**, *299*, 126857. [CrossRef]
114. Alkahtani, M.; Khalid, Q.S.; Jalees, M.; Omair, M.; Hussain, G.; Pruncu, C.I. E-Agricultural Supply Chain Management Coupled with Blockchain Effect and Cooperative Strategies. *Sustainability* **2021**, *13*, 816. [CrossRef]
115. Vodenicharova, M.S. Supply Chain Study in Food Industry in Bulgaria. *Int. J. Retail Distrib. Manag.* **2020**, *48*, 921–938. [CrossRef]
116. Nurgazina, J.; Pakdeetrakulwong, U.; Moser, T.; Reiner, G. Distributed Ledger Technology Applications in Food Supply Chains: A Review of Challenges and Future Research Directions. *Sustainability* **2021**, *13*, 4206. [CrossRef]
117. Rahman, L.F.; Alam, L.; Marufuzzaman, M.; Sumaila, U.R. Traceability of Sustainability and Safety in Fishery Supply Chain Management Systems Using Radio Frequency Identification Technology. *Foods* **2021**, *10*, 2265. [CrossRef] [PubMed]
118. Kumar, A.; Mangla, S.K.; Kumar, P. Barriers for Adoption of Industry 4.0 in Sustainable Food Supply Chain: A Circular Economy Perspective. *Int. J. Product. Perform. Manag.* **2022**. [CrossRef]
119. Adams, D.; Donovan, J.; Topple, C. Achieving Sustainability in Food Manufacturing Operations and Their Supply Chains: Key Insights from a Systematic Literature Review. *Sustain. Prod. Consum.* **2021**, *28*, 1491–1499. [CrossRef]
120. Haji, M.; Kerbache, L.; Muhammad, M.; Al-Ansari, T. Roles of Technology in Improving Perishable Food Supply Chains. *Logist.-Basel* **2020**, *4*, 33. [CrossRef]
121. Qian, J.; Ruiz-Garcia, L.; Fan, B.; Villalba, J.I.R.; McCarthy, U.; Zhang, B.; Yu, Q.; Wu, W. Food Traceability System from Governmental, Corporate, and Consumer Perspectives in the European Union and China: A Comparative Review. *Trends Food Sci. Technol.* **2020**, *99*, 402–412. [CrossRef]
122. Oruma, S.O.; Misra, S.; Fernandez-Sanz, L. Agriculture 4.0: An Implementation Framework for Food Security Attainment in Nigeria's Post-Covid-19 Era. *IEEE Access* **2021**, *9*, 83592–83627. [CrossRef]
123. Kazancoglu, Y.; Ozbiltekin-Pala, M.; Sezer, M.D.; Luthra, S.; Kumar, A. Resilient Reverse Logistics with Blockchain Technology in Sustainable Food Supply Chain Management during COVID-19. *Bus. Strategy Environ.* **2022**. [CrossRef]
124. Barbosa, M.W. Uncovering Research Streams on Agri-Food Supply Chain Management: A Bibliometric Study. *Glob. Food Secur.* **2021**, *28*, 100517. [CrossRef]
125. Mendi, A.F. Blockchain for Food Tracking. *Electronics* **2022**, *11*, 2491. [CrossRef]
126. Wünsche, J.F.; Fernqvist, F. The Potential of Blockchain Technology in the Transition Towards Sustainable Food Systems. *Sustain. Switz.* **2022**, *14*, 7739. [CrossRef]
127. Dayioglu, M.A.; Turker, U. Digital Transformation for Sustainable Future—Agriculture 4.0: A Review. *J. Agric. Sci.-Tarim Bilim. Derg.* **2021**, *27*, 373–399. [CrossRef]
128. Lin, S.-Y.; Zhang, L.; Li, J.; Ji, L.; Sun, Y. A Survey of Application Research Based on Blockchain Smart Contract. *Wirel. Netw.* **2022**, *28*, 635–690. [CrossRef]
129. Rejeb, A.; Keogh, J.G.; Zailani, S.; Treiblmaier, H.; Rejeb, K. Blockchain Technology in the Food Industry: A Review of Potentials, Challenges and Future Research Directions. *Logistics* **2020**, *4*, 27. [CrossRef]

130. Ekawati, R.; Arkeman, Y.; Suprihatin; Sunarti, T.C. Proposed Design of White Sugar Industrial Supply Chain System Based on Blockchain Technology. *Int. J. Adv. Comput. Sci. Appl.* **2021**, *12*, 459–465. [CrossRef]
131. Ali, M.H.; Chung, L.; Kumar, A.; Zailani, S.; Tan, K.H. A Sustainable Blockchain Framework for the Halal Food Supply Chain: Lessons from Malaysia. *Technol. Forecast. Soc. Chang.* **2021**, *170*, 120870. [CrossRef]
132. Bechtsis, D.; Tsolakis, N.; Iakovou, E.; Vlachos, D. Data-Driven Secure, Resilient and Sustainable Supply Chains: Gaps, Opportunities, and a New Generalised Data Sharing and Data Monetisation Framework. *Int. J. Prod. Res.* **2022**, *60*, 4397–4417. [CrossRef]
133. Kayikci, Y.; Usar, D.D.; Aylak, B.L. Using Blockchain Technology to Drive Operational Excellence in Perishable Food Supply Chains during Outbreaks. *Int. J. Logist. Manag.* **2022**, *33*, 836–876. [CrossRef]
134. Rana, R.L.; Tricase, C.; De Cesare, L. Blockchain Technology for a Sustainable Agri-Food Supply Chain. *Br. Food J.* **2021**, *123*, 3471–3485. [CrossRef]
135. Kumar, A.; Srivastava, S.K.; Singh, S. How Blockchain Technology Can Be a Sustainable Infrastructure for the Agrifood Supply Chain in Developing Countries. *J. Glob. Oper. Strateg. Sourc.* **2022**, *15*, 380–405. [CrossRef]
136. Joo, J.; Han, Y. An Evidence of Distributed Trust in Blockchain-Based Sustainable Food Supply Chain. *Sustainability* **2021**, *13*, 10980. [CrossRef]
137. Tsolakis, N.; Niedenzu, D.; Simonetto, M.; Dora, M.; Kumar, M. Supply Network Design to Address United Nations Sustainable Development Goals: A Case Study of Blockchain Implementation in Thai Fish Industry. *J. Bus. Res.* **2021**, *131*, 495–519. [CrossRef]
138. Kramer, M.P.; Bitsch, L.; Hanf, J. Blockchain and Its Impacts on Agri-Food Supply Chain Network Management. *Sustainability* **2021**, *13*, 2168. [CrossRef]
139. Phua, C.; Andradi-Brown, D.A.; Mangubhai, S.; Ahmadia, G.N.; Mahajan, S.L.; Larsen, K.; Friel, S.; Reichelt, R.; Hockings, M.; Gill, D. Marine Protected and Conserved Areas in the Time of COVID. *Parks* **2021**, *27*, 85–102. [CrossRef]
140. Amentae, T.K.; Gebresenbet, G. Digitalization and Future Agro-Food Supply Chain Management: A Literature-Based Implications. *Sustain. Switz.* **2021**, *13*, 12181. [CrossRef]
141. Mercuri, F.; della Corte, G.; Ricci, F. Blockchain Technology and Sustainable Business Models: A Case Study of Devoleum. *Sustain. Switz.* **2021**, *13*, 5619. [CrossRef]
142. Jo, J.; Yi, S.; Lee, E. Including the Reefer Chain into Genuine Beef Cold Chain Architecture Based on Blockchain Technology. *J. Clean. Prod.* **2022**, *363*, 132646. [CrossRef]
143. Wang, H.; Liu, Z.; Liang, Y. Research on the Three-in-One Model of Agricultural Products E-Commerce Logistics under the Combination of Resource Saving and Blockchain Technology. In *Proceedings of the IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2019; Volume 677, p. 032111. [CrossRef]
144. Bager, S.L.; Singh, C.; Persson, U.M. Blockchain is not a silver bullet for agro-food supply chain sustainability: Insights from a coffee case study. *Curr. Res. Environ. Sustain.* **2022**, *4*, 100163. [CrossRef]
145. Griffin, T.W.; Harris, K.D.; Ward, J.K.; Goeringer, P.; Richard, J.A. Three Digital Agriculture Problems in Cotton Solved by Distributed Ledger Technology. *Appl. Econ. Perspect. Policy* **2022**, *44*, 237–252. [CrossRef]
146. Fakkhong, K.; Rangsaritvorakarn, N.; Tantitecha, C. Using Blockchain Technology for a Sustainable Agri-Food Supply Chain in Thailand. In Proceedings of the 2022 International Conference on Decision Aid Sciences and Applications, DASA 2022, Chiangrai, Thailand, 23–25 March 2022; pp. 1783–1786. [CrossRef]
147. Vlachopoulou, M.; Ziakis, C.; Vergidis, K.; Madas, M. Analyzing AgriFood-Tech e-Business Models. *Sustainability* **2021**, *13*, 5516. [CrossRef]
148. Friedman, N.; Ormiston, J. Blockchain as a Sustainability-Oriented Innovation?: Opportunities for and Resistance to Blockchain Technology as a Driver of Sustainability in Global Food Supply Chains. *Technol. Forecast. Soc. Chang.* **2021**, *175*, 121403. [CrossRef]
149. Mangla, S.K.; Kazançoğlu, Y.; Yıldızbaşı, A.; Öztürk, C.; Çalık, A. A Conceptual Framework for Blockchain-Based Sustainable Supply Chain and Evaluating Implementation Barriers: A Case of the Tea Supply Chain. *Bus. Strategy Environ.* **2022**, *31*, 3693–3716. [CrossRef]
150. Han, J.-W.; Zuo, M.; Zhu, W.-Y.; Zuo, J.-H.; Lu, E.-L.; Yang, X.-T. A Comprehensive Review of Cold Chain Logistics for Fresh Agricultural Products: Current Status, Challenges, and Future Trends. *Trends Food Sci. Technol.* **2021**, *109*, 536–551. [CrossRef]
151. Samoggia, A.; Beyhan, Z. Fairness-Enabling Practices in Agro-Food Chain. *Sustainability* **2022**, *14*, 6391. [CrossRef]
152. Motta, G.A.; Tekinerdogan, B.; Athanasiadis, I.N. Blockchain Applications in the Agri-Food Domain: The First Wave. *Front. Blockchain* **2020**, *3*, 6. [CrossRef]
153. Kohler, S.; Pizzol, M. Technology Assessment of Blockchain-Based Technologies in the Food Supply Chain. *J. Clean. Prod.* **2020**, *269*, 122193. [CrossRef]
154. Varavallo, G.; Caragnano, G.; Bertone, F.; Vernetti-Prot, L.; Terzo, O. Traceability Platform Based on Green Blockchain: An Application Case Study in Dairy Supply Chain. *Sustainability* **2022**, *14*, 3321. [CrossRef]
155. Mirabelli, G.; Solina, V. Blockchain-Based Solutions for Agri-Food Supply Chains: A Survey. *Int. J. Simul. Process Model.* **2021**, *17*, 1–15. [CrossRef]
156. Bager, S.L.; Dudder, B.; Henglein, F.; Hebert, J.M.; Wu, H. Event-Based Supply Chain Network Modeling: Blockchain for Good Coffee. *Front. Blockchain* **2022**, *5*, 846783. [CrossRef]
157. Durrant, A.; Markovic, M.; Matthews, D.; May, D.; Leontidis, G.; Enright, J. How Might Technology Rise to the Challenge of Data Sharing in Agri-Food? *Glob. Food Secur.* **2021**, *28*, 100493. [CrossRef]

158. Rünzel, M.A.; Hassler, E.E.; Rogers, R.E.; Formato, G.; Cazier, J.A. Designing a Smart Honey Supply Chain for Sustainable Development. *IEEE Consum. Electron. Mag.* **2021**, *10*, 69–78. [CrossRef]
159. Dos Santos, R.B.; Torrisi, N.M.; Pantoni, R.P. Third Party Certification of Agri-Food Supply Chain Using Smart Contracts and Blockchain Tokens. *Sensors* **2021**, *21*, 5307. [CrossRef]
160. Kaur, H. Modelling Internet of Things Driven Sustainable Food Security System. *Benchmarking- Int. J.* **2021**, *28*, 1740–1760. [CrossRef]
161. Niu, B.; Shen, Z.; Xie, F. The Value of Blockchain and Agricultural Supply Chain Parties' Participation Confronting Random Bacteria Pollution. *J. Clean. Prod.* **2021**, *319*, 128579. [CrossRef]
162. Qian, J.; Wu, W.; Yu, Q.; Ruiz-Garcia, L.; Xiang, Y.; Jiang, L.; Shi, Y.; Duan, Y.; Yang, P. Filling the Trust Gap of Food Safety in Food Trade between the EU and China: An Interconnected Conceptual Traceability Framework Based on Blockchain. *Food Energy Secur.* **2020**, *9*, e249. [CrossRef]
163. Astill, J.; Dara, R.A.; Campbell, M.; Farber, J.M.; Fraser, E.D.G.; Sharif, S.; Yada, R.Y. Transparency in Food Supply Chains: A Review of Enabling Technology Solutions. *Trends Food Sci. Technol.* **2019**, *91*, 240–247. [CrossRef]
164. Galanakis, C.M.; Rizou, M.; Aldawoud, T.M.S.; Ucak, I.; Rowan, N.J. Innovations and Technology Disruptions in the Food Sector within the COVID-19 Pandemic and Post-Lockdown Era. *Trends Food Sci. Technol.* **2021**, *110*, 193–200. [CrossRef]
165. Anastasiadis, F.; Manikas, I.; Apostolidou, I.; Wahbeh, S. The Role of Traceability in End-to-End Circular Agri-Food Supply Chains. *Ind. Mark. Manag.* **2022**, *104*, 196–211. [CrossRef]
166. Lin, K.; Chavalarias, D.; Panahi, M.; Yeh, T.; Takimoto, K.; Mizoguchi, M. Mobile-Based Traceability System for Sustainable Food Supply Networks. *Nat. Food* **2020**, *1*, 673–679. [CrossRef]
167. Liu, W.; Shao, X.-F.; Wu, C.-H.; Qiao, P. A Systematic Literature Review on Applications of Information and Communication Technologies and Blockchain Technologies for Precision Agriculture Development. *J. Clean. Prod.* **2021**, *298*, 126763. [CrossRef]
168. Ada, N.; Kazancoglu, Y.; Sezer, M.D.; Ede-Senturk, C.; Ozer, I.; Ram, M. Analyzing Barriers of Circular Food Supply Chains and Proposing Industry 4.0 Solutions. *Sustainability* **2021**, *13*, 6812. [CrossRef]
169. Smetana, S.; Aganovic, K.; Heinz, V. Food Supply Chains as Cyber-Physical Systems: A Path for More Sustainable Personalized Nutrition. *Food Eng. Rev.* **2021**, *13*, 92–103. [CrossRef]
170. Duan, J.; Zhang, C.; Gong, Y.; Brown, S.; Li, Z. A Content-Analysis Based Literature Review in Blockchain Adoption within Food Supply Chain. *Int. J. Environ. Res. Public. Health* **2020**, *17*, 1784. [CrossRef]
171. della Corte, G.; Ricci, F.; Modaffari, G.; Scafarto, V. Blockchain as a Strategic Enabler of Agri-Food Sustainability. In Proceedings of the 2021 IEEE International Conference on Technology Management, Operations and Decisions (ICTMOD), Marrakech, Morocco, 24–26 November 2021; pp. 1–6. [CrossRef]
172. Bansal, L.; Chaurasia, S.; Sabharwal, M.; Vij, M. Blockchain Integration with End-to-End Traceability in the Food Supply Chain. In Proceedings of the 2022 2nd International Conference on Advance Computing and Innovative Technologies in Engineering, ICACITE 2022, Greater Noida, India, 28–29 April 2022; pp. 1152–1156. [CrossRef]
173. Kraft, S.K.; Kellner, F. Can Blockchain Be a Basis to Ensure Transparency in an Agricultural Supply Chain? *Sustain. Switz.* **2022**, *14*, 8044. [CrossRef]
174. Leduc, G.; Kubler, S.; Georges, J.-P. Innovative Blockchain-Based Farming Marketplace and Smart Contract Performance Evaluation. *J. Clean. Prod.* **2021**, *306*, 127055. [CrossRef]
175. Song, L.; Luo, Y.; Chang, Z.; Jin, C.; Nicolas, M. Blockchain Adoption in Agricultural Supply Chain for Better Sustainability: A Game Theory Perspective. *Sustainability* **2022**, *14*, 1470. [CrossRef]
176. Nayal, K.; Raut, R.D.; Narkhede, B.E.; Priyadarshinee, P.; Panchal, G.B.; Gedam, V.V. Antecedents for Blockchain Technology-Enabled Sustainable Agriculture Supply Chain. *Ann. Oper. Res.* **2021**, 1–45. [CrossRef]
177. Remondino, M.; Zanin, A. Logistics and Agri-Food: Digitization to Increase Competitive Advantage and Sustainability. Literature Review and the Case of Italy. *Sustain. Switz.* **2022**, *14*, 787. [CrossRef]
178. Morales, M.L.V.; Elkader, M.A.A. Logistics 4.0 Technologies in Agriculture Systems: Potential Impacts in the Sdg. In *Proceedings of the Towards the Digital World and Industry X.0—Proceedings of the 29th International Conference of the International Association for Management of Technology, IAMOT 2020*; Pretorius, L.P.M.W., Ed.; University of Pretoria: Pretoria, South Africa, 2020; pp. 976–989.
179. Sharma, R.; Samad, T.A.; Jabbour, C.J.C.; de Queiroz, M.J. Leveraging Blockchain Technology for Circularity in Agricultural Supply Chains: Evidence from a Fast-Growing Economy. *J. Enterp. Inf. Manag.* **2021**. [CrossRef]
180. Bai, C.; Quayson, M.; Sarkis, J. Analysis of Blockchain's Enablers for Improving Sustainable Supply Chain Transparency in Africa Cocoa Industry. *J. Clean. Prod.* **2022**, *358*, 131896. [CrossRef]
181. Luzzani, G.; Grandis, E.; Frey, M.; Capri, E. Blockchain Technology in Wine Chain for Collecting and Addressing Sustainable Performance: An Exploratory Study. *Sustain. Switz.* **2021**, *13*, 12898. [CrossRef]
182. Richter, B.; Hanf, J.H. Cooperatives in the Wine Industry: Sustainable Management Practices and Digitalisation. *Sustainability* **2021**, *13*, 5543. [CrossRef]
183. Paul, T.; Mondal, S.; Islam, N.; Rakshit, S. The Impact of Blockchain Technology on the Tea Supply Chain and Its Sustainable Performance. *Technol. Forecast. Soc. Chang.* **2021**, *173*, 121163. [CrossRef]
184. Mangla, S.K.; Kazancoglu, Y.; Ekinci, E.; Liu, M.; Ozbiltekin, M.; Sezer, M.D. Using System Dynamics to Analyze the Societal Impacts of Blockchain Technology in Milk Supply Chainsrefer. *Transp. Res. Part E-Logist. Transp. Rev.* **2021**, *149*, 102289. [CrossRef]

185. Howson, P. Building Trust and Equity in Marine Conservation and Fisheries Supply Chain Management with Blockchain. *Mar. Policy* **2020**, *115*, 103873. [CrossRef]
186. Rowan, N.J. The Role of Digital Technologies in Supporting and Improving Fishery and Aquaculture across the Supply Chain–Quo Vadis? *Aquac. Fish.* 2022, *in press*. [CrossRef]
187. Arena, A.; Bianchini, A.; Perazzo, P.; Vallati, C.; Dini, G. BRUSCHETTA: An IoT Blockchain-Based Framework for Certifying Extra Virgin Olive Oil Supply Chain. In Proceedings of the 2019 IEEE International Conference on Smart Computing (Smartcomp 2019), Washington, DC, USA, 12–15 June 2019; pp. 173–179. [CrossRef]
188. Violino, S.; Pallottino, F.; Sperandio, G.; Figorilli, S.; Antonucci, F.; Ioannoni, V.; Fappiano, D.; Costa, C. Are the Innovative Electronic Labels for Extra Virgin Olive Oil Sustainable, Traceable, and Accepted by Consumers? *Foods* **2019**, *8*, 529. [CrossRef]
189. Vo, K.T.; Nguyen-Thi, A.-T.; Nguyen-Hoang, T.-A. Building Sustainable Food Supply Chain Management System Based On Hyperledger Fabric Blockchain. In Proceedings of the 2021 15th International Conference on Advanced Computing and Applications (Acomp 2021), Ho Chi Minh City, Vietnam, 24–26 November 2021; Le, L.S., Nguyen, H., Phan, T.A., Clavel, M., Dang, T.K., Eds.; pp. 9–16. [CrossRef]
190. Feng, H.; Wang, X.; Duan, Y.; Zhang, J.; Zhang, X. Applying Blockchain Technology to Improve Agri-Food Traceability: A Review of Development Methods, Benefits and Challenges. *J. Clean. Prod.* **2020**, *260*, 121031. [CrossRef]
191. Saurabh, S.; Dey, K. Blockchain Technology Adoption, Architecture, and Sustainable Agri-Food Supply Chains. *J. Clean. Prod.* **2020**, *284*, 124731. [CrossRef]
192. Kittipanya-ngam, P.; Tan, K.H. A Framework for Food Supply Chain Digitalization: Lessons from Thailand. *Prod. Plan. Control* **2020**, *31*, 158–172. [CrossRef]
193. Awan, S.; Ahmed, S.; Ullah, F.; Nawaz, A.; Khan, A.; Uddin, M.I.; Alharbi, A.; Alosaimi, W.; Alyami, H. IoT with BlockChain: A Futuristic Approach in Agriculture and Food Supply Chain. *Wirel. Commun. Mob. Comput.* **2021**, *2021*, 5580179. [CrossRef]
194. Yadav, S.; Luthra, S.; Garg, D. Modelling Internet of Things (IoT)-Driven Global Sustainability in Multi-Tier Agri-Food Supply Chain under Natural Epidemic Outbreaks. *Environ. Sci. Pollut. Res.* **2021**, *28*, 16633–16654. [CrossRef] [PubMed]
195. Rainero, C.; Modarelli, G. Food Tracking and Blockchain-Induced Knowledge: A Corporate Social Responsibility Tool for Sustainable Decision-Making. *Br. Food J.* **2021**, *123*, 4284–4308. [CrossRef]
196. Benyam, A.; Soma, T.; Fraser, E. Digital Agricultural Technologies for Food Loss and Waste Prevention and Reduction: Global Trends, Adoption Opportunities and Barriers. *J. Clean. Prod.* **2021**, *323*, 129099. [CrossRef]
197. Wang, B.; Luo, W.; Zhang, A.; Tian, Z.; Li, Z. Blockchain-Enabled Circular Supply Chain Management: A System Architecture for Fast Fashion. *Comput. Ind.* **2020**, *123*, 103324. [CrossRef]
198. Tam, F.Y.; Lung, J.W. Impact of COVID-19 and Innovative Ideas for a Sustainable Fashion Supply Chain in the Future. *Foresight*, 2022; *ahead-of-print*. [CrossRef]
199. Akram, S.V.; Malik, P.K.; Singh, R.; Gehlot, A.; Juyal, A.; Ghafoor, K.Z.; Shrestha, S. Implementation of Digitalized Technologies for Fashion Industry 4.0: Opportunities and Challenges. *Sci. Program.* **2022**, *2022*, 7523246. [CrossRef]
200. Ahmed, W.A.H.; MacCarthy, B.L. Blockchain-Enabled Supply Chain Traceability in the Textile and Apparel Supply Chain: A Case Study of the Fiber Producer, Lenzing. *Sustainability* **2021**, *13*, 10496. [CrossRef]
201. Abreu, A.; Afonso, A.P.; Freitas, J. Blockchain Towards Supply Chain Management. In Proceedings of the International Conference on Tourism, Technology and Systems, Cartagena, Colombia, 29–31 October 2020; pp. 396–407.
202. Noonan, J.; Doran, P. Blockchain's Impact on Consumer's Perspective in the Luxury Fashion Industry: A Position Paper. *Lect. Notes Comput. Sci. Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinforma.* **2021**, *12896*, 596–606. [CrossRef]
203. Benstead, A.V.; Mwesiumo, D.; Moradlou, H.; Boffelli, A. Entering the World behind the Clothes That We Wear: Practical Applications of Blockchain Technology. *Prod. Plan. Control* **2022**, 1–18. [CrossRef]
204. Ribeiro, F.A.; Brito, M.A. Blockchain Technology Applications: Enhancing Fashion Supply Chain Sustainability. In Proceedings of the 2022 17th Iberian Conference on Information Systems and Technologies (CISTI), Madrid, Spain, 22–25 June 2022; pp. 1–4. [CrossRef]
205. Caldarelli, G.; Zardini, A.; Rossignoli, C. Blockchain Adoption in the Fashion Sustainable Supply Chain: Pragmatically Addressing Barriers. *J. Organ. Chang. Manag.* **2021**, *34*, 507–524. [CrossRef]
206. Agrawal, T.K.; Kumar, V.; Pal, R.; Wang, L.; Chen, Y. Blockchain-Based Framework for Supply Chain Traceability: A Case Example of Textile and Clothing Industry. *Comput. Ind. Eng.* **2021**, *154*, 107130. [CrossRef]
207. Huynh, P.H. Enabling Circular Business Models in the Fashion Industry: The Role of Digital Innovation. *Int. J. Product. Perform. Manag.* **2021**, *71*, 870–895. [CrossRef]
208. Guo, S.; Sun, X.; Lam, H.K.S. Applications of Blockchain Technology in Sustainable Fashion Supply Chains: Operational Transparency and Environmental Efforts. *IEEE Trans. Eng. Manag.* **2020**, 1–17. [CrossRef]
209. Oguntegbe, K.F.; Di Paola, N.; Vona, R. Communicating Responsible Management and the Role of Blockchain Technology: Social Media Analytics for the Luxury Fashion Supply Chain. *TQM J.* **2022**. [CrossRef]
210. Oguntegbe, K.F.; Di Paola, N.; Vona, R. Blockchain Technology, Social Capital and Sustainable Supply Chain Management. *Sinergie* **2021**, *39*, 163–188. [CrossRef]
211. Nath, S.D.; Khayer, A.; Majumder, J.; Barua, S. Factors Affecting Blockchain Adoption in Apparel Supply Chains: Does Sustainability-Oriented Supplier Development Play a Moderating Role? *Ind. Manag. Data Syst.* **2022**, *122*, 1183–1214. [CrossRef]

212. Choi, T.-M.; Luo, S. Data Quality Challenges for Sustainable Fashion Supply Chain Operations in Emerging Markets: Roles of Blockchain, Government Sponsors and Environment Taxes. *Transp. Res. Part E-Logist. Transp. Rev.* **2019**, *131*, 139–152. [CrossRef]
213. Zhang, H. Blockchain Facilitates a Resilient Supply Chain in Steel Manufacturing under COVID-19. In *Proceedings of the Proceedings of the 22nd European Conference on Knowledge Management (ECKM 2021)*; GarciaPerez, A., Simkin, L., Eds.; Acad Conferences Ltd.: Nr Reading, UK, 2021; pp. 964–972.
214. Matenga, A.E.; Mpofu, K. Blockchain-Based Cloud Manufacturing SCM System for Collaborative Enterprise Manufacturing: A Case Study of Transport Manufacturing. *Appl. Sci.-Basel* **2022**, *12*, 8664. [CrossRef]
215. Govindan, K. Tunneling the Barriers of Blockchain Technology in Remanufacturing for Achieving Sustainable Development Goals: A Circular Manufacturing Perspective. *Bus. Strategy Environ.* **2022**, *31*, 3769–3785. [CrossRef]
216. Ko, T.; Lee, J.; Ryu, D. Blockchain Technology and Manufacturing Industry: Real-Time Transparency and Cost Savings. *Sustainability* **2018**, *10*, 4274. [CrossRef]
217. Mubarik, M.; Rasi, R.Z.R.M.; Mubarak, M.F.; Ashraf, R. Impact of Blockchain Technology on Green Supply Chain Practices: Evidence from Emerging Economy. *Manag. Environ. Qual.* **2021**, *32*, 1023–1039. [CrossRef]
218. Tan, C.L.; Tei, Z.; Yeo, S.F.; Lai, K.-H.; Kumar, A.; Chung, L. Nexus among Blockchain Visibility, Supply Chain Integration and Supply Chain Performance in the Digital Transformation Era. *Ind. Manag. Data Syst.* 2022; *in press*. [CrossRef]
219. Fernando, Y.; Rozuar, N.H.M.; Mergeresa, F. The Blockchain-Enabled Technology and Carbon Performance: Insights from Early Adopters. *Technol. Soc.* **2021**, *64*, 101507. [CrossRef]
220. Sun, Y.; Shahzad, M.; Razzaq, A. Sustainable Organizational Performance through Blockchain Technology Adoption and Knowledge Management in China. *J. Innov. Knowl.* **2022**, *7*, 100247. [CrossRef]
221. Chidepatil, A.; Bindra, P.; Kulkarni, D.; Qazi, M.; Kshirsagar, M.; Sankaran, K. From Trash to Cash: How Blockchain and Multi-Sensor-Driven Artificial Intelligence Can Transform Circular Economy of Plastic Waste? *Adm. Sci.* **2020**, *10*, 23. [CrossRef]
222. Ghimire, T.; Joshi, A.; Sen, S.; Kapruan, C.; Chadha, U.; Selvaraj, S.K. Blockchain in Additive Manufacturing Processes: Recent Trends&Its Future Possibilities. In *Proceedings of the Materials Today-Proceedings*; Elsevier: Amsterdam, The Netherlands, 2021; Volume 50, pp. 2170–2180.
223. Han, X.; Rani, P. Evaluate the Barriers of Blockchain Technology Adoption in Sustainable Supply Chain Management in the Manufacturing Sector Using a Novel Pythagorean Fuzzy-CRITIC-CoCoSo Approach. *Oper. Manag. Res.* **2022**, *15*, 725–742. [CrossRef]
224. Zhang, F.; Gu, Y. Approach to an Equivalent Freight-Based Sustainable Joint-Quotation Strategy for Shipping Blockchain Alliance. *Sustainability* **2022**, *14*, 10441. [CrossRef]
225. Henriquez, R.; Martinez De Oses, R.X.; Martinez Marin, J.E. Dlt-Based Sustainable Business Models for The Shipping Industry. *Int. J. Transp. Econ.* **2021**, *48*, 433–454. [CrossRef]
226. Bae, H. The Interaction Effect of Information Systems of Shipping and Logistics Firms and Managers' Support for Blockchain Technology on Cooperation with Shippers for Sustainable Value Creation. *Sustainability* **2021**, *13*, 4493. [CrossRef]
227. Wong, S.; Yeung, J.-K.-W.; Lau, Y.-Y.; So, J. Technical Sustainability of Cloud-Based Blockchain Integrated with Machine Learning for Supply Chain Management. *Sustainability* **2021**, *13*, 8270. [CrossRef]
228. Philipp, R.; Prause, G.; Gerlitz, L. Blockchain and Smart Contracts for Entrepreneurial Collaboration in Maritime Supply Chains. *Transp. Telecommun.* **2019**, *20*, 365–378. [CrossRef]
229. Tan, W.K.A.; Sundarakani, B. Assessing Blockchain Technology Application for Freight Booking Business: A Case Study from Technology Acceptance Model Perspective. *J. Glob. Oper. Strateg. Sourc.* **2020**, *14*, 202–223. [CrossRef]
230. Vujicic, S.; Hasanspahic, N.; Car, M.; Campara, L. Distributed Ledger Technology as a Tool for Environmental Sustainability in the Shipping Industry. *J. Mar. Sci. Eng.* **2020**, *8*, 366. [CrossRef]
231. Jovic, M.; Tijan, E.; Zgaljic, D.; Aksentijevic, S. Improving Maritime Transport Sustainability Using Blockchain-Based Information Exchange. *Sustainability* **2020**, *12*, 8866. [CrossRef]
232. Gong, Y.; Wang, Y.; Frei, R.; Wang, B.; Zhao, C. Blockchain Application in Circular Marine Plastic Debris Management. *Ind. Mark. Manag.* **2022**, *102*, 164–176. [CrossRef]
233. Nguyen, S.; Chen, P.S.-L.; Du, Y. Risk Assessment of Maritime Container Shipping Blockchain-Integrated Systems: An Analysis of Multi-Event Scenarios. *Transp. Res. Part E-Logist. Transp. Rev.* **2022**, *163*, 102764. [CrossRef]
234. Kazancoglu, I.; Ozbiltekin-Pala, M.; Mangla, S.K.; Kumar, A.; Kazancoglu, Y. Using Emerging Technologies to Improve the Sustainability and Resilience of Supply Chains in a Fuzzy Environment in the Context of COVID-19. *Ann. Oper. Res.* **2022**, 1–24. [CrossRef] [PubMed]
235. Xu, X.; Tatge, L.; Xu, X.; Liu, Y. Blockchain Applications in the Supply Chain Management in German Automotive Industry. *Prod. Plan. Control* **2022**, 1–15. [CrossRef]
236. Kamble, S.S.; Gunasekaran, A.; Subramanian, N.; Ghadge, A.; Belhadi, A.; Venkatesh, M. Blockchain Technology's Impact on Supply Chain Integration and Sustainable Supply Chain Performance: Evidence from the Automotive Industry. *Ann. Oper. Res.* **2021**, 1–26. [CrossRef]
237. Yu, Z.; Umar, M.; Rehman, S.A. Adoption of Technological Innovation and Recycling Practices in Automobile Sector: Under the COVID-19 Pandemic. *Oper. Manag. Res.* **2022**, *15*, 298–306. [CrossRef]
238. Rizvi, S.W.H.; Agrawal, S.; Murtaza, Q. Circularity Issues and Blockchain Technology in the Auto Industry. *Energy Sources Part -Recovery Util. Environ. Eff.* **2022**, *44*, 7132–7144. [CrossRef]

239. Zhang, H.; Li, S.; Yan, W.; Jiang, Z.; Wei, W. A Knowledge Sharing Framework for Green Supply Chain Management Based on Blockchain and Edge Computing. *Smart Innov. Syst. Technol.* **2019**, *155*, 413–420. [CrossRef]
240. Ghadge, A.; Mogale, D.G.; Bourlakis, M.; Maiyar, L.M.; Moradlou, H. Link between Industry 4.0 and Green Supply Chain Management: Evidence from the Automotive Industry. *Comput. Ind. Eng.* **2022**, *169*, 108303. [CrossRef]
241. Ada, N.; Ethirajan, M.; Kumar, A.; Vimal, K.E.K.; Nadeem, S.P.; Kazancoglu, Y.; Kandasamy, J. Blockchain Technology for Enhancing Traceability and Efficiency in Automobile Supply Chain—A Case Study. *Sustain. Switz.* **2021**, *13*, 13667. [CrossRef]
242. Alptekin, B.; Tunaboylu, B.; Zaim, S.; Perlo, P. Smart Manufacturing of Electric Vehicles. *Lect. Notes Mech. Eng.* **2020**, 767–773. [CrossRef]
243. Vishwakarma, A.; Dangayach, G.S.; Meena, M.L.; Gupta, S.; Luthra, S. Adoption of Blockchain Technology Enabled Healthcare Sustainable Supply Chain to Improve Healthcare Supply Chain Performance. *Manag. Environ. Qual. Int. J.* **2022**; *ahead-of-print*. [CrossRef]
244. Wang, B.; Lin, Z.; Wang, M.; Wang, F.; Xiangli, P.; Li, Z. Applying Blockchain Technology to Ensure Compliance with Sustainability Standards in the PPE Multi-Tier Supply Chain. *Int. J. Prod. Res.* **2022**, 1–17. [CrossRef]
245. Bhaskar, S.; Tan, J.; Bogers, M.L.A.M.; Minssen, T.; Badaruddin, H.; Israeli-Korn, S.; Chesbrough, H. At the Epicenter of COVID-19-the Tragic Failure of the Global Supply Chain for Medical Supplies. *Front. Public Health* **2020**, *8*, 562882. [CrossRef]
246. Rahman, T.; Moktadir, M.A.; Paul, S.K. Key Performance Indicators for a Sustainable Recovery Strategy in Health-Care Supply Chains: COVID-19 Pandemic Perspective. *J. Asia Bus. Stud.* **2021**, *16*, 472–494. [CrossRef]
247. Kuberkar, S.; Singhal, T.K. Factors Influencing the Adoption Intention of Blockchain and Internet-of-Things Technologies for Sustainable Blood Bank Management. *Int. J. Healthc. Inf. Syst. Inform.* **2021**, *16*, 1–21. [CrossRef]
248. Alharthi, S.; Cerotti, P.; Far, S.M. The Impact of Blockchain Implementation on Pharmaceutical Supply Chain Sustainability: A Conceptual Study. In *Proceedings of the Education Excellence and Innovation Management: A 2025 Vision to Sustain Economic Development During Global Challenges*; Soliman, K.S., Ed.; Int Business Information Management Assoc-Ibima: Norristown, PA, USA, 2020; pp. 9231–9252.
249. Hastig, G.M.; Sodhi, M.S. Blockchain for Supply Chain Traceability: Business Requirements and Critical Success Factors. *Prod. Oper. Manag.* **2020**, *29*, 935–954. [CrossRef]
250. Sylim, P.; Liu, F.; Marcelo, A.; Fontelo, P. Blockchain Technology for Detecting Falsified and Substandard Drugs in Distribution: Pharmaceutical Supply Chain Intervention. *Jmir Res. Protoc.* **2018**, *7*, e10163. [CrossRef]
251. Mugurusi, G.; Ahishakiye, E. Blockchain Technology Needs for Sustainable Mineral Supply Chains: A Framework for Responsible Sourcing of Cobalt. In *Proceedings of the Procedia Computer Science*; Longo, F., Affenzeller, M.P.A., Eds.; Elsevier B.V.: Amsterdam, The Netherlands, 2022; Volume 200, pp. 638–647.
252. Kshetri, N. Blockchain Systems and Ethical Sourcing in the Mineral and Metal Industry: A Multiple Case Study. *Int. J. Logist. Manag.* **2022**, *33*, 1–27. [CrossRef]
253. Deberdt, R.; Le Billon, P. Conflict Minerals and Battery Materials Supply Chains: A Mapping Review of Responsible Sourcing Initiatives. *Extr. Ind. Soc.-Int. J.* **2021**, *8*, 100935. [CrossRef]
254. Calvao, F.; Archer, M. Digital Extraction: Blockchain Traceability in Mineral Supply Chains. *Polit. Geogr.* **2021**, *87*, 102381. [CrossRef]
255. Liu, J.; Li, J.; Wang, J.; Uddin, M.M.; Zhang, B. Research on the Application of Blockchain Technology in Coal Supply Chain Finance. *Sustainability* **2022**, *14*, 10099. [CrossRef]
256. Batwa, A.; Norrman, A.; Arvidsson, A. How Blockchain Interrelates with Trust in the Supply Chain Context: Insights from Tracing Sustainability in the Metal Industry. In *Proceedings of the Proceedings of the Hamburg International Conference of Logistics*; Kersten, W., Ringle, C.M.B.T., Eds.; Institute of Business Logistics and General Management, Hamburg University of Technology: Hamburg, Germany, 2021; Volume 31, pp. 329–351.
257. Wu, Y.; Wu, Y.; Cimen, H.; Vasquez, J.C.; Guerrero, J.M. Towards Collective Energy Community: Potential Roles of Microgrid and Blockchain to Go beyond P2P Energy Trading. *Appl. Energy* **2022**, *314*, 119003. [CrossRef]
258. Mangina, E.; Narasimhan, P.K.; Saffari, M.; Vlachos, I. Data Analytics for Sustainable Global Supply Chains. *J. Clean. Prod.* **2020**, *255*, 120300. [CrossRef]
259. Almutairi, K.; Hosseini Dehshiri, S.J.; Hosseini Dehshiri, S.S.; Hoa, A.X.; Arockia Dhanraj, J.; Mostafaeipour, A.; Issakhov, A.; Techato, K. Blockchain Technology Application Challenges in Renewable Energy Supply Chain Management. *Environ. Sci. Pollut. Res.* **2022**, 1–18. [CrossRef] [PubMed]
260. Zhu, S.; Song, M.; Lim, M.K.; Wang, J.; Zhao, J. The Development of Energy Blockchain and Its Implications for China's Energy Sector. *Resour. Policy* **2020**, *66*, 101595. [CrossRef]
261. Park, L.W.; Lee, S.; Chang, H. A Sustainable Home Energy Prosumer-Chain Methodology with Energy Tags over the Blockchain. *Sustainability* **2018**, *10*, 658. [CrossRef]
262. Schletz, M.; Cardoso, A.; Prata Dias, G.; Salomo, S. How Can Blockchain Technology Accelerate Energy Efficiency Interventions? A Use Case Comparison. *Energies* **2020**, *13*, 5869. [CrossRef]
263. Tayal, A.; Solanki, A.; Kondal, R.; Nayyar, A.; Tanwar, S.; Kumar, N. Blockchain-Based Efficient Communication for Food Supply Chain Industry: Transparency and Traceability Analysis for Sustainable Business. *Int. J. Commun. Syst.* **2021**, *34*, e4696. [CrossRef]
264. Ma, X.; Zhang, Q. Tracing Information for Agricultural Product and Identifying Key Regulatory Decisions towards Eco-Economics Sustainability. *Math. Probl. Eng.* **2022**, *2022*, 8142802. [CrossRef]

265. Sharma, M.; Joshi, S.; Luthra, S.; Kumar, A. Managing Disruptions and Risks amidst COVID-19 Outbreaks: Role of Blockchain Technology in Developing Resilient Food Supply Chains. *Oper. Manag. Res.* **2022**, *15*, 268–281. [CrossRef]
266. Yadav, S.; Singh, S.P. An Integrated Fuzzy-ANP and Fuzzy-ISM Approach Using Blockchain for Sustainable Supply Chain. *J. Enterp. Inf. Manag.* **2021**, *34*, 54–78. [CrossRef]
267. Botelho, A.; Silva, I.R.; Ribeiro, L.; Lopes, M.S.; Au-Yong-Oliveira, M. Improving Food Transparency through Innovation and Blockchain Technology. In *Proceedings of the European Conference on Innovation and Entrepreneurship, ECIE*; De Nisco, A., Ed.; Academic Conferences and Publishing International Limited: Reading, UK, 2020; pp. 128–136.
268. Rogerson, M.; Parry, G.C. Blockchain: Case Studies in Food Supply Chain Visibility. *Supply Chain Manag.-Int. J.* **2020**, *25*, 601–614. [CrossRef]
269. Violino, S.; Pallottino, F.; Sperandio, G.; Figorilli, S.; Ortenzi, L.; Tocci, F.; Vasta, S.; Imperi, G.; Costa, C. A Full Technological Traceability System for Extra Virgin Olive Oil. *Foods* **2020**, *9*, 624. [CrossRef]
270. Yadav, V.S.; Singh, A.R.; Raut, R.D.; Mangla, S.K.; Luthra, S.; Kumar, A. Exploring the Application of Industry 4.0 Technologies in the Agricultural Food Supply Chain: A Systematic Literature Review. *Comput. Ind. Eng.* **2022**, *169*, 108304. [CrossRef]
271. Alves, L.; Ferreira Cruz, E.; Lopes, S.I.; Faria, P.M.; Rosado da Cruz, A.M. Towards Circular Economy in the Textiles and Clothing Value Chain through Blockchain Technology and IoT: A Review. *Waste Manag. Res.* **2022**, *40*, 3–23. [CrossRef]
272. Carrieres, V.; Lemieux, A.-A.; Pellerin, R. Opportunities of Blockchain Traceability Data for Environmental Impact Assessment in a Context of Sustainable Production. In *Advances in Production Management Systems: Artificial Intelligence for Sustainable and Resilient Production Systems, Apms 2021, Pt I.*; Dolgui, A., Bernard, A., Lemoine, D., VonCieminski, G., Romero, D., Eds.; Springer International Publishing Ag: Cham, Switzerland, 2021; Volume 630, pp. 124–133; ISBN 978-3-030-85874-2.
273. Mubarik, M.; Mubarak, M.F. Fostering Supply Chain Integration through Blockchain Technology: A Study of Malaysian Manufacturing Sector. *Int. J. Manag. Sustain.* **2020**, *9*, 135–147. [CrossRef]

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Article

Current Trend of Industry 4.0 in Logistics and Transformation of Logistics Processes Using Digital Technologies: An Empirical Study in the Slovak Republic

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Abstract: *Background*: The digital transformation towards Industry 4.0 has become a necessity for businesses as it makes them more flexible, agile and responsive. Logistics is no exception, as it is constantly undergoing a significant transformation supported by revolutionary Industry 4.0 technologies that are fundamentally changing logistics processes and operations. *Methods*: In the construction of the paper, the following classical scientific methods were used: analysis, synthesis, induction, deduction, analogy, specification and comparison. Among the special scientific methods, the method of classification, concretisation, graphical methods, questionnaire survey and statistical methods were used. *Results*: The analysed enterprises perceive digital transformation in logistics. In the analysed enterprises in Slovakia, the Industry 4.0 strategy is implemented in logistics. Industry 4.0 in logistics has the largest representation in production logistics in each enterprise category. In implementing Industry 4.0 in logistics, enterprises confront the biggest barrier, namely, investment costs. *Conclusions*: Through one-way analysis of variance (ANOVA) and Pearson's correlation coefficient, several significant relationships were confirmed. The significant relationship between manufacturing logistics and selected Industry 4.0 technologies was demonstrated. The significant relationship between procurement logistics and selected Industry 4.0 technologies was also demonstrated. The statistical analysis also confirmed a significant relationship between distribution logistics and the selected Industry 4.0 technologies.

Keywords: digital transformation; Industry 4.0; Industry 4.0 technologies; Logistics 4.0; statistical methods

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Citation: Richnák, P. Current Trend of Industry 4.0 in Logistics and Transformation of Logistics Processes Using Digital Technologies: An Empirical Study in the Slovak Republic. *Logistics* **2022**, *6*, 79. https://doi.org/10.3390/logistics6040079

Academic Editors: Benjamin Nitsche, Frank Straube and Robert Handfield

Received: 18 August 2022
Accepted: 10 November 2022
Published: 15 November 2022

1. Introduction

The business environment is facing a dizzying transformation, rapid change and dynamic development. The logistics industry has seen many changes over the years, and as technology continues to transform the world, its impact on logistics will only expand. This is expected to cause a paradigm shift in how enterprises deliver their goods to customers quickly and efficiently. In the wake of the global pandemic, the logistics industry is under more pressure than ever to improve its processes. Everyone needs seamless logistics flows without any dangers or disruptions. Industry 4.0 is having a profound impact on the economy of every country, as it is revolutionising not only logistics, but also fundamentally changing society itself and the economy of the world. Industry 4.0 represents the use of automation and digitalisation with the application of new revolutionary technologies. Industry 4.0 is based on the interconnection of the Internet of Things with modern devices that communicate with each other through cyber-physical systems and are independent of humans. The actual implementation and subsequent use of Industry 4.0 and its technologies in the enterprise concerns not only logistics, but the entire supply chain. Industry 4.0 brings transformational changes that offer significant challenges and opportunities that affect many operational aspects of logistics.

The intention of the paper was to identify and explain the definitions and terminology that identify Industry 4.0 in logistics, based on the analysis of the literature, and also to interpret the research results that analyse the current state of the ongoing digital transformation of logistics through digital technologies in enterprises in the Slovak Republic.

Research and studies carried out in the field of digital transformation of logistics towards Logistics 4.0 still have a limited presence in the scientific sphere. Partial studies have been realised elsewhere in the world which highlight the importance of digital technologies in logistics for the sake of a continuous flow in logistics and to ensure an efficient management of logistics processes and activities with elements of artificial intelligence. It is this gap in research that has created a prerequisite for an in-depth analysis of the issue in the conditions of the Slovak Republic, where no similar research has been conducted in small, medium-sized and large enterprises through a questionnaire which has been evaluated by descriptive analysis and inferential analysis.

In the first part of the paper, a comprehensive and in-depth analysis of the views on the conceptual framework for Industry 4.0, the role of technology in the Industry 4.0 era, and the digital transformation of logistics is conducted through classical scientific methods. In the next part of the paper, the methodology of the paper is identified, which includes a review of similar research conducted in the world, thus establishing the theoretical basis for the construction of the research question and hypotheses. Subsequently, the paper conducts a descriptive analysis of the questionnaire survey and an inferential analysis of the questionnaire survey, where one-way analysis of variance (ANOVA) and Pearson's correlation coefficient is used. The last part of the paper is the summary of the research and identification of the research limitations.

2. Literature Overview

Digitalisation represents a complex and radical change in which enterprises need to identify and implement digital measures [1]. Digital transformation affects different dimensions of enterprises while enabling the creation of new business models through digital technologies [2]. Digital transformation focuses on creating added value for customers through smart technologies [3]. Digital technologies have changed the nature of business processes as they create new methods of management whereby the enterprise achieves a competitive advantage in a network of stakeholders [4]. In a study by Mittal et al. [5], Pfohl et al. [6] include among digital technologies: augmented reality, virtual reality, cyber-physical infrastructure, cloud computing, Internet of Things, artificial intelligence, big data analytics, additive manufacturing, smart sensors, autonomous robots and systems, and mobile technologies. Digitalisation in the logistics and supply chain management industry is increasingly inflected as it is of strategic importance to enterprises and is impacting established paradigms and business models [7,8]. Fragapane et al. [9] state that new technologies are emerging, especially in the Industry 4.0 era. These technologies include cloud operations and artificial intelligence, while creating new flexible manufacturing systems. The essence of flexibility lies in the ability of the enterprise to respond to customer demands in a timely manner while increasing productivity, without incurring excessive costs and overcommitting resources. Schniederjans et al. [10] state that digitalisation is a current trend in the logistics industry. The opportunities associated with digitalisation have enabled the entire supply chain to access, store and process large amounts of data, whereby enterprises are able to capture individualised customer data to personalise the sales process, product and service design.

We are currently in the Fourth Industrial Revolution, which is characterised by the implementation of smart technologies that interconnect the physical and biological worlds with the digital world [11]. The Fourth Industrial Revolution represents the integration of manufacturing with intelligent information and communication technologies, which enable the manufacturing of products according to individual customer requirements. They also allow production in batches of one piece, but at the cost of mass-produced goods [12]. The Fourth Industrial Revolution differs from the First, Second and Third

Industrial Revolutions because technology plays a much greater role in it. A significant factor is the establishment of technology policy to create an innovation ecosystem [13]. The Fourth Industrial Revolution is also defined as Industry 4.0. Its essence is based on the rapid development of digital technologies. Industry 4.0 digital technologies include the Internet of Things and cyber-physical systems [14]. The Fourth Industrial Revolution is causing changes, especially in manufacturing, as it sees a shift from mass production to personalised production. At the same time, this leads to greater flexibility in production processes while providing tools with which to more efficiently cater to individual customer needs [15]. The Fourth Industrial Revolution has seen significant advances as it embraces robotics and artificial intelligence, whereby machines do the heavy lifting and automated robots carry out constantly repetitive operations [16]. In the Fourth Industrial Revolution, a digital revolution is underway that is fundamentally changing the way individuals work and the way they use the advanced technologies that are integral to manufacturing processes [17]. Industry 4.0 is considered the Fourth Industrial Revolution. It is driven by the automatization of production processes and also by their digitalisation [18]. The Fourth Industrial Revolution enables a higher level of manufacturing efficiency through new, disruptive, smart technologies. These technologies also aim to influence the social and environmental sustainability of enterprises [19].

2.1. Conceptual Framework for Industry 4.0

Industry 4.0 represents a new level of organisation and control of the entire product life cycle value chain. It also focuses on increasingly individualised customer requirements. Industry 4.0 is a visionary yet realistic concept. Industry 4.0 encompasses the Internet of Things, smart manufacturing and cloud manufacturing [20]. Industry 4.0 encompasses an industrial revolution that is based on cyber-physical systems. Industry 4.0 envisages the interconnection of physical and digital systems, all in real time with the help of new enabling technologies. These technologies are changing the way work is done and the way work systems are used. Industry 4.0 is changing the traditional way of doing enterprise, including agility, flexibility and quality [21]. Industry 4.0 focuses on the automation and digitalisation of processes and systems and the exchange of data across the enterprise. The main goal of Industry 4.0 is to create a smart factory to increase productivity in the production system [22]. Nierostek and Horváthová [23] see the success of the enterprise and its future in the Industry 4.0 concept, as Industry 4.0 transforms enterprises and replaces old technologies and processes. Porubčinová and Fidlerová [24] assume that the essence of Industry 4.0 is in the interconnection of the different technological components, with machines, people and products interacting with each other. Mokrá et al. [25] consider it important in the current revolution to take care of efficient employees, who represent a decisive role in business processes. Industry 4.0 is a new industrialisation strategy. Within it, cyber-physical systems, big data, cloud computing, the Internet of Things and the Internet of Services are applied [26]. Industry 4.0 represents a technological revolution where industrial automatization, simulation, integration systems, IoT, cloud computing, additive manufacturing, and augmented reality have important roles to play. It is these technologies that represent the main drivers of the technological revolution [27]. With the help of Industry 4.0, it is possible to connect all elements related to manufacturing processes. The implementation of advanced technologies, techniques and management methodologies specific to Industry 4.0 covers the entire manufacturing process. The intention is to achieve the creation of a Smart Factory [28]. Fidlerová et al. [29] connect the implementation of Industry 4.0 with the introduction of innovations that aim to increase the competitiveness of sustainable business. Imran et al. [30] define Industry 4.0 as the increasing digitalisation and automatization of manufacturing. At the same time, digital value chains are being created that communicate between products, business partners and their environment. Industry 4.0 is creating smart factories that combine physical and cyber technologies. At the same time, technologies are becoming more complex and precise, making manufacturing more efficient, controllable, quality, and transparent [31]. Industry 4.0 is associated with disruptive innovation [32]. These innovations have an important impact on radical changes in technological processes. In order to face the digital transformation, the enterprise has to deal with many challenges, which include fragmentation of the value chain, integration of production systems, and globalisation and decentralisation of manufacturing [33–35]. Industry 4.0 represents the era of digitalisation, where there are digital business models, digital environments, digital production systems and digital machines. In digitalisation, physical flows are implemented and continuously mapped on digital platforms. The higher level of automatization is represented by systems and software that enable communication with intelligent information and communication technologies. This ensures a digital factory not only internally, but also externally as it reaches all elements of the value chain [36].

2.2. Role of Technologies in the Age of Industry 4.0

The pillars of Industry 4.0 are an essential part of this. The core pillars of Industry 4.0 include: the Industrial Internet of Things, cyber-physical systems, vertical and horizontal software integration, augmented reality, predictive techniques, autonomous robots, additive technologies, mass individualisation, innovative methods for collecting and processing big data, and many other real-time data analytics techniques that exploit the potential of cloud computing [37]. Tutak and Brodny [38], Pivoto et al. [39], and Sony and Naik [40] agree on the nine core technology pillars of Industry 4.0. According to the authors, it is these nine pillars that significantly influence the activities in the industry and service sector. These pillars include optimisation and simulation, cloud technologies, virtual and augmented reality, big data analytics, horizontal and vertical system integration, industrial IoT, autonomous robots, incremental technologies, and cybersecurity. The integration of Industry 4.0 technologies into business processes has sparked the transformation of tangible objects into intangible ones. This transformation has made objects more portable and accessible [41]. Industry 4.0 includes artificial intelligence, Internet of Things, augmented reality, additive manufacturing, advanced robotics and cobots, human-machine interfaces, machine-to-machine communication, blockchain, data stored in the cloud, the Internet of Services, autonomous vehicles, and drones [42]. The core technologies of Industry 4.0 include: simulation, industrial IoT, big data analytics, cloud technologies, additive manufacturing, autonomous robots, augmented reality, cybersecurity, and business intelligence [43]. The key elements of Industry 4.0 that are creating disruptive change include: advanced simulation, nanotechnology, biotechnology, neurotechnology, artificial intelligence, Internet of Things, cloud computing, big data, industrial IoT, smart factory and intelligent factory, autonomous robots, cybersecurity, additive manufacturing, virtual reality, smart sensors, drones, vertical and horizontal systems integration, renewable energy and advanced energy storage, machine-to-machine communication, 5G network, quantum computing, mobile devices, predictive maintenance, advanced human-machine interface, and digital twin [44]. The key pillar of Industry 4.0 is new technologies that are fundamentally changing business processes. Industry 4.0 technologies include: simulation, nanotechnology, cloud computing, virtual reality, 3D printing, big data analytics, radio frequency identification, Internet of Things, cybersecurity, machine-to-machine communication, robots, and drones [45–47]. The main advantage of Industry 4.0 technologies is to ensure the implementation of different capabilities depending on the needs of the production system. The level of complexity of the decisions to be made, the amount of information to be processed or the autonomy of the systems to be able to apply decisions without human intervention are taken into account. Industry 4.0 and related technologies are increasingly presented as essential for the increase of productivity in manufacturing enterprises. By focusing on instantaneous communication between machines and objects, it is possible to make manufacturing systems more responsive to product changes and better able to react to unpredictable events [48].

2.3. Digital Transformation of Logistics-Logistics 4.0

In order for logistics systems to respond flexibly to the dynamic changes in the globalised international environment, it is essential that logistics systems become more and more efficient, flexible and secure [49]. Enterprises can achieve this by implementing Industry 4.0 technologies in logistics. The challenge in modern logistics is also supply chain management is the automation of supply chain processes [50]. It is the automation of logistics processes that is still one of the most pressing needs and to manage the current crisis that is also affecting logistics [51]. The trend towards digitalisation has made Industry 4.0 inevitable and is playing a decisive role in the development of new logistics and manufacturing concepts [52]. The ongoing digital transformation of logistics, including the whole supply chain, is a source of competitive advantage [53]. With the support of autonomous and digital Industry 4.0 technologies, faster delivery and minimised logistics costs will be achieved in logistics [54]. With the concept of Industry 4.0, the terms smart logistics and Logistics 4.0 are inflected in logistics. These terms are associated with the Industry 4.0 phenomenon in logistics and describe the interconnection of logistics with the Internet of Things and cyber-physical systems. The main aim of Logistics 4.0 is to speed up logistics processes by sharing information in real time and minimising inaccuracies. The benefits of Logistics 4.0 in the enterprise include: simplified monitoring of logistics systems, increased environmental considerateness, increased logistics awareness, minimised waste of costs, time and energy, creation of new business models, creation of flexible logistics processes that respond promptly to consumer demands [55]. The benefits of Logistics 4.0 are especially noticeable in resource planning, transportation management systems, warehouse management systems, and intelligent transportation systems superstructure [56].

Logistics processes themselves are also under the influence of Logistics 4.0. The logistics paths most affected by the Fourth Industrial Revolution are procurement, inventory management, warehousing and transport. The definition of these logistics processes is identified in Table 1.

Table 1. Definition of logistics process 4.0.

Author	Logistics Process 4.0	Definition of Logistics Process 4.0
Nicoletti [57]	Procurement 4.0	Procurement 4.0 uses technologies such as warehouse robots, self-driving vehicles to enable the introduction of processes that do not require operators and minimise human labour. The main intention is to integrate automation and information and communication solutions.
Kozma et al. [58]	Inventory management 4.0	Inventory management 4.0 represents the processes of warehouse and stock management, which are becoming more transparent and predictable with the development of the Industrial Internet of Things. Inventory management 4.0 is subject to monitoring and controlling the use of space by means of information and communication devices, for example, actual pallet location data is transmitted via RFID technology.
Tutam [59]	Warehousing 4.0	Warehousing 4.0 represents intelligent, automated and connected systems and represents a transformation to autonomy in industry by removing human participation. Autonomous systems, which require less space and operate 24/7, complement mechanical, electromechanical and automated systems by increasing productivity, efficiency, flexibility, modularity and agility, making warehouses more efficient.
Brach [60]	Transport 4.0	Transport 4.0 involves more autonomous transport, the core of which is based on automation and autonomy. Transport 4.0 concentrates on reducing the negative impact on the environment, on the process of movement along with all transport activities that are dominant in the networked environment.

Jeschke [61] defines Logistics 4.0 as the application of smart technologies within Industry 4.0. These technologies include advanced robotics, cloud computing, artificial intelligence, big data and the Internet of Things. Amr et al. [62] says that Logistics 4.0 is a new technological direction that combines technologies with the intention of making the entire supply chain more efficient and effective, while changing the focus of enterprises on value chains, maximising value for consumers and customers by increasing competitiveness through digitalisation. Logistics 4.0 is a combination of smart technologies whose applications are in the areas of inventory management, warehousing, distribution and transportation [63]. Logistics 4.0 represents intelligent logistics, which includes connectivity and integration, real-time localisation, automated data collection and processing, automatic identification, and business and analytical services. Through the new generation technologies, logistics processes are being industrialised through rationalisation and standardisation [64]. Strandhagen et al. [65] defined Logistics 4.0 through Industry 4.0 technologies through which the need for warehousing is reduced, leading to optimised inventory management, information exchange and no information disruptions. Logistics 4.0 is a strategic logistics system that is characterised by flexibility, perfect adaptability to the market, minimisation of costs and meeting customer requirements [66]. Logistics 4.0 consists of autonomous subsystems that interact with each other in order to achieve individual goals and to ensure the efficient behaviour of individual entities [67]. Logistics 4.0 includes networking and integration, data collection and processing, self-organization, decentralisation and independence [68].

Logistics 4.0 mainly uses the following Industry 4.0 technologies: virtual reality and augmented reality, big data, Internet of Things, advanced simulation, artificial intelligence, smart sensors and autonomous robots. These technologies perform an indispensable role in procurement logistics, production logistics and distribution logistics in the context of the Fourth Industrial Revolution. The characteristics of these technologies are presented in Table 2.

Table 2. Definition of Logistics 4.0 technologies.

Author	Logistics 4.0 Technologies	Definition of Logistics 4.0 Technologies
Gattullo et al. [69]	Virtual Reality and Augmented Reality	Virtual Reality and Augmented Reality are complementary Industry 4.0 technologies. With the help of virtual reality, users are transported, via a headset, into a virtual world. But with augmented reality, applications present the illusion of multiple graphical layers of information layered on top of each other over a specific part of the user's field of view.
Diniz et al. [70]	Big Data	The large amount of structured and unstructured data from different types of sources, which may come from interconnected objects, describes a large amount of data. A fundamental characteristic of Big Data is performing analysis on this data.
Kamble et al. [71]	Internet of Things	Internet of Things is creating an industrial system that enables a combination of intelligent machines, advanced predictive analytics, and machine-human collaboration to promote productivity, efficiency, and reliability.
Klee and Allen [72]	Advanced simulation	Simulation is a common method of analysing the behaviour of complex systems. Simulation is a classical technology whose foundations date back to the era of analog computers.
Sigov et al. [73]	Artificial intelligence	Artificial intelligence involves building intelligent machines capable of performing tasks that typically require human intelligence. The essence of artificial intelligence lies in reasoning, knowledge representation, planning, learning, processing machine learning approaches including artificial neural networks.
Kumar and Nayyar [74]	Smart sensors	Smart sensors act as manufacturing assets that collect large amounts of data about products and their environment. This is data for example to measure temperature, humidity and smoke in the air. Smart sensors can detect anomalous activities and can provide the ability to communicate wirelessly, making the data synthetic through a cloud interface as well.
Graetz and Michaels [75]	Autonomous robots	Autonomous robots perform autonomous manufacturing more precisely and can work alongside humans or even in places where humans are constrained. Autonomous robots have the ability to complete tasks on time and accurately, with a focus on flexibility, safety, versatility and collaboration.

3. Research Methodology

The main objective of the present paper was to determine and explicate the definitions and terminology that identify Industry 4.0 in logistics based on a literature analysis and to interpret the research results that analyse the current state of the ongoing digital transformation of logistics through digital technologies in enterprises in Slovakia. In providing a comprehensive view of the issue, it was necessary to define the partial objectives of the paper, which included:

- The comparative overview of views on a conceptual framework for Industry 4.0,
- The comparative analysis of views on the role of technology in the age of Industry 4.0,
- The comparative review of views on the digital transformation of logistics-Logistics 4.0,
- Descriptive analysis of the questionnaire survey,
- Inferential analysis of the questionnaire survey,
- Summarisation of the research issues.

3.1. Description of Collection Tool

The research and studies conducted on the digital transformation of logistics towards Logistics 4.0 still have a limited presence in the scientific sphere. It is this research gap that has created the prerequisite for an in-depth analysis of the topic at hand through statistical induction. Perona et al. [76] conducted research in 91 Italian manufacturing enterprises. The results of the research showed that the implementation of Logistics 4.0 is still immature but has a huge potential. Awareness that the goal of Logistics 4.0 is the harmonious and integrated implementation of digital technologies to support logistics processes has not yet spread in Italian manufacturing enterprises. Nobrega et al. [77] investigated the evolution of Logistics 4.0 in Brazilian enterprises. The authors consider that Logistics 4.0 will represent a major disruptive transformation. Technological advances will allow the entire supply chain to be connected and information will be able to be exchanged in real time, providing greater control over information and better decision making. In addition, Brazilian enterprises consider that the implementation of Logistics 4.0 will also increase identification capabilities and provide better commercial demand forecasting, thereby increasing the flexibility of enterprises. Batz et al. [78] conducted research to determine whether Polish enterprises are aware of the Logistics 4.0 concept and whether they use solutions commonly described as Logistics 4.0 solutions. Based on the results of the research conducted in logistics and manufacturing enterprises in Poland, 33% of the surveyed enterprises are aware of the Logistics 4.0 concept, 50% of the enterprises are aware of the big data concept, 83% of the enterprises want to apply automated data exchange systems and are willing to automate their processes as well as to introduce partial robotisation of their processes. Group-IPS [79] analyses the degree of digitalisation of the supply chain in Spanish enterprises. The research shows that 65% of Spanish enterprises have limitations in the visibility of their supply chain. The main priorities of the surveyed enterprises are the digitalisation of their logistics planning, production and execution. The Industry 4.0 technologies considered most useful in logistics are Internet of Things, big data analytics and artificial intelligence. Correa et al. [80] investigated in 108 Brazilian enterprises the level of corporate interest in investing in IoT and big data analytics of Industry 4.0 technologies oriented towards logistics innovation. More than half of the respondent enterprises are already investing in these two technologies. Enterprises intend to use big data analytics to reduce operational costs, predict consumer behaviour and forecasting. The main reason for adopting IoT and big data analytics is to be more competitive. Alamsjah and Yunus [81] investigated the key determinants of supply chain 4.0 maturity in 154 Indonesian manufacturing enterprises. The analysis revealed that supply chain ambidexterity with an emphasis on innovation positively influences firm agility and the level of supply chain 4.0 maturity. Dallasega et al. [82] investigated the level of maturity of Logistics 4.0 implementation in manufacturing enterprises based in Central Europe, the Northeastern United States, and Northern Thailand. Based on 239 responses, they concluded that Logistics 4.0 is a relatively new area of research that requires further development through empirical validation. To the best of the authors' knowledge, there is no empirically validated multidimensional construct to measure Logistics 4.0 in manufacturing enterprises. Woschank and Dallasega [83] conducted research between December 2020 and January 2021 that was distributed in Central Europe. The results of the research confirmed the impact of Logistics 4.0 on the performance of manufacturing enterprises.

The results also confirmed that smart and lean supply chains have a significant impact on logistics performance indicators.

Based on the conceptual framework of the paper, the foreign research realised in the period 2019–2022 and the author's previous research (Richnák [84] investigated Industry 4.0 in the metallurgical industry in Slovakia; Richnák [85] evaluated the current situation in the area of Industry 4.0 in logistics in the machinery and equipment industry in Slovakia; Richnák [86] investigated the rate of innovation adoption in enterprises in Slovakia in the era of Industry 4.0), in the years 2021–2022, the research question was conceived and subsequently the null and the alternative hypothesis was formulated for it:

Research Question (RQ): How is Industry 4.0 affecting corporate logistics?

Hypothesis 1 (H1). *We assume that there is no significant relationship between production logistics and selected Industry 4.0 technologies.*

Hypothesis 1 (H1a). *We assume that there is a significant relationship between production logistics and selected Industry 4.0 technologies.*

Hypothesis 2 (H2). *We assume that there is no significant relationship between procurement logistics and selected Industry 4.0 technologies.*

Hypothesis 2 (H2a). *We assume that there is a significant relationship between procurement logistics and selected Industry 4.0 technologies.*

Hypothesis 3 (H3). *We assume that there is no significant relationship between distribution logistics and selected Industry 4.0 technologies.*

Hypothesis 3 (H3a). *We assume that there is a significant relationship between distribution logistics and selected Industry 4.0 technologies.*

Hypothesis 4 (H4). *We assume that there is no significant relationship between Industry 4.0 and logistics processes.*

Hypothesis 4 (H4a). *We assume that there is a significant relationship between Industry 4.0 and logistics processes.*

In the construction of the paper, the following classical scientific methods were used: analysis, synthesis, induction, deduction, analogy, specification, and comparison. Among the special scientific methods, the method of classification, concretisation, graphical methods, questionnaire survey, and statistical methods were used.

Data collection through a questionnaire survey was conducted between November 2021 and May 2022 through an electronic standardized questionnaire. The questionnaire was distributed to managers of small, medium-sized and large enterprises in Slovakia through e-mail addresses. The questionnaire was structured into several areas. The first area concentrated on the identification of the respondents and then other parts of the questionnaire were related to digital transformation in logistics. The construction of the questions in the questionnaire used identification questions and closed questions where the respondent had a choice of options or selection through a numerical scale from 0–6. Descriptive and inferential statistical analysis was used in the analysis. One-way analysis of variance (ANOVA) and Pearson's correlation coefficient were applied in the statistical analysis.

3.2. Research Design

The research design was a process that consisted of several successive phases. Their development is illustrated in Figure 1 and represents the process of realising the research problem.

Figure 1. Research design of the studied theme. Source: Author's own.

3.3. Descriptions of Research Participants

The object of the research were enterprises located in the Slovak Republic. There were 144 relevant respondents whose answers were included in the analysis. Enterprises were categorised according to size on the basis of the European Commission 2003/361/EC, which defines the small enterprise (10–49 employees), the medium-sized enterprise (50–249 employees) and the large enterprise (≥250 employees). Medium-sized enterprises from industry in Slovakia participated in the survey in the highest proportion (46.5%; N = 67). Large enterprises were represented with the second largest share (44.4%; N = 64). The smallest proportion (9%; N = 13) was from the participation of small enterprises. The summarised data is presented in Figure 2. For the purpose of the analysis conducted, we can conclude that the sample of respondents represented is at a representative level, as medium-sized and large enterprises from Slovak industry are dominant.

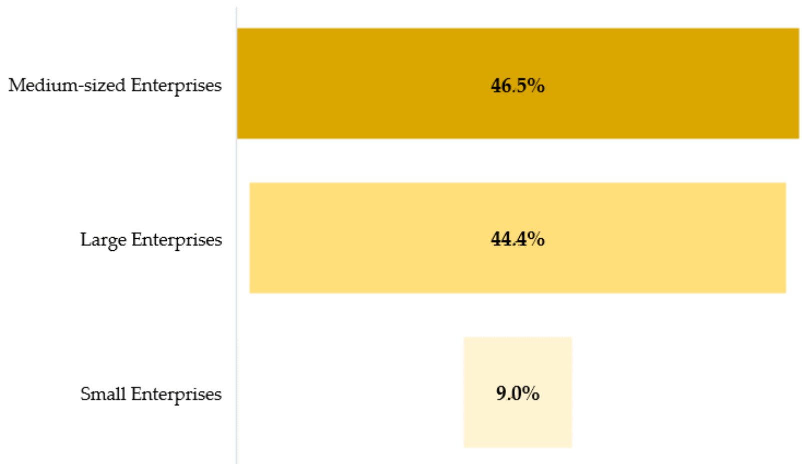

Figure 2. Data file structure by enterprise category. Source: Author's own.

The choropleth map is a graphical representation of the relative quantitative data obtained by the research in the map of Slovakia. The choropleth map is illustrated in Figure 3. By using the most commonly used expression method of thematic cartography, we can monitor the aperiodic representation of individual regions. Coloured shades of yellow-brown indicate identical representation of respondents in the Bratislava and Trnava Regions (20.1%; N = 29). Western Slovakia was represented by the Trenčín Region (17.4%; N = 25) and the Nitra Region (11.1%; N = 16). Central Slovakia was represented by the Žilina Region (9.7%; N = 14) and the Banská Bystrica Region (7.6%; N = 11). Eastern Slovakia, represented by the Prešov Region (8.3%; N = 12) and the Košice Region (5.6%; N = 8), featured the lowest participation.

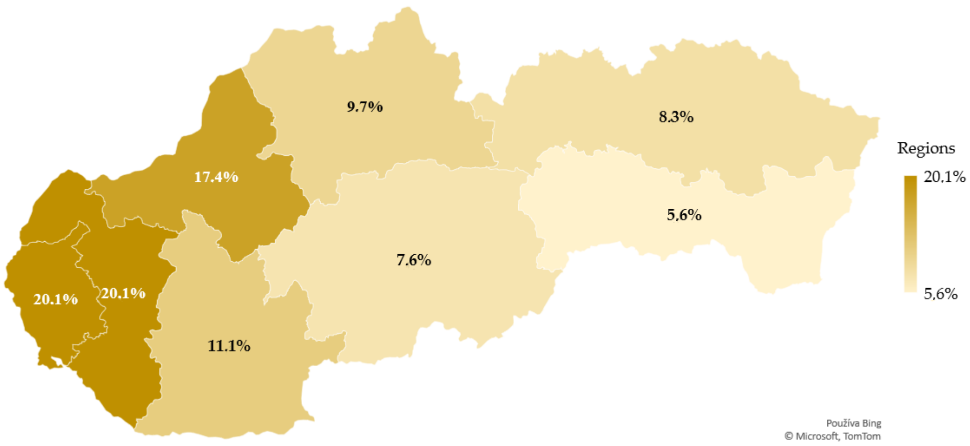

Figure 3. Data file structure by regions of Slovakia. Source: Author's own.

In the research, we wanted to know in which industrial sector the analysed enterprise operates. Figure 4 provides a representation of the different industrial sectors. The largest part of the research sample was the mechanical industry with a share of 19.4% (28 enterprises). The automotive industry and the electrical engineering industry also received a high representation in the research sample, with an identical share of 17.4% (25 enterprises). This was followed by the food industry (15.3%; N = 22), extractive industry (9.7%; N = 14); timber and wood processing industry (6.9%; N = 10), and light industry (5.6%, N = 8). Enterprises from the construction industry and the chemical and pharmaceutical industry (3.5%; N = 5) and the glass industry (1.4%; N = 2) were the least represented in the research.

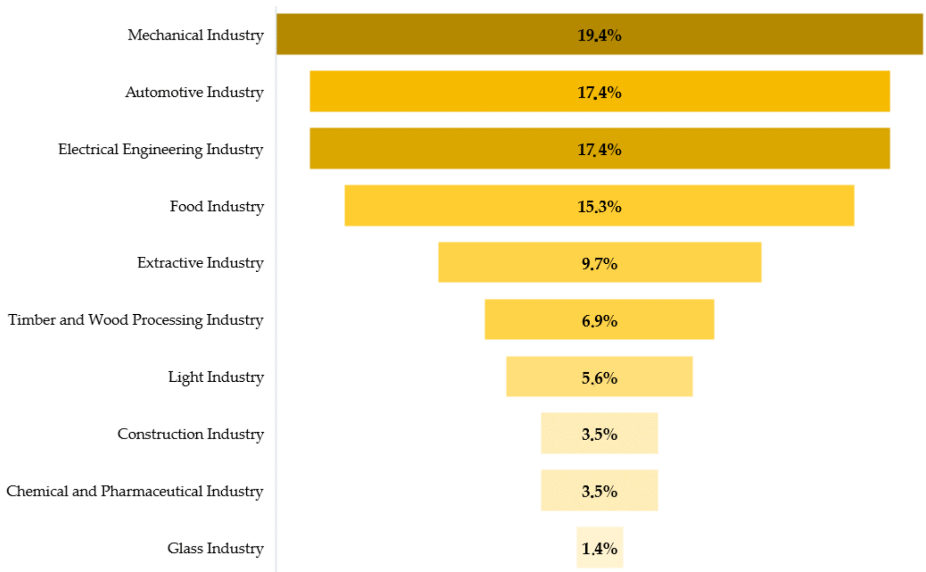

Figure 4. Data file structure by industrial sector. Source: Author's own.

In identifying the research sample, the territorial location of the enterprises was also included in the analysis. The largest representation of enterprises was recorded in transnational markets (76.0%; N = 110). Enterprises operating in national markets occupied the second position (15.3%; N = 22). The lowest shares were observed for enterprises that operate in regional markets (5.6%; N = 8) and local markets (2.8%; N = 4). The results of the descriptive analysis are presented in Figure 5.

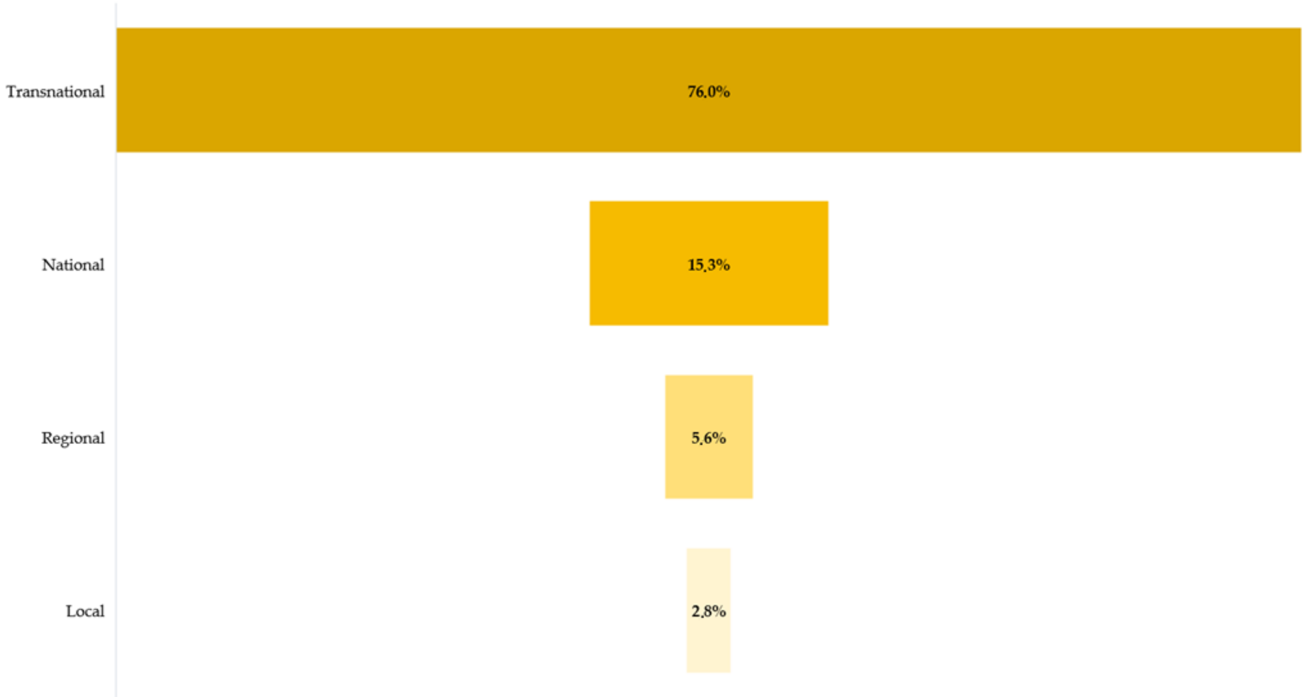

Figure 5. Data file structure by territorial location of enterprises. Source: Author's own.

4. Results Analysis and Discussion

4.1. Evaluation of Descriptive Analysis

Through descriptive analysis, the following selected results were evaluated, results which dealt with the theme of digitalisation and Industry 4.0 in the logistics of enterprises in Slovakia.

The data analysed is segmented by the size of the participating enterprises. Table 3 clearly summarises the results of the analysis, based on which we can see that 89.1% (N = 57) of large enterprises perceive digital transformation in logistics. Also 77.6% (N = 52) of medium-sized enterprises in Slovakia reflect the ongoing digital transformation in logistics. The interesting findings are that also in the small enterprise category (69.2%, N = 9) there are interests that dominate the digital transformation in logistics.

Table 3. Data file structure by digital transformation in logistics.

Digital Transformation in Logistics		Small Enterprises	Medium-Sized Enterprises	Large Enterprises
Yes	Absolute Frequency	9	52	57
	Relative Frequency	69.2%	77.6%	89.1%
No	Absolute Frequency	4	15	7
	Relative Frequency	30.8%	22.4%	10.9%
Total	Absolute Frequency	13	67	64
	Relative Frequency	100.0%	100.0%	100.0%

Industry 4.0 in logistics requires having the logistics strategy that deals with the digital transformation of logistics processes and logistics activities. In the analysed enterprises

in Slovakia, the Industry 4.0 strategy is implemented in logistics. Large enterprises have it at this level with a share of 59.4% (N = 38). Medium-sized enterprises have the highest share (47.8%, N = 32) of Industry 4.0 strategy in logistics in implementation. Also, small enterprises in Slovakia have the highest share (76.9%, N = 10) of implementation for the Industry 4.0 strategy in logistics. The interesting finding is that there is no Industry 4.0 strategy in only 1.6% (N = 1) of large enterprises and 6% (N = 4) of medium-sized enterprises. Table 4 summarises the results of the analysis.

Table 4. Data file structure by implementing Industry 4.0 in logistics.

		Small Enterprises	Medium-Sized Enterprises	Large Enterprises
Strategy implemented	Absolute Frequency	1	18	38
	Relative Frequency	7.7%	26.9%	59.4%
Strategy in implementation	Absolute Frequency	10	32	17
	Relative Frequency	76.9%	47.8%	26.6%
Pilot initiatives launched	Absolute Frequency	0	13	8
	Relative Frequency	0.0%	19.4%	12.5%
No strategy exists	Absolute Frequency	2	4	1
	Relative Frequency	15.4%	6.0%	1.6%
Total	Absolute Frequency	13	67	64
	Relative Frequency	100.0%	100.0%	100.0%

When implementing Industry 4.0 in logistics, it is important to recognise in which type of logistics it has the largest participation. Based on the results of Table 5, we can determine that Industry 4.0 in logistics has the largest representation in production logistics in each category of enterprise. In large enterprises it is represented with a share of 79.7% (N = 51), in medium-sized enterprises it is represented with a share of 80.6% (N = 54) and in small enterprises it is represented with a share of 38.5% (N = 5). The interesting finding is the fact that procurement logistics reached an identical number (N = 4) in each category of enterprise. On a small scale, large, medium-sized and small enterprises in Slovakia are implementing Industry 4.0 in distribution logistics.

Table 5. Data file structure of Industry 4.0 implementation in various types of logistics.

		Small Enterprises	Medium-Sized Enterprises	Large Enterprises
Production Logistics	Absolute Frequency	5	54	51
	Relative Frequency	38.5%	80.6%	79.7%
Procurement Logistics	Absolute Frequency	4	4	4
	Relative Frequency	30.8%	6.0%	6.2%
Distribution Logistics	Absolute Frequency	4	9	9
	Relative Frequency	30.8%	13.4%	14.1%
Total	Absolute Frequency	13	67	64
	Relative Frequency	100.0%	100.0%	100.0%

When implementing Industry 4.0 in logistics, enterprises face barriers to its implementation. The selected barriers that were most inflected in the research have been summarised in Table 6. From the responses, we determined that within large enterprises, the biggest barrier was the investment cost in implementing Industry 4.0 in logistics (59.4%, N = 38). Also, both medium-sized enterprises (88.1%, N = 59) and small enterprises (84.6%, N = 11) consider investment costs as the biggest barrier. New supply chain upgrading will also be a major challenge for large enterprises (37.5%, N = 24). Enterprises in Slovakia are not concerned about the shortage of skilled labour. Only one large enterprise (1.6%) considers it as a barrier.

Table 6. Data file structure by barriers.

		Small Enterprises	Medium-Sized Enterprises	Large Enterprises
Investment costs	Absolute Frequency	11	59	38
	Relative Frequency	84.6%	88.1%	59.4%
New supply chain setting	Absolute Frequency	1	8	24
	Relative Frequency	7.7%	11.9%	37.5%
Concern about meeting objectives	Absolute Frequency	1	0	1
	Relative Frequency	7.7%	0.0%	1.6%
Shortage of skilled labour	Absolute Frequency	0	0	1
	Relative Frequency	0.0%	0.0%	1.6%
Total	Absolute Frequency	13	67	64
	Relative Frequency	100.0%	100.0%	100.0%

4.2. Evaluation of Inferential Analysis

The studied topic was also analysed by using inferential statistics. One-way analysis of variance ANOVA and Pearson's correlation coefficient were used to evaluate the null and alternative hypotheses.

Research Question (RQ): How Is Industry 4.0 Affecting Corporate Logistics?

The null hypothesis (H1) and alternative hypothesis (H1a) were tested using one-way analysis of variance (ANOVA). The results of the testing are presented in Table 7. Considering the value of statistical significance, there is a significant relationship between the production logistics and the selected technologies in Industry 4.0: Virtual reality and Augmented reality ($F(6, 137) = 2.628$, $p = 0.019$; Drones $F(6, 137) = 3.257$, $p = 0.005$; Big Data ($F(6, 137) = 2.498$, $p = 0.025$; 5G network ($F(6, 137) = 2.567$, $p = 0.022$; Additive manufacturing $F(6, 137) = 5.053$, $p = 0.000$; Internet of Things ($F(6, 137) = 4.180$, $p = 0.001$; Advanced simulation $F(6, 137) = 3.161$, $p = 0.006$; Artificial intelligence $F(6, 137) = 2.818$, $p = 0.013$; Smart sensors $F(6, 137) = 2.962$, $p = 0.009$; Autonomous robots $F(6, 137) = 3.823$, $p = 0.001$; Cloud computing $F(6, 137) = 3.477$, $p = 0.003$; Cyber-physical systems $F(6, 137) = 2.690$, $p = 0.017$.

The null hypothesis (H2) and alternative hypothesis (H2a) were tested using one-way analysis of variance (ANOVA). The results of the testing are presented in Table 8. With respect to the value of statistical significance, there is a significant relationship between procurement logistics and the selected Industry 4.0 technologies: Big Data ($F(6, 137) = 3.282$, $p = 0.005$; 5G network ($F(6, 137) = 3.537$, $p = 0.003$; Internet of Things ($F(6, 137) = 6.247$, $p = 0.000$; Advanced simulation $F(6, 137) = 2.661$, $p = 0.018$; Artificial intelligence $F(6, 137) = 4.760$, $p = 0.000$; Smart sensors $F(6, 137) = 4.341$, $p = 0.000$; Cloud computing $F(6, 137) = 3.705$, $p = 0.002$.

The relationship between procurement logistics and Industry 4.0 technologies: Virtual reality and Augmented reality ($F(6, 137) = 0.726$, $p = 0.630$; Drones $F(6, 137) = 1.190$, $p = 0.315$; Additive manufacturing $F(6, 137) = 1.298$, $p = 0.262$; Autonomous robots $F(6, 137) = 1.975$, $p = 0.073$; Cyber-physical systems $F(6, 137) = 0.541$, $p = 0.776$ was non-significant.

The null hypothesis (H3) and alternative hypothesis (H3a) were tested using one-way analysis of variance (ANOVA). The results of the testing are presented in Table 9. With respect to the value of statistical significance, there is a significant relationship between distribution logistics and the selected Industry 4.0 technologies: Big Data ($F(6, 137) = 2.774$, $p = 0.014$; 5G network ($F(6, 137) = 2.164$, $p = 0.050$; Internet of Things ($F(6, 137) = 4.439$, $p = 0.000$; Advanced simulation $F(6, 137) = 3.140$, $p = 0.006$; Artificial intelligence $F(6, 137) = 2.703$, $p = 0.016$; Smart sensors $F(6, 137) = 3.041$, $p = 0.008$; Autonomous robots $F(6, 137) = 3.265$, $p = 0.005$; Cloud computing $F(6, 137) = 2.197$, $p = 0.047$.

Table 7. Industry 4.0 technologies used in production logistics.

ANOVA		Sum of Squares	df	Mean Square	F	Sig.
Virtual reality and Augmented reality	Between Groups	58.102	6	9.684	2.628	0.019
	Within Groups	504.836	137	3.685		
	Total	562.937	143			
Drones	Between Groups	84.849	6	14.142	3.257	0.005
	Within Groups	594.901	137	4.342		
	Total	679.750	143			
Big Data	Between Groups	63.194	6	10.532	2.498	0.025
	Within Groups	577.632	137	4.216		
	Total	640.826	143			
5G network	Between Groups	15.581	6	2.597	2.567	0.022
	Within Groups	138.578	137	1.012		
	Total	154.160	143			
Additive manufacturing	Between Groups	135.580	6	22.597	5.053	0.000
	Within Groups	612.643	137	4.472		
	Total	748.222	143			
Internet of Things	Between Groups	97.277	6	16.213	4.180	0.001
	Within Groups	531.383	137	3.879		
	Total	628.660	143			
Advanced simulation	Between Groups	73.336	6	12.223	3.161	0.006
	Within Groups	529.664	137	3.866		
	Total	603.000	143			
Artificial intelligence	Between Groups	69.328	6	11.555	2.818	0.013
	Within Groups	561.831	137	4.101		
	Total	631.160	143			
Smart sensors	Between Groups	63.494	6	10.582	2.962	0.009
	Within Groups	489.444	137	3.573		
	Total	552.938	143			
Autonomous robots	Between Groups	47.976	6	7.996	3.823	0.001
	Within Groups	286.579	137	2.092		
	Total	334.556	143			
Cloud computing	Between Groups	62.366	6	10.394	3.477	0.003
	Within Groups	409.523	137	2.989		
	Total	471.889	143			
Cyber-physical systems	Between Groups	52.693	6	8.782	2.690	0.017
	Within Groups	447.196	137	3.264		
	Total	499.889	143			

The relationship between distribution logistics and Industry 4.0 technologies: Virtual reality and Augmented reality ($F(6, 137) = 1.135$, $p = 0.345$; Drones $F(6, 137) = 1.701$, $p = 0.125$; Additive manufacturing $F(6, 137) = 1.490$, $p = 0.186$; Cyber-physical systems $F(6, 137) = 0.712$, $p = 0.641$ was non-significant.

The null hypothesis (H4) and the alternative hypothesis (H4a) were tested using Pearson's correlation coefficient. Based on the evaluation of the coefficient, we conclude that a positively significant relationship emerged between Industry 4. 0 and logistics processes: customer service ($r = 0.333$; $p = 0.000$), inventory management ($r = 0.328$; $p = 0.000$), logistics communication ($r = 0.341$; $p = 0.000$), material handling ($r = 0.197$; $p = 0.018$), order processing ($r = 0.275$; $p = 0.001$), packaging ($r = 0.168$; $p = 0.044$), procurement/purchasing ($r = 0.172$; $p = 0.039$), transport and transportation ($r = 0.266$; $p = 0.001$), warehousing ($r = 0.353$; $p = 0.000$). The results indicate that we are inclined towards the alternative hypothesis. The values are shown in Table 10.

Table 8. Industry 4.0 technologies used in procurement logistics.

ANOVA		Sum of Squares	df	Mean Square	F	Sig.
Virtual reality and Augmented reality	Between Groups	24.550	6	4.092	0.726	0.630
	Within Groups	772.450	137	5.638		
	Total	797.000	143			
Drones	Between Groups	36.567	6	6.095	1.190	0.315
	Within Groups	701.655	137	5.122		
	Total	738.222	143			
Big Data	Between Groups	70.746	6	11.791	3.282	0.005
	Within Groups	492.191	137	3.593		
	Total	562.938	143			
5G network	Between Groups	91.178	6	15.196	3.537	0.003
	Within Groups	588.572	137	4.296		
	Total	679.750	143			
Additive manufacturing	Between Groups	34.457	6	5.743	1.298	0.262
	Within Groups	606.369	137	4.426		
	Total	640.826	143			
Internet of Things	Between Groups	126.091	6	21.015	6.247	0.000
	Within Groups	460.847	137	3.364		
	Total	586.938	143			
Advanced simulation	Between Groups	57.713	6	9.619	2.661	0.018
	Within Groups	495.224	137	3.615		
	Total	552.938	143			
Artificial intelligence	Between Groups	57.709	6	9.618	4.760	0.000
	Within Groups	276.847	137	2.021		
	Total	334.556	143			
Smart sensors	Between Groups	75.379	6	12.563	4.341	0.000
	Within Groups	396.510	137	2.894		
	Total	471.889	143			
Autonomous robots	Between Groups	12.272	6	2.045	1.975	0.073
	Within Groups	141.888	137	1.036		
	Total	154.160	143			
Cloud computing	Between Groups	107.693	6	17.949	3.705	0.002
	Within Groups	663.745	137	4.845		
	Total	771.438	143			
Cyber-physical systems	Between Groups	18.452	6	3.075	0.541	0.776
	Within Groups	778.548	137	5.683		
	Total	797.000	143			

Table 9. Industry 4.0 technologies used in distribution logistics.

ANOVA		Sum of Squares	df	Mean Square	F	Sig.
Virtual reality and Augmented reality	Between Groups	32.186	6	5.364	1.135	0.345
	Within Groups	647.564	137	4.727		
	Total	679.750	143			
Drones	Between Groups	44.437	6	7.406	1.701	0.125
	Within Groups	596.389	137	4.353		
	Total	640.826	143			
Big Data	Between Groups	68.096	6	11.349	2.774	0.014
	Within Groups	560.564	137	4.092		
	Total	628.660	143			
5G network	Between Groups	52.202	6	8.700	2.164	0.050
	Within Groups	550.798	137	4.020		
	Total	603.000	143			
Additive manufacturing	Between Groups	47.271	6	7.878	1.490	0.186
	Within Groups	724.167	137	5.286		
	Total	771.438	143			

Table 9. *Cont.*

ANOVA		Sum of Squares	df	Mean Square	F	Sig.
Internet of Things	Between Groups	102.735	6	17.122	4.439	0.000
	Within Groups	528.425	137	3.857		
	Total	631.160	143			
Advanced simulation	Between Groups	70.957	6	11.826	3.140	0.006
	Within Groups	515.980	137	3.766		
	Total	586.938	143			
Artificial intelligence	Between Groups	49.953	6	8.325	2.703	0.016
	Within Groups	421.936	137	3.080		
	Total	471.889	143			
Smart sensors	Between Groups	86.766	6	14.461	3.041	0.008
	Within Groups	651.456	137	4.755		
	Total	738.222	143			
Autonomous robots	Between Groups	78.959	6	13.160	3.265	0.005
	Within Groups	552.200	137	4.031		
	Total	631.160	143			
Cloud computing	Between Groups	43.875	6	7.313	2.197	0.047
	Within Groups	456.013	137	3.329		
	Total	499.889	143			
Cyber-physical systems	Between Groups	4.661	6	.777	0.712	0.641
	Within Groups	149.498	137	1.091		
	Total	154.160	143			

Table 10. Industry 4.0 effects on logistics processes.

	Pearson Correlation	Sig. (2-tailed)	N
Customer service	0.333	0.000	144
Inventory Management	0.328	0.000	144
logistics Communication	0.341	0.000	144
Material handling	0.197	0.018	144
Order processing	0.275	0.001	144
Packaging	0.168	0.044	144
Procurement/Purchasing	0.172	0.039	144
Transport and Transportation	0.266	0.001	144
Warehousing	0.353	0.000	144

5. Conclusions

Digital transformation towards Industry 4.0 has become a necessity for enterprises, as it makes them more flexible, agile and responsive in the current uncompromising competitive environment. Logistics is no exception, as it is constantly undergoing a dramatic transformation with the support of disruptive Industry 4.0 technologies that are fundamentally changing logistics processes and activities.

The aim of the paper was to identify the current state of digital transformation in the form of Industry 4.0 and its technologies in the logistics of enterprises in Slovakia. The object of the quantitative research, which was realised in the form of an electronic questionnaire, were small, medium-sized and large enterprises located in the Slovak Republic. Medium-sized enterprises from the industry in Slovakia participated in the survey with the largest share. The largest part of the research sample was represented by the mechanical industry. The largest representation of enterprises was recorded in the scope of activities on transnational markets. The analysed enterprises perceive digital transformation in logistics. In the analysed enterprises in Slovakia, the Industry 4.0 strategy is implemented in logistics. Industry 4.0 in logistics has the largest representation in production logistics in each enterprise category. In implementing Industry 4.0 in logistics, enterprises confront the biggest barrier, namely investment costs.

Currently, there is no uniform checklist of Industry 4.0 technologies that are used in logistics. Their number and list varies depending on the author's perspective or the capabilities of the enterprise. Some Industry 4.0 technologies are used in small enterprises, and others in large enterprises; other technologies are used primarily in the automotive industry, while others are used in the textile industry. The view of Industry 4.0 technologies in logistics has been compiled by comparing a large number of available sources. Based on the theoretical part of the paper, the following Industry 4.0 technologies have been defined: Virtual reality and Augmented reality, Drones, Big Data, 5G network, Additive manufacturing, Internet of Things, Advanced simulation, Artificial intelligence, Smart sensors, Autonomous robots, Cloud computing, and Cyber-physical systems. These Industry 4.0 technologies were analysed in small, medium-sized and large enterprises in the Slovak Republic. On the basis of inferential analysis, we conclude that in logistics there is a different use of Industry 4.0 technologies according to the type of logistics. It is not possible to compile a unified checklist of Industry 4.0 technologies in logistics. This is also identified by the evaluated hypotheses, which showed dependent relationships between different types of logistics and Industry 4.0 technologies.

Several significant relationships were confirmed through statistical tests. The significant relationship between production logistics and Industry 4.0 technologies, such as Virtual reality and Augmented reality, Drones, Big Data, 5G network, Additive manufacturing, Internet of Things, Advanced simulation, Artificial intelligence, Smart sensors, Autonomous robots, Cloud computing, and Cyber-physical systems was demonstrated. The significant relationships between procurement logistics and selected Industry 4.0 technologies, such as Big Data, 5G network, Internet of Things, Advanced simulation, Artificial intelligence, Smart sensors, and Cloud computing was also demonstrated. Statistical analysis also confirmed a significant relationship between distribution logistics and selected Industry 4.0 technologies: Big Data, 5G network, Internet of Things, Advanced simulation, Artificial intelligence, Smart sensors, Autonomous robots, Cloud computing. The results of the inferential analysis showed a positively significant relationship emerged between Industry 4.0 and logistics processes.

Research and studies on digitalisation of logistics transformation, digital technologies, Industry 4.0 in logistics, and Logistics 4.0 are constantly evolving and are relevant in the light of the ongoing industrial revolution. Also, research and studies on this issue bring new possibilities and opportunities for enterprises, as there are still many gaps at the enterprise level that have not yet been addressed in the Fourth Industrial Revolution. The conducted research of the author in the presented article from the digital transformation of logistics in the conditions of enterprises in Slovakia is one of them. This research is exceptional and unique as no similar research has been published by Slovak authors yet. The validity and significance of the conducted research is confirmed by similar research conducted elsewhere in the world, which were performed in the range of 2019–2022.

5.1. Research Implications

There is currently no uniform strategy or measures for the implementation of Industry 4.0 in Slovakia. It is the results of the quantitative research conducted in 144 enterprises in Slovakia that creates the potential for their use by the Ministry of Economy of the Slovak Republic, which represents the smart industry in Slovakia. Also, the conducted research can be helpful for the Slovak Investment and Trade Development Agency, which is a state agency of the Ministry of Economy of the Slovak Republic. The Slovak Investment and Trade Development Agency can use the research to create studies and documents for Slovak enterprises, which will better ensure the transfer of the most modern innovative technologies into production practice. At the same time, the investigation of Industry 4.0 in logistics in Slovakia is an unexplored research area, which has opened up further possibilities for further research.

In future research, the authors plan to conduct research that would be extended to enterprises in the Visegrad Group countries. These countries (Slovak Republic, Czech Republic, Poland, Hungary) are developing their economies, infrastructure, energy, digitalisation and innovation with the aim of mutual cooperation and transformation of their economies. Also, the author wants to extend the research to include sustainable development goals in the context of the Industry 5.0 concept, as he believes that sustainability will have a significant impact not only on logistics processes and activities, but on the entire supply chain.

5.2. Limitations

The processed research results have several limitations. The first limitation relates to the research sample, which concentrates only on enterprises that are based in the Slovak Republic. Subsequent research would include enterprises from the Visegrad Group countries in order to give the study an international context. The second limitation of the research is the targeting of only one business area-logistics. In further research it would be appropriate to compare the impact of the ongoing industrial revolution in manufacturing as well. As manufacturing and logistics form one inherent corporate unit that intersects with many business processes and activities. The third limitation of the research was the ongoing global pandemic, which reduced the resulting number of respondents who participated in the research due to national lockdowns. For this reason, it would be interesting to conduct future longitudinal research to compare the results of research conducted during and after the pandemic.

Funding: This research was funded by a grant—VEGA, No. 1/0375/20—New dimension in the development of production management and logistics under the influence of Industry 4.0 in enterprises in Slovakia.

Data Availability Statement: Not applicable.

Acknowledgments: This research was supported by the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and the Slovak Academy of Sciences (VEGA) Project No. 1/0375/20—"New dimension in the development of production management and logistics under the influence of Industry 4.0 in enterprises in Slovakia".

Conflicts of Interest: The author declares no conflict of interest.

References

1. Bohsali, S.; Samad, R.A. Preparing for the Digital Era: The State of Digitalization in GCC Businesses. Available online: https://www.strategyand.pwc.com/reports/preparingdigital-era (accessed on 10 June 2022).
2. Nwaiwu, F. Review and Comparison of Conceptual Frameworks on Digital Business Transformation. *J. Compet.* **2018**, *10*, 86–100. [CrossRef]
3. Rymaszewska, A.; Helo, P.; Gunasekaran, A. IoT powered servitization of manufacturing—An exploratory case study. *Int. J. Prod. Econ.* **2017**, *192*, 92–105. [CrossRef]
4. Brunswicker, S.; Bertino, E.; Matei, S. Big Data for Open Digital Innovation—A Research Roadmap. *Big Data Res.* **2015**, *2*, 53–58. [CrossRef]
5. Mittal, S.; Khan, M.A.; Romero, D.; Wuest, T. Smart manufacturing: Characteristics, technologies and enabling factors. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* **2017**, *233*, 1342–1361. [CrossRef]
6. Pfohl, H.-C.; Yahsi, B.; Kuznaz, T. The impact of Industry 4.0 on the Supply Chain. In Proceedings of the Hamburg International Conference of Logistic (HICL), Berlin, Germany, 20 August 2015; pp. 32–58.
7. Barrett, M.; Davidson, E.; Prabhu, J.; Vargo, S.L. Service Innovation in the Digital Age: Key Contributions and Future Directions. *MIS Q.* **2015**, *39*, 135–154. [CrossRef]
8. Cichosz, M.; Wallenburg, C.M.; Knemeyer, A.M. Digital transformation at logistics service providers: Barriers, success factors and leading practices. *Int. J. Logist. Manag.* **2020**, *31*, 209–238. [CrossRef]
9. Fragapane, G.; Ivanov, D.; Peron, M.; Sgarbossa, F.; Strandhagen, J.O. Increasing flexibility and productivity in Industry 4.0 production networks with autonomous mobile robots and smart intralogistics. *Ann. Oper. Res.* **2020**, *308*, 125–143. [CrossRef]
10. Schniederjans, D.G.; Curado, C.; Khalajhedayati, M. Supply chain digitisation trends: An integration of knowledge management. *Int. J. Prod. Econ.* **2019**, *220*, 107439. [CrossRef]
11. Rotatori, D.; Lee, E.J.; Sleeva, S. The evolution of the workforce during the fourth industrial revolution. *Hum. Resour. Dev. Int.* **2020**, *24*, 92–103. [CrossRef]
12. Ustundag, A.; Cevikcan, E. *Industry 4.0: Managing the Digital Transformation*; Springer International: Cham, Switzerland, 2018.
13. Schäfer, M. The fourth industrial revolution: How the EU can lead it. *Eur. View* **2018**, *17*, 5–12. [CrossRef]
14. Suleiman, Z.; Shaikholla, S.; Dikhanbayeva, D.; Shehab, E.; Turkyilmaz, A. Industry 4.0: Clustering of concepts and characteristics. *Cogent Eng.* **2022**, *9*, 2034264. [CrossRef]

15. Nosalska, K.; Mazurek, G. Marketing principles for Industry 4.0—A conceptual framework. *Eng. Manag. Prod. Serv.* **2019**, *11*, 9–20. [CrossRef]
16. Bláha, J.; Klimsza, L.; Lokaj, A.; Nierostek, L. Multidimensional Analysis of Ethical Leadership for Business Development. *Eur. J. Sustain. Dev.* **2021**, *10*, 290. [CrossRef]
17. Ghobakhloo, M. Industry 4.0, digitization, and opportunities for sustainability. *J. Clean. Prod.* **2020**, *252*, 119869. [CrossRef]
18. Bauer, W.; Schlund, S.; Hornung, T.; Schuler, S. Digitalization of Industrial Value Chains—A Review and Evaluation of Existing Use Cases of Industry 4.0 in Germany. *Logforum* **2018**, *14*, 331–340. [CrossRef]
19. Bai, C.; Dallasega, P.; Orzes, G.; Sarkis, J. Industry 4.0 technologies assessment: A sustainability perspective. *Int. J. Prod. Econ.* **2020**, *229*, 107776. [CrossRef]
20. Vaidya, S.; Ambad, P.; Bhosle, S. Industry 4.0—A Glimpse. *Procedia Manuf.* **2018**, *20*, 233–238. [CrossRef]
21. Lennon Olsen, T.; Tomlin, B. Industry 4.0: Opportunities and Challenges for Operations Management. *SSRN Electron. J.* **2019**, *22*, 113–122. [CrossRef]
22. Abdirad, M.; Krishnan, K. Industry 4.0 in Logistics and Supply Chain Management: A Systematic Literature Review. *Eng. Manag. J.* **2020**, *33*, 187–201. [CrossRef]
23. Nierostek, L.; Horváthová, P. Importance of Intellectual Capital and Business Education as Global Topic in Development of Company International Business from the Perspective of Company Management. *SHS Web Conf.* **2021**, *92*, 1–9. [CrossRef]
24. Porubčinová, M.; Fidlerová, H. Determinants of Industry 4.0 Technology Adaption and Human—Robot Collaboration. *Res. Pap. Fac. Mater. Sci. Technol. Slovak Univ. Technol.* **2020**, *28*, 10–21. [CrossRef]
25. Mokrá, K.; Horváthová, P.; Kauerová, L. The level of health and safety promotion in workplaces of Czech family-owned manufacturing firms: A case study. *J. Hum. Resour. Manag. Comenius Univ. Bratisl. Fac. Manag.* **2021**, *24*, 12–27.
26. Adamson, G.; Wang, L.; Moore, P. Feature-based control and information framework for adaptive and distributed manufacturing in cyber physical systems. *J. Manuf. Syst.* **2017**, *43*, 305–315. [CrossRef]
27. Lopes de Sousa Jabbour, A.B.; Jabbour, C.J.C.; Godinho Filho, M.; Roubaud, D. Industry 4.0 and the circular economy: A proposed research agenda and original roadmap for sustainable operations. *Ann. Oper. Res.* **2018**, *270*, 273–286. [CrossRef]
28. Grabowska, S. Smart Factories in the Age of Industry 4.0. *Manag. Syst. Prod. Eng.* **2020**, *28*, 90–96. [CrossRef]
29. Fidlerová, H.; Stareček, A.; Vraňaková, N.; Bulut, C.; Keaney, M. Sustainable Entrepreneurship for Business Opportunity Recognition: Analysis of an Awareness Questionnaire among Organisations. *Energies* **2022**, *15*, 849. [CrossRef]
30. Imran, M.; Hameed, W.U.; Haque, A.u. Influence of Industry 4.0 on the Production and Service Sectors in Pakistan: Evidence from Textile and Logistics Industries. *Soc. Sci.* **2018**, *7*, 246. [CrossRef]
31. Kalsoom, T.; Ramzan, N.; Ahmed, S.; Ur-Rehman, M. Advances in Sensor Technologies in the Era of Smart Factory and Industry 4.0. *Sensors* **2020**, *20*, 6783. [CrossRef]
32. Bigliardi, B.; Bottani, E.; Casella, G. Enabling technologies, application areas and impact of industry 4.0: A bibliographic analysis. *Procedia Manuf.* **2020**, *42*, 322–326. [CrossRef]
33. Ibarra, D.; Ganzarain, J.; Igartua, J.I. Business model innovation through Industry 4.0: A review. *Procedia Manuf.* **2018**, *22*, 4–10. [CrossRef]
34. De Giovanni, P.; Cariola, A. Process innovation through industry 4.0 technologies, lean practices and green supply chains. *Res. Transp. Econ.* **2020**, *90*, 100869. [CrossRef]
35. Dilyard, J.; Zhao, S.; You, J.J. Digital innovation and Industry 4.0 for global value chain resilience: Lessons learned and ways forward. *Thunderbird Int. Bus. Rev.* **2021**, *63*, 577–584. [CrossRef]
36. Alcácer, V.; Cruz-Machado, V. Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems. *Eng. Sci. Technol. Int. J.* **2019**, *22*, 899–919. [CrossRef]
37. Chiarini, A. Industry 4.0 technologies in the manufacturing sector: Are we sure they are all relevant for environmental performance? *Bus. Strategy Environ.* **2021**, *30*, 3194–3207. [CrossRef]
38. Tutak, M.; Brodny, J. Business Digital Maturity in Europe and Its Implication for Open Innovation. *J. Open Innov. Technol. Mark. Complex.* **2022**, *8*, 27. [CrossRef]
39. Pivoto, D.G.S.; de Almeida, L.F.F.; da Rosa Righi, R.; Rodrigues, J.J.P.C.; Lugli, A.B.; Alberti, A.M. Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0: A literature review. *J. Manuf. Syst.* **2021**, *58*, 176–192. [CrossRef]
40. Sony, M.; Naik, S. Key ingredients for evaluating Industry 4.0 readiness for organizations: A literature review. *Benchmarking Int. J.* **2019**, *27*, 2213–2232. [CrossRef]
41. Rayna, T.; Striukova, L. 360° Business Model Innovation: Toward an Integrated View of Business Model Innovation. *Res. Technol. Manag.* **2016**, *59*, 21–28. [CrossRef]
42. Markov, K.; Vitliemov, P. Logistics 4.0 and supply chain 4.0 in the automotive industry. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *878*, 012047. [CrossRef]
43. Ghadge, A.; Er Kara, M.; Moradlou, H.; Goswami, M. The impact of Industry 4.0 implementation on supply chains. *J. Manuf. Technol. Manag.* **2020**, *31*, 669–686. [CrossRef]
44. Bongomin, O.; Gilibrays Ocen, G.; Oyondi Nganyi, E.; Musinguzi, A.; Omara, T. Exponential Disruptive Technologies and the Required Skills of Industry 4.0. *J. Eng.* **2020**, *2020*, 1–17. [CrossRef]
45. Kosacka-Olejnik, M.; Pitakaso, R. Industry 4.0: State of the art and research implications. *Logforum* **2019**, *15*, 478–485. [CrossRef]

46. Ammar, M.; Haleem, A.; Javaid, M.; Walia, R.; Bahl, S. Improving material quality management and manufacturing organizations system through Industry 4.0 technologies. *Mater. Today Proc.* **2021**, *45*, 5089–5096. [CrossRef]
47. Sahal, R.; Alsamhi, S.H.; Breslin, J.G.; Brown, K.N.; Ali, M.I. Digital Twins Collaboration for Automatic Erratic Operational Data Detection in Industry 4.0. *Appl. Sci.* **2021**, *11*, 3186. [CrossRef]
48. Rosin, F.; Forget, P.; Lamouri, S.; Pellerin, R. Impacts of Industry 4.0 technologies on Lean principles. *Int. J. Prod. Res.* **2019**, *58*, 1644–1661. [CrossRef]
49. Čemerková, Š.; Malátek, V. Human Resources Management in Multinational Companies in Response to Logistics Needs and Meeting Their Goals. In Proceedings of the 2nd International Conference on Decision Making for Small and Medium-Sized Enterprises; Conference Proceedings. Silesian University in Opava, School of Business Administration in Karviná: Karviná, Czech Republic, 2019; pp. 61–69.
50. Nitsche, B.; Straube, F.; Wirth, M. Application areas and antecedents of automation in logistics and supply chain management: A conceptual framework. *Supply Chain. Forum Int. J.* **2021**, *22*, 223–239. [CrossRef]
51. Nitsche, B.; Straube, F. Defining the "New Normal" in International Logistics Networks: Lessons Learned and Implications of the COVID-19 Pandemic. *WiSt—Wirtsch. Stud.* **2021**, *50*, 16–25. [CrossRef]
52. Nitsche, B. Exploring the Potentials of Automation in Logistics and Supply Chain Management: Paving the Way for Autonomous Supply Chains. *Logistics* **2021**, *5*, 51. [CrossRef]
53. Gerlach, B.; Zarnitz, S.; Nitsche, B.; Straube, F. Digital Supply Chain Twins—Conceptual Clarification, Use Cases and Benefits. *Logistics* **2021**, *5*, 86. [CrossRef]
54. Winkelhaus, S.; Grosse, E.H. Logistics 4.0: A systematic review towards a new logistics system. *Int. J. Prod. Res.* **2019**, *58*, 18–43. [CrossRef]
55. Dördüncü, H. Logistics, Supply Chains and Smart Factories. In *Accounting, Finance, Sustainability, Governance & Fraud: Theory and Application*; Springer: Singapore, 2021; pp. 137–152. [CrossRef]
56. Barreto, L.; Amaral, A.; Pereira, T. Industry 4.0 implications in logistics: An overview. *Procedia Manuf.* **2017**, *13*, 1245–1252. [CrossRef]
57. Nicoletti, B. *The Future: Procurement 4.0. Agile Procurement*; Palgrave Macmillan: Cham, Switzerland, 2017; pp. 189–230. [CrossRef]
58. Kozma, D.; Varga, P.; Hegedüs, C. Supply Chain Management and Logistics 4.0—A Study on Arrowhead Framework Integration. In Proceedings of the 8th International Conference on Industrial Technology and Management (ICITM), Cambridge, UK, 2–4 March 2019. [CrossRef]
59. Tutam, M. Warehousing 4.0. In *Accounting, Finance, Sustainability, Governance & Fraud: Theory and Application*; Springer: Singapore, 2021; pp. 95–118. [CrossRef]
60. Brach, J. Formation of transport 4.0 and transport system 4.0 in the context of the impact of revolution 4.0 on modern road transport. *Ekon. XXI Wieku* **2019**, *3*, 87–101. [CrossRef]
61. Jeschke, S. Logistics 4.0—Artificial Intelligence and Other Modern Trends in Transport and Logistics. In *XIII Forum of Polish Logistics Managers POLISH LOGISTICS; Center for Innovation Management and Transfer of Technology in Warsaw*; University of Technology: Warsaw, Poland, 2016.
62. Amr, M.; Ezzat, M.; Kassem, S. Logistics 4.0: Definition and Historical Background. In Proceedings of the 2019 Novel Intelligent and Leading Emerging Sciences Conference (NILES), Giza, Egypt, 28–30 October 2019. [CrossRef]
63. Glistau, E.; Coello Machado, N.I. Industry 4.0, Logistics 4.0 and Materials—Chances and Solutions. *Mater. Sci. Forum* **2018**, *919*, 307–314. [CrossRef]
64. Kim, E.; Kim, Y.; Park, J. The Necessity of Introducing Autonomous Trucks in Logistics 4.0. *Sustainability* **2022**, *14*, 3978. [CrossRef]
65. Strandhagen, J.O.; Vallandingham, L.R.; Fragapane, G.; Strandhagen, J.W.; Stangeland, A.B.H.; Sharma, N. Logistics 4.0 and emerging sustainable business models. *Adv. Manuf.* **2017**, *5*, 359–369. [CrossRef]
66. Şekkeli, Z.H.; Bakan, İ. By the Effect of the Industry 4.0 on Logistics 4.0. *J. Life Econ.* **2018**, *5*, 17–36. [CrossRef]
67. Timm, I.J.; Lorig, F. Logistics 4.0—A challenge for simulation. In Proceedings of the 2015 Winter Simulation Conference (WSC), Huntington Beach, CA, USA, 6–9 December 2015. [CrossRef]
68. Prinz, C.; Morlock, F.; Freith, S.; Kreggenfeld, N.; Kreimeier, D.; Kuhlenkötter, B. Learning Factory Modules for Smart Factories in Industrie 4.0. *Procedia CIRP* **2016**, *54*, 113–118. [CrossRef]
69. Gattullo, M.; Scurati, G.W.; Fiorentino, M.; Uva, A.E.; Ferrise, F.; Bordegoni, M. Towards augmented reality manuals for industry 4.0: A methodology. *Robot. Comput. -Integr. Manuf.* **2019**, *56*, 276–286. [CrossRef]
70. Diniz, F.; Duarte, N.; Amaral, A.; Pereira, C. Industry 4.0: Individual Perceptions About Its Nine Technologies. In *Lecture Notes in Information Systems and Organisation*; Springer: Cham, Switzerland, 2022; pp. 257–267. [CrossRef]
71. Kamble, S.S.; Gunasekaran, A.; Gawankar, S.A. Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. *Process Saf. Environ. Prot.* **2018**, *117*, 408–425. [CrossRef]
72. Klee, H.; Allen, R. *Simulation of Dynamic Systems with MATLAB and Simulink*, 3rd ed.; Taylor & Francis: Boca Raton, FL, USA, 2018.
73. Sigov, A.; Ratkin, L.; Ivanov, L.A.; Xu, L.D. Emerging Enabling Technologies for Industry 4.0 and Beyond. *Information Systems Front. A J. Res. Innov.* **2022**, *24*, 1–11. [CrossRef]
74. Kumar, A.; Nayyar, A. si3-Industry: A Sustainable, Intelligent, Innovative, Internet-of-Things Industry. In *A Roadmap to Industry 4.0: Smart Production, Sharp Business and Sustainable Development*; Springer: Cham, Switzerland, 2019; pp. 1–21. [CrossRef]
75. Graetz, G.; Michaels, G. Robots at Work. *Rev. Econ. Stat.* **2018**, *100*, 753–768. [CrossRef]

76. Perona, M.; Zheng, T.; Adrodegari, F.; Ardolino, M.; Bacchetti, A. An exploratory survey on the impacts of Logistics 4.0 on Italian manufacturing companies. *Int. J. Logist. Syst. Manag.* **2021**, *1*, 1. [CrossRef]
77. Nobrega, J.H.C.; Rampasso, I.S.; Sanchez-Rodrigues, V.; Quelhas, O.L.G.; Leal Filho, W.; Serafim, M.P.; Anholon, R. Logistics 4.0 in Brazil: Critical Analysis and Relationships with SDG 9 Targets. *Sustainability* **2021**, *13*, 13012. [CrossRef]
78. Batz, A.; Oleśków-Szłapka, J.; Stachowiak, A.; Pawłowski, G.; Maruszewska, K. Identification of Logistics 4.0 Maturity Levels in Polish Companies—Framework of the Model and Preliminary Research. In *Sustainable Logistics and Production in Industry 4.0*; Springer: Cham, Switzerland, 2019; pp. 161–175. [CrossRef]
79. Group-IPS—Industrial Projects Services. New Survey Analyses the Degree of Spanish Supply Chain Digitalization. Group-IPS. Available online: https://www.group-ips.com/ips-news/detail/new-survey-analyses-the-degree-of-spanish-supply-chain-digitalization (accessed on 10 June 2022).
80. Correa, J.S.; Sampaio, M.; Barros, R.D.C.; Hilsdorf, W.D.C. IoT and BDA in the Brazilian future logistics 4.0 scenario. *Production* **2020**, *30*, 1–14. [CrossRef]
81. Alamsjah, F.; Yunus, E.N. Achieving Supply Chain 4.0 and the Importance of Agility, Ambidexterity, and Organizational Culture: A Case of Indonesia. *J. Open Innov. Technol. Mark. Complex.* **2022**, *8*, 83. [CrossRef]
82. Dallasega, P.; Woschank, M.; Sarkis, J.; Tippayawong, K.Y. Logistics 4.0 measurement model: Empirical validation based on an international survey. *Ind. Manag. Data Syst.* **2022**, *122*, 1384–1409. [CrossRef]
83. Woschank, M.; Dallasega, P. The Impact of Logistics 4.0 on Performance in Manufacturing Companies: A Pilot Study. *Procedia Manuf.* **2021**, *55*, 487–491. [CrossRef]
84. Richnák, P. Key Challenges and Opportunities of Industry 4.0 in Metallurgical Industry in Slovakia. *DANUBE* **2022**, *13*, 137–154. [CrossRef]
85. Richnák, P. Current Perspectives on Development of Industry 4.0 in Logistics of Machinery and Equipment Industry in Slovakia. *LOGI—Sci. J. Transp. Logist.* **2022**, *13*, 25–36. [CrossRef]
86. Richnák, P. Intensity of Innovation Activity and its Progressivity in Enterprises in Slovakia in the Era of Industry 4.0. *AD ALTA* **2021**, *11*, 250–254. [CrossRef]

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Selecting Partners in Strategic Alliances: An Application of the SBM DEA Model in the Vietnamese Logistics Industry

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Abstract: *Background:* Strategic alliance is a popular strategic option for business entities to strengthen the competitive advantages of all partners in a partnership. The global logistics industry has witnessed the formulation of several successful strategic alliances. However, the Vietnamese logistics industry seems to grow slowly and lacks long-term inter-firm partnerships. In such a context, it is critical to have a more effective approach to selecting partners in strategic alliances to increase long-term relationships and firm performance. *Method:* Thus, this study proposes using the SBM-I-C DEA model to examine and suggest partners for Vietnamese logistics firms to form strategic alliances. *Results:* Our findings show that integrating technology in managing strategic alliances will foster companies in the alliance to formulate a better strategy with up-to-date information on policies. *Conclusion:* Using the SBM-I-C DEA model, companies can minimize operating costs and optimize delivery time. Thus, companies can better satisfy customers. From the research findings, some implications are proposed for Vietnamese logistics companies.

Keywords: super-SBM-I-C DEA model; strategic alliance; Vietnam domestic logistics companies

Citation: Ho, N.-N.-Y.; Nguyen, P.M.; Luu, T.-M.-N.; Tran, T.-T.-A. Selecting Partners in Strategic Alliances: An Application of the SBM DEA Model in the Vietnamese Logistics Industry. *Logistics* **2022**, *6*, 64. https://doi.org/10.3390/logistics6030064

Academic Editors: Benjamin Nitsche and Frank Straube

Received: 22 June 2022
Accepted: 2 September 2022
Published: 15 September 2022

1. Introduction

International commerce has been steadily increasing in recent years due to globalization and economic connectivity among countries, which is deepening and broadening, creating numerous opportunities for import–export enterprises and the country's economy. Logistics services, in particular, are a vital component of international trade. Furthermore, businesses in wealthier countries are rapidly outsourcing their operations to rising regions such as Southeast Asia to reduce manufacturing costs. In addition, with urbanization rates increasing at a massive pace, population densities in cities are on the rise, and supplying those urban areas with goods in a sustainable manner is becoming more and more challenging (Nitsche, 2021, Logistics) [1]. Due to its vast natural resources, low raw material costs, and labor wage, Vietnam is considered one of the most desirable emerging markets. Additionally, our country's topography is suitable for encouraging geographical and political advantages in developing logistics infrastructures such as deep-water harbors, international airports, the Trans-Asian railway system, and international transport hubs.

The logistics industry in Vietnam is considered an emerging market and has an increasing role to play in the development of Vietnam's economy. According to the Vietnam Association of Logistics Service Enterprises, along with the GDP growth rate, industrial production value, import–export turnover, and retail value of goods and services, in recent years, Vietnam's logistics has had a relatively high growth rate of 12–14% [2]. The total import and export turnover of goods since 2010 has increased by 3.6 times. Meanwhile, the GDP has increased by 2.4 times, from USD 157 billion in 2010 to USD 544 billion in 2020, of which exports have increased at an average rate of 4.5%/year, becoming a vital driving force of economic growth. In the past two years, the COVID-19 epidemic has had a strong impact on the economy, facing unprecedented difficulties in all aspects from economy, culture, and tourism to people's lives globally, especially putting heavy pressure on production capacity as well as the global supply chain. However, the import and export sector still has positive double-digit growth. The total import–export turnover of goods reached USD 600 billion, recognizing the uptrend of 22.3% over the same period, of which exports were nearly USD 300 billion. This result positively contributes to Vietnam's logistics industry as a supporting factor in the transshipment of goods. Logistics enterprises have managed to ensure the regular operation of Vietnam's supply chains in the most challenging times, helping to transship large volumes of import and export goods [3].

Despite the positive growth rate, Vietnamese logistics companies have fewer strategic benefits and face multiple difficulties in size, capital, infrastructure, warehousing, equipment, information technology application, management capacity, and human resources [4]. According to the Ministry of Industry and Trade's Vietnamese Logistics Report 2021, most logistics businesses in Vietnam are still small- and medium-sized in terms of capital, labor, and technology. Moreover, the financial potential is still limited (80% of existing companies have registered capital of VND 1.5–2 billion). In addition to capital problems, Vietnam's logistics are still inexperienced and have limited competitiveness, so it has not had the opportunity to reach the market with huge demand. In addition, there is a lack of synchronous linkage between enterprises and between different stages of logistics activities. Nevertheless, logistics services in the direction of outsourcing of manufacturing companies (3PL, 4PL services) have been present and have great potential for development in Vietnam [5]. However, to enhance the logistics system significantly, the Vietnamese government has only focused on developing infrastructure to create the most advantageous conditions for the logistics business development, as evidenced by different national modal transport development plans [3].

Furthermore, one of the significant issues in the Vietnamese logistic industry is the high cost compared with other countries such as Thailand, China, and Malaysia. Therefore, cutting costs is an excellent way to achieve better performance. Therefore, this study desires to analyze the effectiveness of strategic alliances in Vietnamese logistics firms to enhance their performance. The collaboration of logistics companies allows small- and medium-sized businesses in Vietnam to obtain finance, cut transportation costs, and increase operating efficiency. Furthermore, this collaboration will assist Vietnamese logistic firms in meeting local demand rates, organizing to connect transport activities, expanding the source of information, and opening more service sectors in this billion-dollar service value chain. As a result, these firms may compete with foreign logistic corporations operating in Vietnam.

For years, strategic alliance has emerged as a popular business strategy for many industries. As a result, numerous transportation companies have identified the potential benefits of forming strategic alliances. Logistics alliance is the logistics model between self-operated logistics and outsourcing logistics. It combines the advantages of self-operated and outsourcing logistics and reduces the risks of the two opposite models. Regarding the new trends in the logistics industry in the coming years, sustainability is a buzzword that will drive industry changes. Strategic alliance is primarily focused on as it is considered one of several ways to promote sustainability in the global supply chain because it helps reduce transportation costs and air emissions.

Furthermore, a strategic alliance in the logistics industry also helps to connect various members in the global supply chain and make it easier for goods transportation worldwide. According to Nitsche (2021), optimization to plan, control or execute the physical flow of goods and the corresponding informational and financial flows within the focal firm and with sustainable supply chain partners helps productivity increase in logistics networks (applied economics) [1].

However, only a few pieces of research on strategic alliances in the logistics industry have been conducted in Vietnam. In this regard, we use the super (SBM-I-C) DEA (Data Envelopment Analysis) model to analyze and evaluate the ability of domestic enterprises to cooperate [6]. Our sample included 16 Vietnamese logistics companies, and data for analysis were obtained for three years, from 2018 to 2021. The primary goal of our research is to validate the application of the SBM-I-C DEA model in selecting strategic alliance partners for logistics firms in Vietnam.

2. Literature Review

2.1. Logistics Industry and Strategic Alliance

Logistics is a service consisting of people, processes, and technology to deliver the right product at the right cost, time, and place in the right quantity and condition to the right customer. Logistics processes manage the movement and storage of goods among the different supply chain partners [7]. Therefore, measuring the performance of the supply chain is fundamental to identifying and addressing deficiencies in logistics activities, and it serves as a good input for managerial decision making. However, logistics is a well-integrated trading and product movement system, not only a transportation system.

According to Glaister (1998), a strategic alliance is described as an "inter-firm collaboration over a given economic space and time for the attainment of mutually defined goals" [8]. Similarly, Taylor (2005) stated that a strategic alliance is an interconnection between multi-business partners that shares resources, managerial control, and rewards in collaboration and makes ongoing contributions in one or perhaps more strategic areas, such as technological or product innovation [9]. It is also an efficient paradigm for assisting organizations in accessing and conserving the resources required for dynamic development innovation and risk sharing. Vyas et al. (1995) and Mockler (1997) established a strategic alliance model that emphasizes the essential traits of a successful partnership, including goal integration, should move towards a similar direction, synergy—joint actions should add more value than the sum of their parts by leveraging the strengths of each partner [10,11].

The logistics alliance concept is formed when we combine the strategic alliance definition and the logistics industry characteristics. A logistics alliance is organized by two or more business entities to cooperate through signing contracts in the long term. The primary purpose of the alliance is to leverage members' advantages to share resources, have complementary advantages, and achieve logistics objectives together. A strategic alliance is characterized by interdependence, cooperation, risk, and benefit sharing among alliance members. 2M, Ocean Alliances, and The Alliance are examples of global carrier shipping alliances that pool resources to expand service offerings and geographic coverage. Collaboration among local transportation and logistics industries is expected to increase their ability to compete against multinational firms significantly.

Some studies on strategic alliances have been conducted in Vietnam. For example, Vu (2019) stated that collaboration and joint ventures are critical strategies for improving the performance of logistics businesses in Vietnam [12]. Thus, the authors also emphasize that many enterprises are not capable of accomplishing it with their strength, so a logistics alliance is a reasonable choice. To achieve the best possible outcome from these criteria, we must examine transportation, human resource systems, buildings, upgrading and extending warehouse systems, loading and unloading equipment, and other support services. Moreover, a logistic company should connect and expand its service network in the country and worldwide to create foreign markets and enhance the professional capacity of officials from there. If domestic firms seek to compete for market share with foreign corporations, these variables will be an enormous difficulty to deal with.

2.2. Data Envelopment Analysis Model and Its Application

Charnes et al. (1978) established Data Envelopment Analysis (DEA), a statistical approach for identifying the impact of a decision-making unit (DMU) [5]. A DMU is a group of entities that receive the same set of inputs and produce the same set of outputs. In cases of one or more inputs or outputs, the DEA is used to determine relative efficiency [13].

DEA has changed over the years as different models have been modified. Non-radial models, such as Tone's (2001), provided slacks-based measures (SBM-I-C) and input excess and output deficit measurement. However, because early models produce the same score (equal 1) for all units in the efficient frontier, they cannot distinguish between efficient DMUs' performance [14]. The need to evaluate efficient DMUs prompted the creation of a number of super-efficiency models. According to Du et al. (2010) the super-SBM-I-C model accomplishes this by calculating the target DMU's shortest distance to the efficient frontier while excluding the target DM [15].

Much research on the use of DEA in various industries has recently been published. Oum et al. (2008) used DEA models to evaluate the strategic and functional productivity of a Spanish airline in 2001 [16]. Furthermore, Das and Teng (2003) and Wang et al. (2016) applied the DEA model in various areas in businesses such as Renault–Nissan, Merck, and AB Astra [17,18]. Liang et al. (2006) used DEA to enhance the feasibility of supply management sectors. In addition, a substantial study has been conducted to measure the efficiency of the logistics industry in specific cities using a variety of inputs and outputs in conjunction with data envelopment analysis (DEA) [19]. For example, Gen and Syarif (2005) researched the logistics industry's efficiency based on the selection of four variables: delivery reliability, delivery flexibility, delivery cycle, and inventory level [20]. Hamdan investigates the efficiency of the logistics industry with a focus on the rate of return, the delayed arrival rate, and the price. Li and Liu (2019) focused on the number of trucks, the transportation and warehousing and fixed postal investment, the urban road area, and the urban road length. The latter consists of the freight volume and the freight turnover [21].

Similarly, Nguyen and Tran (2018) used the DEA model to evaluate the strategic alliance in Vietnamese logistic firms. They concluded that collaboration among local enterprises could boost supply chain integration, making it more productive and increasing the industry's competitiveness. In addition, they analyzed that the contemporary background of Vietnam is that it is a developing country with a lengthy and dynamic geographical structure. Its logistics are likewise in the development process and appear to have a high potential [22]. However, a lack of experience and technology, fragmented operations, severe price competition among local firms, and dominance by global logistics giants are all challenges that may hinder the local sector's growth. Therefore, strategic alliance is a good strategy for Vietnamese logistics firms.

3. Methodology

3.1. Research Methodology

3.1.1. Research Procedure

This research uses a procedure with 7 steps. Each of the steps is detailed as follows:

- Step 1: Data collection.
- The data of DMUs were collected from VietStock, which is a famous stock market in Vietnam [23]. In this research, one DMU was selected and is defined as a target company that is a basic company that selects other companies as partners for a strategic alliance.
- Step 2: Selection of input/output variables.
- Inputs and outputs are the main impact factors used by DEA model to measure the relative efficiency of a DMU to other DMUs.
- Step 3: Selection of DEA model.
- In this step, the super-SBM-I-C was used to measure the efficiency of different DMUs.
- Step 4: Pearson correlation analysis
- DEA was used for incompetency estimation for DMUs by developing a comparative effectiveness score through the change in the multiple foundation data into a ratio of a single virtual output to a single virtual input. Subsequently, correlation testing for collected input and output is quite important. In this research, the Pearson Correlation Coefficient Test was used to check the suitability of selected input and output variables.
- Step 5: Analysis before strategic alliance.

- This step aimed to select one target company and understand its performance before applying strategic alliance with allied members. This helped to understand the performance of the target company after applying the strategic alliance in the next step.
- Step 6: Analysis after strategic alliance.
- This step aimed to analyze the performances of various alliances available for the target company selected in the previous step. From the results available from different alliance strategies, we can identify the best one for a selected target company. The performance of each strategic alliance can be estimated by using the super-SBM-I-C model.
- Step 7: Summary (Partner Selection).
- This step aimed to summarize a suggestion, based on the previous step. Basically, the strategic alliance should result in positive results that can benefit all allied members.
- An overview of the steps is drawn in Figure 1

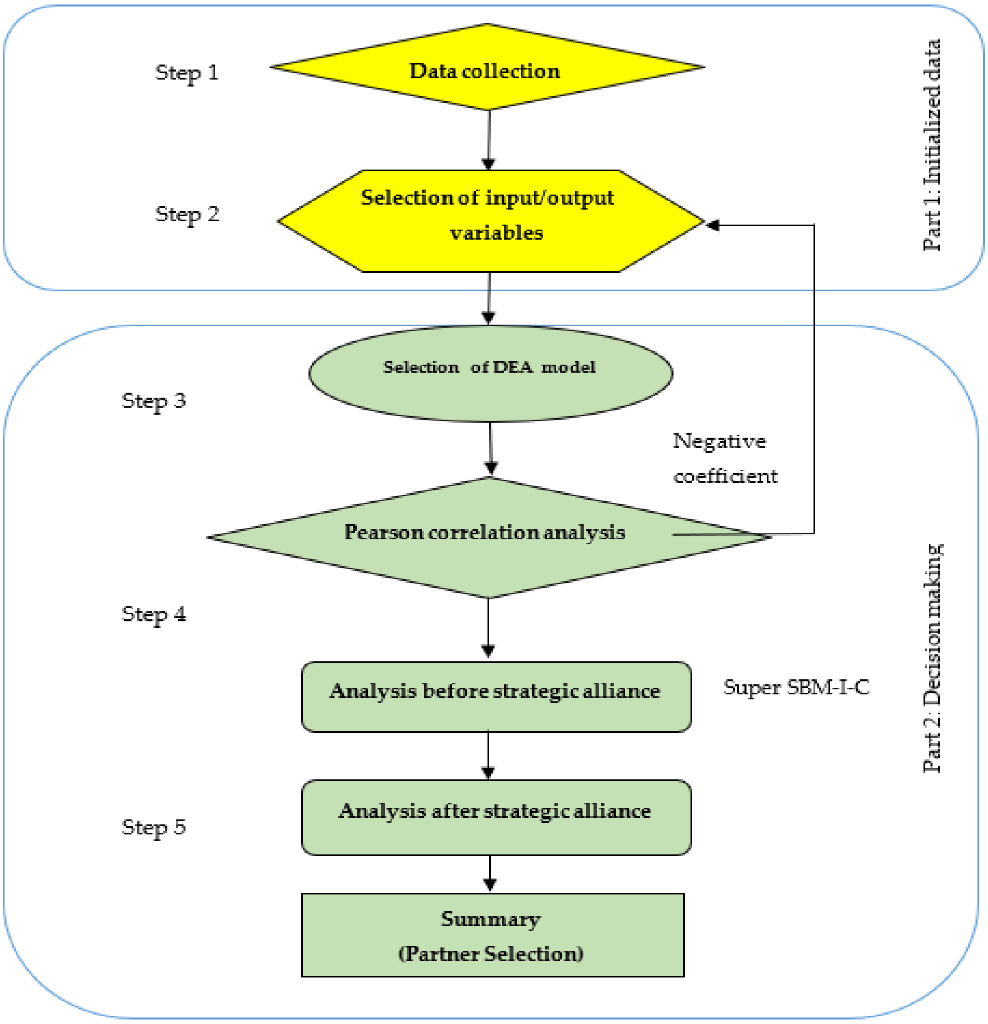

Figure 1. Framework of research.

3.1.2. Non-Radial Super Efficiency Model (Super-SBM)

In this study, the non-radial slack-based measure of super-efficiency (super SBM) of DEA is applied. This model was introduced by Tone in 2001 [14].

In the super SBM model, given n DMUs with the input and output matrices $X = (Xij) \in R^{m \times n}$ and $Y = (Yij) \in R^{8 \times n}$, respectively. Let λ be a non-negative vector in R^n.

The vectors $S^- \in R^m$ and $S^+ \in R^s$ indicate the input excess and output shortfall, respectively. This model provides a constant return to scale. It is defined in Equation (1) that subjects to Equation (2).

$$\min\rho = \frac{1 - \frac{1}{m}\sum_{i=1}^{m} S_i^- / x_{i0}}{1 + \frac{1}{8}\sum_{i=1}^{8} S_i^- / y_{i0}} \tag{1}$$

$$s.t\ x_0 = X\lambda\ + S^-,\ y_0 = Y\lambda\ - S^+,\ \lambda \geq 0, S^- \geq 0,\ S^+ \geq 0 \tag{2}$$

The variable S^+ measure the distance of inputs $X\lambda$ and outputs $Y\lambda$ of a virtual unit from those of the unit evaluated. The numerator and the denominator in the objective function measure the average distance of inputs and outputs, respectively, from the efficiency threshold. The DMUs $(X_0,\ Y_0)$ is SBM-efficient, if $p^* = 1$. This condition is equivalent to $s^{-^*} = 0$ and $s^{+^*}, s^{+^*} = 0$ if there are no input excesses and no output shortfalls in any optimal solution. The SBM-I-C model is non-radial and deals with input/output slacks directly. The SBM-I-C returns and efficiency measure between 0 and 1.

The best performers have the full efficient status denoted by unity. The super-SBM-I-C model is based on the SBM-I-C model. Tone (2001) discriminated these efficient DMUs and ranked the efficient DMUs by super-SBM-I-C model. Assuming that the DMU (X_0, Y_0) is SBM-I-C-efficient, $p^* = 1$; the super-SBM-I-C model is defined in Equation (3) and subject to Equation (4).

$$\min\delta = \frac{\frac{1}{m}\sum_{i=1}^{m} \overline{X}_i / x_{i0}}{\frac{1}{8}\sum_{r=1}^{8} \overline{y}_r / y_{r0}} \tag{3}$$

$$s.t\ \overline{x} \geq \sum_{j=1,\neq 0}^{n} \lambda_j x_j,\ \overline{y} \leq \sum_{j=1,\neq 0}^{n} \lambda_j x_j,\ \ \overline{y} \geq x_0\ and\ \overline{y} \leq y_0,\ \overline{y} \geq y_0,\ \lambda \geq 0 \tag{4}$$

The input-oriented super-SBM-I-C model is derived from Equation (3) with the denominator set to 1. The super-SBM-I-C model returns a value of the objective function that is greater or equal to 1. The higher the value, the more efficient the unit.

Suppose that $y_{r0} \leq 0$. It defines $\overline{y}\,_r^+$ and $\overline{y}\,_{-r}^+$ by:

$$\overline{y}\,_r^+ = max_{j=1,\ldots,n}\{y_{rj} | y_{rj} > 0\} \tag{5}$$

$$\overline{y}\,_r^+ = min_{j=1,\ldots,n}\{y_{rj} | y_{rj} > 0\} \tag{6}$$

In the objective function, if the output r has no positive elements, then it is defined as $\overline{y}\,_r^+ = y\,_{-r}^+ - 1$ The term s_r^+ / y_{r0} will be replaced in the following way. (The value y_{r0} of in the constraints has never changed.)

If $\overline{y}\,_r^+ > y\,_{-r}^+$ the term is replaced by:

$$s_r^+ / \frac{y_{-r}^+\ (\overline{y}\,_r^+ - y_{-r}^+)}{\overline{y}\,_r^+ - y_{r0}} \tag{7}$$

If $\overline{y}\,_r^+ = y\,_{-r}^+$ the term is replaced by:

$$s_r^+ / \frac{\overline{y}\,_r^{+2}}{B(\overline{y}\,_r^+ - y_{r0})} \tag{8}$$

where B is a large positive number (in DEA-Solver B = 100).

Furthermore, the denominator is positive and strictly less than $\overline{y}\,_r^+$. Moreover, it is inverse to the distance $\overline{y}\,_r^+ - y_{r0}$. Hence, this scheme concerns the magnitude of the nonpositive output positively. The score obtained is units invariant; it is independent of the units of measurement used.

3.1.3. Data Collection

In this research, 16 companies were recorded as the most notable market logistic organizations. Initial capitalization is targeted at DMUs due to their importance in the logistics industry in Vietnam published in the stock market. The list of 16 companies were included and listed in Table A1 (Appendix A)

3.1.4. Input and Output Variables Selection

In this exploration, some previous research in logistic industries were referred to in order to find suitable variables as inputs and outputs. Input and output are the two most important data for evaluating DMUs. These selected variables should be able to reveal the performance of DMUs. Table 1 below shows the summary of input and output variables used in some past research for the assessment of DMUs.

Table 1. Summary of input and output variables used in previous studies.

Research Title	Input Variable	Output Variable
Raising Opportunities in Strategic Alliance by Evaluating Efficiency of Logistics Companies in Vietnam: A Case of Cat Lai Port Nguyen and Tran (2019) [22].	Total Asset Cost of Goods Sold Liabilities	Net Revenue Operating Profit
Automobile Industry Strategic Alliance Partner Selection: The Application of a Hybrid DEA and Grey Theory Model Wang et al., 2016 [18].	Fixed Assets Cost of Goods Sold Operating Expenses Long-Term Investments	Revenues Total Equity Net Income
Strategic Alliance for Vietnam Domestic Real Estate Companies Using a Hybrid Approach Combining GM (1,1) with Super SBM DEA Wang et al., 2020 [24]	Charter Capital Asset Value Selling Expense General and Administrative Expense	Revenue from Sales of Goods and Services Profit Before Tax

Let an optimal solution for SBM-I-C be $\left(p^{*}, \lambda^{n}, s^{-^{*}}, s^{+^{*}}\right)$.

There are numerous input and output factors that are routinely used to assess the logistics industry's efficiency. The nature of the study and the peculiarities of a certain efficiency evaluation situation determine which input and output variables are used. Based on the theory of "Operational Efficiency" by Lee and Johnson (2013), which emphasizes the relationship between output revenue and the cost of using input resources or the ability to turn input resources into outputs the best in business activities, the input and output variables were selected in this study [25]. Because of logistics operations in Vietnam cost highly compared with other countries such as Thailand, China, and Malaysia, to improve the operational efficiency, cutting down the logistic costs is essential. The input variables include fixed assets, operating expenses, and the cost of goods sold. These are chosen based on the factors occupying the high percentage on Vietnamese logistics costs such as transport cost, warehousing cost, investment in infrastructure, and technology. The output variables are capital, revenue, and operating income. We believe these factors reflect the essential business resources and outcomes of the respective industry. Details of each variable are shown below:

- Fixed assets (I): The assets owned by, leased by, or required for the functioning of any Logistics Group firm, as well as any future expansions thereof [22,26,27].
- Operating expense (I): An operating expense is an expense a business incurs through its normal business operations. Often abbreviated as OPEX, operating expenses include rent, equipment, inventory costs, marketing, payroll, insurance, step costs, and funds allocated for research and development [28].
- Cost of goods sold (I): The total costs incurred related to a shipment from the time a transaction is generated to the end of a transaction for a shipment. For export services, the cost of goods sold includes sea freight for export, lifting fee, warehousing fee, and document fee [29]

- Total equity (O): The amount invested in a company by investors in exchange for stock, plus all subsequent earnings of the business minus all subsequent dividends paid out [18,30].
- Operating income (O): The measurement of a company's profit once operating costs, taxes, interest, and depreciation have all been subtracted from its total revenues [31,32].
- Net profit (O): The measurement of a company's profit once operating costs, taxes, interest, and depreciation have all been subtracted from its total revenues [18,26].
- Data collection
- Data of these input and output variables 2018–2021 collected from the Vietstock Website are presented in Tables 2–5 [23]

Table 2. The data of Vietnam logistics company 2018 (Unit: million dong).

DMUs	Input			Output		
	Fixed Assets	**Operating Expense**	**Cost of Goods Sold**	**Total Equity**	**Account Receivable**	**Net Profit**
VIN	421,660	48,178	48,912	373,161	89,065	39,968
CQN	3,133,283	133,726	143,228	557,619	56,168	57,119
GMD	10,030,889	2,961,152	4,251,303	4,526,885	1,128,059	443,735
VTP	1,031,937	709,803	714,535	361,028	362,985	111,894
CIA	204,238	92,667	140,517	172,763	8533	7206
CCT	380,786	49,644	119,729	275,091	24,786	12,973
CDN	1,037,629	150,786	22,569	819,599	126,312	127,605
PHP	5,093,773	504,735	1,281,066	3,713,079	298,335	598,557
NCT	485,955	49,970	52,807	436,574	53,496	270,304
TCW	671,512	169,707	373,426	268,924	110,043	62,998
VGR	1,354,535	119,846	761,051	594,444	23,399	28,641
DDG	208,304	84,641	113,87	123,955	70,672	7972
HRT	1,166,448	342,559	450,865	801,788	110,755	3012
SAS	1,730,259	562,722	565,677	1,458,192	293,708	234,112
STG	2,261,989	371,940	1,054,811	909,794	308,540	111,455
VOS	4,152,641	710,986	3,609,911	619,432	463,110	359,180

Source: authors' collection from finance.vietstock.com (accessed on 6 March 2022).

Table 3. The data of Vietnam logistics company 2019 (Unit: million dong).

DMUs	Input			Output		
	Fixed Assets	**Operating Expense**	**Cost of Goods Sold**	**Total Equity**	**Account Receivable**	**Net Profit**
VIN	447,734	60,756	60,099	285,476	94,308	43,102
CQN	2,195,616	1,005,622	1,005,622	579,714	933,603	71,083
GMD	11,183,416	2,676,232	4,196,680	4,409,030	1,127,689	581,436
VTP	1,731,850	1,261,370	1,261,789	479,388	478,704	96,946
CIA	408,066	111,440	199,307	235,445	27,514	20,945
CCT	377,979	39,952	115,726	272,473	35,674	89
CDN	1,277,299	230,973	416,488	870,351	103,294	131,566
PHP	5,194,358	498,609	1,228,735	3,799,561	362,605	482,285
NCT	505,987	64,762	69,888	439,106	54,055	272,817
TCW	673,570	180,423	354,667	322,166	127,304	62,766
VGR	1,322,217	205,988	583,166	745,953	44,946	96,102
DDG	274,242	97,665	157,355	133,383	85,718	9427
HRT	1,570,245	552,471	927,021	715,834	105,257	−87,768
SAS	1,863,906	590,035	607,358	1,542,419	134,952	290,322
STG	2,441,307	518,851	956,061	1,192,403	335,709	521,278
VOS	3,778,130	1,018,129	3,225,726	628,765	510,212	10,736

Source: authors' collection from finance.vietstock.com (accessed on 6 March 2022).

Table 4. The data of Vietnam logistics company 2020 (Unit: million dong).

DMUs	Input			Output		
	Fixed Assets	Operating Expense	Cost of Goods Sold	Total Equity	Account Receivable	Net Profit
VIN	487,886	85,444	85,678	286,480	67,731	42,148
CQN	1,487,272	2,223,351	2,223,351	599,673	2,162,228	75,763
GMD	9,918,515	1,564,165	3,455,081	5,552,787	948,717	1,900,250
VTP	2,714,069	2,153,736	2,153,879	664,768	832,320	102,645
CIA	377,700	56,031	95,993	247,964	84,604	−14,800
CCT	384,938	49,644	121,978	263,680	41,849	110
CDN	1,617,220	199,175	401,877	1,224,527	97,310	147,484
PHP	5,418,363	652,653	1,371,405	3,748,771	318,281	515,702
NCT	502,230	65,546	71,122	434,311	70,711	241,000
TCW	607,283	136,597	269,323	340,517	130,234	60,549
VGR	1,227,418	119,846	351,096	889,201	77,333	148,249
DDG	389,042	172,839	255,186	143,461	164,403	10,078
HRT	1,694,083	423,977	1,060,992	718,676	104,342	2,842
SAS	1,873,148	673,938	674,693	1,538,797	169,449	341,114
STG	2,316,457	574,471	724,029	1,370,972	396,061	157,775
VOS	3,509,305	1,231,050	2,990,817	643,346	605,219	17,138

Source: authors' collection from finance.vietstock.com (accessed on 6 March 2022).

Table 5. The data of Vietnam logistics company 2021 (Unit: million dong).

DMUs	Input			Output		
	Fixed Assets	Operating Expense	Cost of Goods Sold	Total Equity	Account Receivable	Net Profit
VIN	525,094	98,172	98,656	286,480	67,159	38,892
CQN	1,693,879	2,568,371	2,568,371	599,673	2,539,666	66,752
GMD	10,041,526	1,828,483	3,552,650	5,269,823	787,249	613,569
VTP	3,346,549	2,426,061	2,426,253	950,869	1,072,975	106,777
CIA	462,628	67,576	76,171	348,855	105,779	70,953
CCT	372,514	16,275	112,946	260,640	42,365	3947
CDN	1,651,329	120,265	308,418	1,353,878	119,947	184,160
PHP	5,727,560	686,801	1,376,894	3,971,822	330,828	502,802
NCT	582,390	64,289	70,945	514,277	63,593	221,379
TCW	623,811	167,919	266,892	359,439	155,129	68,593
VGR	1,103,650	95,060	154,674	966,081	77,626	133,479
DDG	635,811	142,057	481,179	157,663	133,902	14,203
HRT	1,885,436	592,921	1,226,865	732,568	115,576	13,893
SAS	1,959,692	755,567	760,709	1,586,676	159,773	372,606
STG	2,253,882	458,530	574,618	1,566,795	456,497	122,918
VOS	3.029,303	1,176,479	2,412,692	695,755	548,274	51,070

Source: authors' collection from finance.vietstock.com (accessed on 6 March 2022).

4. Result and Discussion

4.1. Pearson Correlation

There are two major factors of the basic DEA data assumptions; they are homogeneity and isotonicity. Basically, the DEA input data and output data need to be isotonic, which means they have a positive correlation. Therefore, we apply the correlation test as an importance step to make sure the input and output data are isotonic. For example, any increase. In this research, we decide to use Pearson correlation to measure the strength of the linear relationship of normal distribution. According to Lo et al. (2001), the correlation coefficient is always between −1 and +1. If the coefficient of correlation is positive, the factor demonstrates an isotonic solid relationship will be put into the DEA model. On the other hand, if the correlation coefficient is negative, showing a weak isotonic relationship, it will be re-examined [16,33].

The results of correlation coefficients between input and output variables are show in Tables 6–9.

Table 6. Correlation of input and output data in 2018.

	Fixed Assets	Operating Expense	Cost of Goods Sold	Total Equity	Account Receivable	Net Profit
Fixed assets	1	0.891	0.872	0.227	0.890	0.894
Operating expense	0.891	1	0.811	0.304	0.791	0.973
Cost of goods sold	0.872	0.811	1	0.167	0.660	0.870
Total equity	0.227	0.304	0.167	1	0.263	0.326
Account receivable	0.890	0.791	0.660	0.263	1	0.779
Net profit	0.894	0.973	0.870	0.326	0.779	1

Source: authors' calculation.

Table 7. Correlation of input and output data in 2019.

	Fixed Assets	Operating Expense	Cost of Goods Sold	Total Equity	Account Receivable	Net Profit
Fixed assets	1	0.884	0.868	0.323	0.902	0.795
Operating expense	0.884	1	0.880	0.357	0.661	0.900
Cost of goods sold	0.868	0.880	1	0.234	0.622	0.822
Total equity	0.323	0.357	0.234	1	0.357	0.197
Account receivable	0.902	0.661	0.622	0.357	1	0.578
Net profit	0.795	0.900	0.822	0.197	0.578	1

Source: authors' calculation.

Table 8. Correlation of input and output data in 2020.

	Total Assets	Current Liability	Account Payable	Inventory	Total Equity	Account Receivable
Total assets	1	0.511	0.758	0.218	0.944	0.348
Current liability	0.511	1	0.834	0.362	0.320	0.885
Account payable	0.758	0.834	1	0.243	0.534	0.696
Inventory	0.218	0.362	0.243	1	0.174	0.108
Total equity	0.944	0.320	0.534	0.174	1	0.216
Account receivable	0.348	0.885	0.696	0.108	0.216	1

Source: authors' calculation.

Table 9. Correlation of input and output data in 2021.

	Total Assets	Current Liability	Account Payable	Inventory	Total Equity	Account Receivable
Total assets	1	0.538	0.758	0.203	0.942	0.263
Current liability	0.538	1	0.881	0.220	0.329	0.875
Account payable	0.758	0.881	1	0.099	0.533	0.687
Inventory	0.203	0.220	0.099	1	0.239	0.013
Total equity	0.942	0.329	0.533	0.239	1	0.114
Account receivable	0.263	0.875	0.687	0.013	0.114	1

Source: authors' calculation.

Tables 6–9 provide positive correlations that mean correlation coefficients between input and output variables have a strong relationship. Hence, these data can be used for the analysis of DEA calculations.

4.2. Analysis before Alliance

The efficiency of the DERMIs is calculated based on the primary data of 2018, and their ranking before alliances are obtained as well. Table 10 summarizes the empirical results.

Table 10. Rankings and scores before alliances.

DMU	Score	Rank	DMU	Score	Rank
DMU 9	3.884	1	DMU 15	0.997	9
DMU 2	2.457	2	DMU 12	0.869	10
DMU 1	2.291	3	DMU 8	0.626	11
DMU 6	1.573	4	DMU 4	0.417	12
DMU 5	1.406	5	DMU 14	0.372	13
DMU 10	1.353	6	DMU 3	0.308	14
DMU 11	1.328	7	DMU 16	0.273	15
DMU 7	1.233	8	DMU 13	0.176	16

In this research, we used the super-SBM-I-C model in order to measure the efficiency of 16 DMUs and rank them before alliance with the data of 2019. The result of the rankings and scores is shown in Table 10, with DMU 9 having the highest performance (with the score = 3.88457). The DMU 13 has the lowest efficiency (with the score = 0.1676). Thus, we choose to target DMU 3, which is in the 14th ranking. These low efficiencies indicated the important of alliance strategy, which will help the target company to raise its performance.

4.3. Analysis after Alliance

The result form Table 10 shows that the inefficiency score is 0.30894 and low rank is 14th/16. This means the target DMU 3 should enhance the operating activity by implementing alliance strategy. Using the software of the DEA-Solver SBM-I-C model, we combine DMU 3 with 15 other DMUs and obtain the total 31 virtual DMUs. By evaluating this new result, we can see an improvement in the firm's performance after the cooperation.

The results obtained in terms of scores and ranking are presented in Table 11.

Table 11. Performance ranking of virtual DMUs after alliance.

Rank	DMU	Score	Rank	DMU	Score
1	DMU 1	1.895	17	DMU 3 + 8	1
2	DMU 2	1.861	18	DMU 3 + 7	1
3	DMU 5	1.743	19	DMU 3 + 10	0.930
4	DMU 6	1.632	20	DMU 3 + 11	0.925
5	DMU 7	1.601	21	DMU 3 + 9	0.924
6	DMU 9	1.574	22	DMU 3 + 5	0.921
7	DMU 10	1.403	23	DMU 3 + 12	0.920
8	DMU 11	1.328	24	DMU 3 + 6	0.915
9	DMU 15	1.297	25	DMU 3 + 1	0.914
10	DMU 12	1.169	26	DMU 3	0.908
11	DMU 3 + 2	1.150	27	DMU 3 + 16	0.895
12	DMU 8	1.026	28	DMU 16	0.873
13	DMU 4	1.097	29	DMU 3 + 13	0.762
14	DMU 14	1.073	30	DMU 3 + 14	0.662
15	DMU 3 + 15	1.052	31	DMU 13	0.567
16	DMU 3 + 4	1.021			

The score of Table 11 indicates that the target DMU 3 performs the highest efficiency when building an alliance strategy with DMU 2, DMU 15, DMU 4, DMU 8, and DMU 7. This represents the new DMU 3 ranking as being the 26th place. This indicates that any results of cooperation greater than 26th place create better alliance than the original DMUs. Otherwise, if the new ranking is less than the 26th place, then the alliance is even worse. Based on this criterion, this study divided the results obtained into two groups. In order to have an easy comparison, we tabulated 10. The rise in the ranking of DMUs after the alliance demonstrates that the target company can receive advantages from an alliance. Table 10 reveals that 12 companies (i.e., DMU 2, DMU 15, DMU 4, DMU 8, DMU 7, DMU 10, DMU 11, DMU 9, DMU 5, DMU 12, DMU 6, and DMU 1) have the desired features, which correlate with the desire of the partners to do business together.

The virtual companies (DMU 3 + DMU 2; DMU 3 + DMU 15; and DMU 3 + DMU 4) have the greatest number of opportunities to achieve the highest and best efficiency when using a strategic alliance business model (score > 1). Thus, these three companies are highly appreciated when considering a strategic alliance. The second group includes the companies in the category of the not-good alliance partnership.

The first group in the Table 12 display an improvement after an alliance of DMU 3 with 12 other DMUs, including DMU 2, DMU 15, DMU 4, DMU 8, DMU 7, DMU 10, DMU 11, DMU 9, DMU 5, DMU 12, DMU 6, and DMU 1. The top three of the highest efficiencies are defined by the difference of target DMU 3 ranking and virtual alliance ranking (DMU 2, DMU 15 and DMU 4). This means DMU 3 should prioritize to choose these three companies to implement the alliance strategy. Especially, DMU 2 has the greatest potential for cooperation because of its largest difference value (15). In contrast, the second group has three enterprises (DMU 16, DMU 13, and DMU 14) which create a worse cooperate strategy. Therefore, the target DMU 3 should not choose those DMUs for alliance strategy owing to the non-benefits for the target company.

Table 12. The good and bad alliance partnerships.

Number Order	Virtual Alliance	Target DMU3 Ranking (1)	Virtual Alliance Ranking (2)	Difference (1)–(2)
1	DMU 3 + 2	26	11	15
2	DMU 3 + 15	26	15	11
3	DMU 3 + 4	26	16	10
4	DMU 3 + 8	26	17	9
5	DMU 3 + 7	26	18	8
6	DMU 3 + 10	26	19	7
7	DMU 3 + 11	26	20	6
8	DMU 3 + 9	26	21	5
9	DMU 3 + 5	26	22	4
10	DMU 3 + 12	26	23	3
11	DMU 3 + 6	26	24	2
12	DMU 3 + 1	26	25	1
2nd group				
1	DMU 3 + 16	26	27	−1
2	DMU 3 + 13	26	29	−3
3	DMU 3 + 14	26	30	−4

Source: calculated from DEA software.

4.4. Partner Selection

The best alliance partnerships are identified in the previous section based on the position of the target DMU 3. Nonetheless, we must conduct additional research into the viability of alliance partnerships and compare situations before and after alliances. There are clearly 12 good partners, as evidenced by the results in Table 10. In contrast, the other three partners should not. In other words, DMU 9, DMU 2, DMU 1, DMU 6, DMU 5, DMU 10, DMU 11, and DMU 7 are already performing well; if no special circumstances exist, they have no need to form an alliance relationship with DMU 3.

Combined with Tables 8 and 9, the efficiency and ranking of all DMUs before and after alliance are reviewed again in Figure 2. The points that are closest to the middle are given a higher ranking. The partnership will assist in the creation of a manufacturing system that reduces waste, adds value to the consumer, and achieves perfection. Aside from that, the organization must improve mutual understanding by finding new collaboration opportunities from less viable partnership partners. In a nutshell, the results and conclusions of this case study contribute to new guidelines for strategic alliances. The readers will immediately recognize Quang Ninh Port Joint Stock Company as a prominent candidate for an alliance strategy (DMU 2, the best efficiency improvement for the target company).

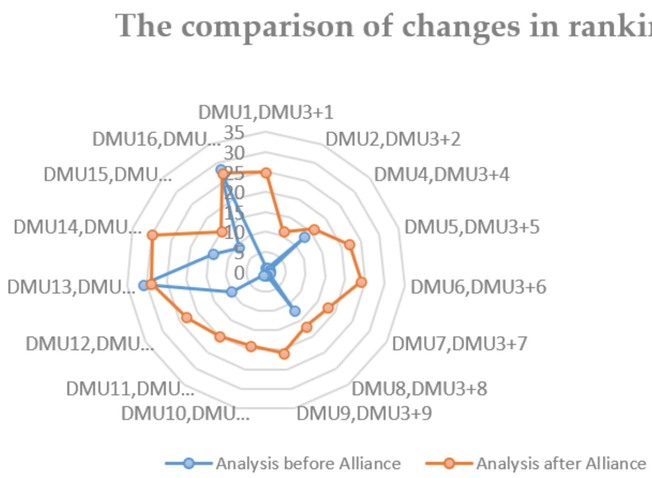

Figure 2. The comparison of changes in ranking.

5. Conclusions

Nowadays, the logistics industry and many other industries face numerous challenges, such as: How to achieve competitive advantage and enter new markets? How to obtain new customers and resources and scale up its business? To solve the above-mentioned problems, this research proposes using the super-SBM-I-C DEA model to analyze and suggest solutions for Vietnamese logistics companies when selecting partners in a strategic alliance.

Based on the public data of 16 Vietnamese logistics enterprises from 2018 to 2021, this study used the SBM-I-C model to evaluate each DMU's performance before and after joining a strategic partnership. In our research, the Gemandept Joint Stock Company (DMU 3) was used as a case study to determine the potential benefits of strategic alliances between firms. The DEA–super-SBM-I-C model was applied to evaluate the efficiency of all real DMUs and virtual DMUs. The empirical analysis showed that 12 candidates are suitable for the Germandept Joint Stock Company to form strategic alliances with, except DMU 16, DMU 13, and DMU 14. However, the Quang Ninh Port Joint Stock Company is feasible for the Gemandept Joint Stock Company. From our findings, this research proposed using the DEA–super-SBM-I-C model as a more accurate, appropriate approach to select partners in strategic alliances by evaluating the performance of logistics companies. The model provides a reference for logistic strategists when choosing alliance partners.

In terms of theory, our study validates the SBM-I-C DEA model in a new context of Vietnam. We found that the model has the greatest number of opportunities to achieve the highest and best efficiency when using a strategic alliance business model. In terms of practice, this study provides a mathematical approach to selecting partners in a strategic alliance in the logistics industry of Vietnam. This approach is our new contribution to the related work in an emerging research context as Vietnam, particularly in the logistics industry, is at its embryonic stage of development.

Nevertheless, this present study has some limitations. Firstly, the DEA is one kind of sensitive method for factor selection. The input/output variables selection could be different, and the results would be impacted. Therefore, a robustness test is necessary. The various input/output variables and removing outliers from DMUs should be re-calculated and re-discussed. For future study, sensitive analysis for different inputs or outputs of DMUs or data of additional years should be included. Moreover, we suggest future research use qualitative methods such as in-depth interviews to verify research results and evaluate the appropriateness of proposed solutions in the actual context of logistics companies. Secondly, the sample size in this study is small. Thus, potential bias in analysis might exist. Expanding the sample to increase the accuracy of analysis results is recommended. Thirdly, this study focuses on data from Vietnamese logistics companies in three recent years, which is limited in terms of timeframe. We strongly suggest that other studies should have a more extended timeframe for analysis to provide more accurate results when using the DEA–super-SBM-I-C model.

Author Contributions: Conceptualization, N.-N.-Y.H. and P.M.N.; methodology and formal analysis, N.-N.-Y.H.; data collection, T.-M.-N.L. and T.-T.-A.T.; writing—original draft preparation, N.-N.-Y.H. and T.-T.-A.T.; writing—review and editing, N.-N.-Y.H., T.-T.-A.T., and P.M.N.; visualization, T.-M.-N.L.; supervision, N.-N.-Y.H. and P.M.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Follow Appendix A.

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

Appendix A

Table A1. List of the 16 logistics companies.

DMUs	Company Code	Company Name	Company's Financial Statement
DMU 1	VIN	Vietnam Foreign Trade Logistics Joint Stock Company	https://finance.vietstock.vn/VIN/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 2	CQN	Quang Ninh Port Joint Stock Company	https://finance.vietstock.vn/CQN/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 3	GMD	Gemandept Joint Stock Company	https://finance.vietstock.vn/GMD/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 4	VTP	Viettel Post Joint Stock Coporation	https://finance.vietstock.vn/VTP/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 5	CIA	Cam Ranh International Airport Service Joint Stock Company	https://finance.vietstock.vn/CIA/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 6	CCT	Can Tho Port Joint Stock Company	https://finance.vietstock.vn/CCT/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 7	CDN	Da Nang Port Joint Stock Company	https://finance.vietstock.vn/CDN/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 8	PHP	Port of Hai Phong Joint Stock Company	https://finance.vietstock.vn/PHP/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 9	NCT	Noi Bai Cargo Terminal Service Joint Stock Company	https://finance.vietstock.vn/NCT/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 10	TCW	Tan Cang Warehousing Joint Stock Company	https://finance.vietstock.vn/TCW/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 11	VGR	Vip Greenport Joint Stock Company	https://finance.vietstock.vn/VGR/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 12	DDG	Indochine Import Export Investment Industrial JSC	https://finance.vietstock.vn/DDG/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 13	HRT	Hanoi Railway Transport JSC	https://finance.vietstock.vn/HRT/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 14	SAS	Southern Airports Service JSC	https://finance.vietstock.vn/SAS/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 15	STG	South Logistics Joint Stock Company	https://finance.vietstock.vn/STG/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)
DMU 16	VOS	Vietnam Ocean Shipping Joint Stock Company	https://finance.vietstock.vn/VOS/tai-tai-lieu.htm?doctype=1 (accessed on 6 March 2022)

Source: authors' collection from [33].

References

1. Nitsche, B. Exploring the Potentials of Automation in Logistics and Supply Chain Management: Paving the Way for Autonomous Supply Chains. *Logistics* **2021**, *5*, 51. [CrossRef]
2. LaoDongNews. Available online: https://laodong.vn/kinh-te/dua-dong-gop-cua-logistics-vao-tang-truong-gdp-o-muc-45-trong-nam-2022-1033793.ldo?gidzl=nN1dAJFb2M_5Q6ygDlaDRyjiRYuW-mfiXsbbUNkl03YAQM5-AgvNFzPkCtqW_LLlqMSwU6F5erTpCUS5Om (accessed on 22 February 2022).

3. Dangcongsan. Available online: https://dangcongsan.vn/cung-ban-luan/bao-dam-vai-tro-mach-mau-cua-nen-kinh-te-600611.html (accessed on 22 February 2022).
4. Dang, V.L.; Yeo, G.T. Weighing the key factors to improve Vietnam's logistics system. *Asian J. Shipp. Logist.* **2018**, *34*, 308–316. [CrossRef]
5. Ministry of Industry and Trade's Vietnamese Logistics Report 2021. Available online: http://investvietnam.gov.vn/FileUpload/Documents/112421_Logistic%20report%202021_Final.pdf (accessed on 22 February 2022).
6. Charnes, A.; Cooper, W.W.; Rhodes, E. Measuring the efficiency of decision making units. *Eur. J. Oper. Res.* **1978**, *2*, 429–444. [CrossRef]
7. Nitsche, B.; Straube, F.; Wirth, M. Application areas and antecedents of automation in logistics and supply chain management: A conceptual framework. In Supply Chain Forum: An International Journal. *Taylor Fr.* **2021**, *22*, 223–239.
8. Glaister, K.W. Strategic motives for UK international alliance formation. In *International Strategic Management and Government Policy*; Springer: Berlin/Heidelberg, Germany, 1998; pp. 40–77.
9. Taylor, A. An operations perspective on strategic alliance success factors: An exploratory study of alliance managers in the software industry. *Int. J. Oper. Prod. Manag.* **2005**, *25*, 469–490. [CrossRef]
10. Vyas, N.M.; Shelburn, W.L.; Rogers, D.C. An analysis of strategic alliances: Forms, functions and framework. *J. Bus. Ind. Mark.* **1995**, *10*, 47–60. [CrossRef]
11. Mockler, R. Multinational strategic alliances: A manager's perspective. *Strateg. Change* **1997**, *6*, 391–405. [CrossRef]
12. Vu, H.N. The strategic development in logistics in Vietnam. *Eur. J. Eng. Technol. Res.* **2019**, *4*, 69–73.
13. Le, T.-M.; Wang, C.-N.; Nguyen, H.-K. Using the optimization algorithm to evaluate and predict the business performance of logistics companies–a case study in Vietnam. *Appl. Econ.* **2020**, *52*, 4196–4212. [CrossRef]
14. Tone, K. A slacks-based measure of efficiency in data envelopment analysis. *Eur. J. Oper. Res.* **2001**, *130*, 498–509. [CrossRef]
15. Du, J.; Liang, L.; Zhu, J. A slacks-based measure of super-efficiency in data envelopment analysis: A comment. *Eur. J. Oper. Res.* **2010**, *204*, 694–697. [CrossRef]
16. Oum, T.H.; Yan, J.; Yu, C. Ownership forms matter for airport efficiency: A stochastic frontier investigation of worldwide airports. *J. Urban Econ.* **2008**, *64*, 422–435. [CrossRef]
17. Das, T.K.; Teng, B.-S. Partner analysis and alliance performance. *Scand. J. Manag.* **2003**, *19*, 279–308. [CrossRef]
18. Wang, C.-N.; Nguyen, X.-T.; Wang, Y.-H. Automobile industry strategic alliance partner selection: The application of a hybrid DEA and grey theory model. *Sustainability* **2016**, *8*, 173. [CrossRef]
19. Liang, L.; Yang, F.; Cook, W.D.; Zhu, J. DEA models for supply chain efficiency evaluation. *Ann. Oper. Res.* **2006**, *145*, 35–49. [CrossRef]
20. Gen, M.; Syarif, A. Hybrid genetic algorithm for multi-time period production/distribution planning. *Comput. Ind. Eng.* **2005**, *48*, 799–809. [CrossRef]
21. Li, Y.; Yang, J.; Liu, F. DEA based efficiency analysis of the logistics industry in Wuhan. *J. Phys. Conf. Ser.* **2019**, *1168*, 032021. [CrossRef]
22. Nguyen, N.-T.; Tran, T.-T. Raising opportunities in strategic alliance by evaluating efficiency of logistics companies in Vietnam: A case of Cat Lai Port. *Neural Comput. Appl.* **2019**, *31*, 7963–7974. [CrossRef]
23. Vietstock. Available online: https://finance.vietstock.vn (accessed on 15 March 2022).
24. Wang, C.-N.; Hsu, H.P.; Wang, J.W.; Kao, Y.C.; Nguyen, T.P. Strategic Alliance for Vietnam Domestic Real Estate Companies Using a Hybrid Approach Combining GM (1, 1) with Super SBM DEA. *Sustainability* **2020**, *12*, 1891. [CrossRef]
25. Lee, C.-Y.; Johnson, A.L. Operational efficiency. In *Handbook of Industrial Systems Engineering, Second Edition Industrial Innovation*; CRC Press: Boca Raton, FL, USA, 2013; pp. 17–44.
26. Nguyen, H.-K. Combining DEA and ARIM A models for partner selection in the supply chain of Vietnam's construction industry. *Mathematics* **2020**, *8*, 866. [CrossRef]
27. Ho, C.-T.B.; Oh, K.-B. Selecting internet company stocks using a combined DEA and AHP approach. *Int. J. Syst. Sci.* **2010**, *41*, 325–336. [CrossRef]
28. Zahedi-Seresht, M.; Jahanshahloo, G.-R.; Jablonsky, J. A robust data envelopment analysis model with different scenarios. *Appl. Math. Model.* **2017**, *52*, 306–319. [CrossRef]
29. Yu, M.-C.; Wang, C.-N.; Ho, N.-N.-Y. A grey forecasting approach for the sustainability performance of logistics companies. *Sustainability* **2016**, *8*, 866. [CrossRef]
30. Oberholzer, M. A model to estimate firms accounting-based performance: A data envelopment approach. *Int. Bus. Econ. Res. J.* **2014**, *13*, 1301–1314. [CrossRef]
31. Andrejić, M.; Bojović, N.; Kilibarda, M.; Nikoličić, S. A framework for assessing logistics costs. *Int. J. Logist. Manag.* **2018**, *27*, 770–794.
32. Nguyen, N.-T.; Nguyen, L.-X.T. Applying DEA Model to Measure the Efficiency of Hospitality Sector: The Case of Vietnam. *Int. J. Anal. Appl.* **2019**, *17*, 994–1018.
33. Lo, F.-Y.; Chien, C.-F.; Lin, J.T. A DEA study to evaluate the relative efficiency and investigate the district reorganization of the Taiwan power company. *IEEE Trans. Power Syst.* **2001**, *16*, 170–178. [CrossRef]

logistics

Article

Analysis of the Activities That Make Up the Reverse Logistics Processes and Their Importance for the Future of Logistics Networks: An Exploratory Study Using the TOPSIS Technique

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Citation: Martins, V.W.B.; Nunes, D.R.d.L.; Melo, A.C.S.; Brandão, R.; Braga Júnior, A.E.; Nagata, V.d.M.N. Analysis of the Activities That Make Up the Reverse Logistics Processes and Their Importance for the Future of Logistics Networks: An Exploratory Study Using the TOPSIS Technique. *Logistics* **2022**, *6*, 60. https://doi.org/10.3390/logistics6030060

Academic Editors: Benjamin Nitsche, Frank Straube and Robert Handfield

Received: 5 July 2022
Accepted: 11 August 2022
Published: 16 August 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Abstract: *Background*: The wide variety of terms that converge in reverse logistics have been more evident and discussed in the current context of the literature, such as reverse channels, reverse supply chain, closed-loop supply chain, and circular supply chain. Regarding this, this paper aimed to investigate the level of uncertainty about the activities that make up the Reverse Logistics process in the opinion of professionals working in this area in Brazil, to develop a discussion relating to the sustainable development goals proposed by the UN and their importance for the future of logistics networks. *Methods*: Initially, through a detailed systematic review of the literature, the activities that make up the RL processes were identified. Then, a questionnaire was elaborated on regarding such activities, and a survey was developed with professionals in the area. The data obtained were analyzed through a descriptive analysis of means, calculation of Cronbach's Alpha, and using the multicriteria decision technique TOPSIS. *Results*: It is possible to see that professionals involved with RL processes in Brazil still have many doubts regarding which activities belong to the RL process. In the opinion of Brazilian professionals, 10 of these activities have generated high levels of uncertainties about their belonging or not to the RL process. On the other hand, with a low level of uncertainty, 3 activities were not considered and 3 were considered to make up the RL process. *Conclusions*: It is believed that this study can contribute to the generation of knowledge by comparing basic information in the scientific literature with the practical knowledge of professionals belonging to the reverse logistics sector working in the Brazilian context.

Keywords: reverse logistics; reverse logistics activities; sustainable development; TOPSIS

1. Introduction

Logistics can have a critical impact on industry's future as the depletion of natural resources and environmental pollution advance [1]. Reverse Logistics (RL) is a process that contributes to economic, environmental, and social benefits [2], and acts to preserve existing resources and reduce harmful emissions and waste generation [3,4]. Studies highlight the importance of making appropriate decisions about RL activities without necessarily following the industry's common practices indiscriminately. For example, one must decide either between reuse or recycling, considering the resources and market limitations present in the company's regional context [5,6]. Advances in issues related to legislation, corporate images, environmental concerns, economic benefits, and sustainable competitiveness are imposing on companies not only to adopt RL practices but also to make them efficient and effective [7–11]. Therefore, industries must make their decisions considering their product's long-term life cycle, rather than just focusing on current waste problems [5,12–14].

Govindan and Bouzon [15] identified 37 motivators for RL implementation by industry and divided them into 8 categories: Policy-related issues, Governance- and supply-chain-process-related issues, Management-related issues, Market- and Competitor-related issues, Technology- and infrastructure-related issues, Economic-related issues, Knowledge-related issues, and Social-related issues. Analyzing the motivators, it was found that those that related to environmental issues add up to 16 and come from the demands of the consumer, society, and current legislation.

In addition, RL contributes to the achievement of the United Nations Sustainable Development Goals (SDGs) (sdgs.un.org/goals accessed on 23 November 2021) mainly concerning building resilient infrastructure, promoting inclusive and sustainable industrialization and encouraging innovation (SDG 9), and ensuring sustainable consumption and production patterns (SDG 12). In SDG 9, governments reaffirmed the importance of solid waste management, committing to give priority attention to waste prevention and minimization, reuse and recycling, as well as the development of environmentally friendly waste disposal facilities. In SDG 12, governments, international organizations, the business sector, and other non-state actors and individuals must contribute to changing unsustainable consumption and production patterns to achieve more sustainable consumption and production patterns [16–18].

Specifically, in Brazil, it can be highlighted that when approving the National Solid Waste Policy (NSWP) in 2010, this increased the discussions on socio-environmental concerns involving solid waste management. In addition, this law presented numerous potential solutions for waste's proper disposal and complete environmental protection as well as highlighted the importance of RL for achieving these previous goals [19]. For the NSWP, RL constitutes: "An instrument of economic and social development, characterized by a set of actions, procedures and means designed to enable the collection and return of solid waste to the business sector, for recovery, in its cycle or other production cycles, or other environmentally proper final disposition" [19].

According to the context, it is clear that logistics activities present constant operational changes and face considerable challenges in the face of growth dynamics and uncertainties at a global level. Due to its relevance to the economy and society, logistics systems have been shaping the various trends and micro and macroeconomic challenges, and consequently, managers involved in the area constantly ask themselves what are the future development paths of logistics to meet the new demands and market requirements. Managing the accelerated pace of digitalization, building resilience for future networks, integrating low-income countries into global value streams, enabling such countries to be part of global logistics networks, and creating sustainable approaches are some examples of the challenges of this decade. In this sense, the analysis of the definitions present in the literature with the understanding of professionals involved in the area becomes important to overcome such challenges. It is precisely at this point that this study proposes to specifically analyze the activities that are part of the RL process, adopting not only the definitions present in the literature but also the perceptions of professionals involved in the management of such activities.

According to the context presented, this research aimed to investigate the level of uncertainty about the activities that make up the Reverse Logistics—RL process in the opinion of professionals working in this area in Brazil, to develop a discussion relating to the sustainable development goals proposed by the UN and their importance for the future of logistics networks. The RL activities considered in this research were mapped through a systematic literature review. The results were treated and validated by calculating Cronbach's alpha, using a descriptive analysis of means, and using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). This study can contribute to the generation of knowledge by comparing information obtained in the scientific literature with practical knowledge of the Brazilian RL industry.

2. Literature Review

Reverse Logistics (RL) is the foundation of other definitions adopted by this study. An initial literature review unveiled the most-cited definitions over the last 20 years, as shown in Table 1. Other widely referenced definitions also agree with this statement [20–22].

Table 1. Reverse logistics definitions in the literature most cited in the last 20 years.

Authors	Reverse Logistics Definitions
The Council of Logistics Management (CLM) (Stock, 1992)	"...the term often used to refer to the role of logistics in recycling, waste disposal, and management of hazardous materials; a broader perspective includes all relating to logistics activities carried out in source reduction, recycling, substitution, reuse of materials, and disposal."
Rogers and Tibben-Lembke (1998)	"The process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal."
The European Working Group on Reverse Logistics, RevLog—1998	"The process of planning, implementing and controlling flows of raw materials, in process inventory, and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal."

Adapted from Brito and Dekker [23].

By reading, the definitions presented in Table 1, the words "process" and "activities" are recurrent terms. This happens as RL works through the execution of a coordinated set of processes to fulfill its objective. According to the literature review, it is possible to have a wide variety of activities cited as components of the RL process. This occurs as a result of the waste variety which transits in a reverse channel, such as carpet [24], batteries [25], vehicles [26], etc. Each of these wastes requires different needs for manipulation and treatment, resulting in different approaches to and characterization of these activities. The work of Rubio and Jiménez-Parra [27] is recommended for a further discussion on the evolution of the RL concept.

Reverse logistics is a relatively new concept, and its basic task is to facilitate the organization of a product's return process to a manufacturer to recycle the product and make it a new product, or to separate components that can be used again; sometimes, it is sent to companies whose main and only activity is recycling, restoration, and the like [28]. Ref. [29] corroborates this understanding and emphasizes that RL is part of logistics, and its main task is to enable the return of products from the customer to the manufacturer to fully recycle the product or to separate the components that could be reused. Additionally, Ref. [30] argues that a reverse logistics system corresponds to a set of activities which form a continuous process of the treatment of returned products until they are properly recovered or discarded. These activities include collection, cleaning, disassembly, testing and sorting, storage, transport, and recovery operations [30].

To identify the RL activities presented in the literature, 1809 publications were reviewed systematically, with no period limitation. The results demonstrated that only 6.68% (121 papers) focused on identifying activities within the RL process, resulting in a set of 16 most-cited activities. It is noteworthy that RL activities directly related to information flows were the least mentioned, despite their importance; 4.96% for Integration, 12.4% for Waste Acquisition, and 9.92% for Gatekeeping. Thus, Table 2 presents the activities identified as being the most-frequently-cited, considering this new subset of 121 reviewed studies.

Table 2. Percentage distribution of most-cited RL process activities in the survey.

Activities	% Distribution	Activities	% Distribution
Collection	76.86%	Sorting	36.36%
Disposal	61.16%	Redistribution	33.88%
Remanufacturing	55.37%	Transport	32.23%
Inspection/Testing	51.24%	Warehousing	27.27%
Recycling	51.24%	Refurbishing	25.62%
Repair	40.50%	Waste Acquisition	12.40%
Disassembly	38.84%	Gatekeeping	9.92%
Direct Reuse	38.84%	Integration	4.96%

In addition to the results presented in Table 2, other activities were mentioned, but in a less significant frequency, such as: Re-sale [31–38]; Donation sale [32,35,37]; Cannibalization [36–38]; Washing [39]; Recertification [40]; Packing or Repacking [30,35,38–40]; and Densification [41].

Another important aspect was that among the 121 systematically reviewed studies, few authors were concerned with actually describing the RL activities considered in their research. Table 3 summarizes the 16 most-cited RL activities and their definitions, considering those same studies. For some RL activities, such as warehousing, definitions or descriptions were not found in the survey. For those, we proposed additional definitions and descriptions based on forwarding logistics activities analogies.

Table 3. Summary of most-cited RL activities definitions in the survey.

Activities	Description
Collection	It constitutes the consolidation of selected waste from generating sources facilities to processing centers [42–44].
Proper Disposal	Final disposal occurs when items (product, part, module, or material) are no longer subject to value recovery, in which case the possible destinations for final disposal are landfills or incineration [35,37,45–50]. The proper disposal must follow the public administration's legal guidelines [24,26,51,52].
Remanufacturing	Refers to the insertion of waste, products, or parts in the manufacturing process of a new product, which may involve a reconditioning step [26,50,53–62].
Inspection/ Testing	This process, in general, has the same objective as Sorting, which is the definition of the appropriate destination for the returned product [7,15,25,43,45,63–65].
Recycling	It constitutes the use of materials recovered from waste or end-of-life products, whether or not this material has its application focused on its original purpose [24,26,32,37,43,45,50,54,55,59,61,66–68].
Repair	Refers to the maintenance required for a product to return to its original functional state [32,45,51,54,55,59,67].
Disassembly	This activity simply represents the separation into parts, perhaps due to the simplicity of its concept [26,41,42,52].
Direct Reuse	Refers to products for which repair or any processing option are not necessary. Products intended for direct reuse still present adequate conditions of functionality and must reach the end customer through second-hand markets or donations. [26,32,39,45,46,50,55,59,61,67].
Sorting	It is a step related to the analysis and general assessment of the conservation status of waste, parts, subparts, or basic components of it [24,26,44].

Table 3. *Cont.*

Activities	Description
Redistribution	It consists of all activities related to the effective forwarding of processed materials (i.e., inspected/tested, disassembled, and sorted materials) from processing points to the recovering plants or proper disposal facilities [32,49].
Transport	Moving secondary assets along the processing stream [43].
Warehousing	Is an important element in the goods distribution activity in all these stages: raw materials, outstanding production, and finished products [69]. Based on the previous definition, we consider warehousing for RL all actions aimed at maintaining the current conservation status of waste to be recovered (i.e., from inspection/testing activity to RL activities before recovery) or the new consumption status of already recovered waste.
Refurbishing	Refers to the product upgrade process, often related to technological updates [26,61,67].
Waste Acquisition	Can be also called product acquisition, which is the process of the acquisition of used products, components, or materials from the end users for further processing [7,70].
Gatekeeping	Constitutes a set of practices, performed usually by retailers, to identify the products which are allowed into the RL system, given back to the user after resolving issues at their end, or are properly disposed [7,49,63].
Integration	According to [63], this activity is also called the coordinating system and constitutes the first key element for the management of reverse flows. Is the most important key element of the system, since it is responsible for the system's overall management and performance.

Table 4 presents the percentages of papers that defined the 16 most-cited RL activities, considering the survey carried out in this research.

Table 4. Percentage of articles in the survey which defined RL process activities.

Activities	% of Papers	Activities	% of Papers
Collection	2.48%	Sorting	2.48%
Disposal	9.92%	Redistribution	1.65%
Remanufacturing	9.09%	Transport	0.82%
Inspection/Testing	5.76%	Warehousing	0.82%
Recycling	10.74%	Refurbishing	3.30%
Repair	4.95%	Waste Acquisition	1.65%
Disassembly	3.30%	Gatekeeping	2.48%
Direct Reuse	3.26%	Integration	0.82%

Figure 1 presents the evolution per year considering the recurrence of papers that cite, display figures, or describe RL processes or activities. Since 2009, there has been a substantial increase in the citation count. Regardless, all these results highlight the growing interest of the literature in RL processes or activities in the last 10 years. This could be explained due to the increase number of problems associated with waste generation and the concern with sustainable aspects related to its recovery or proper disposal.

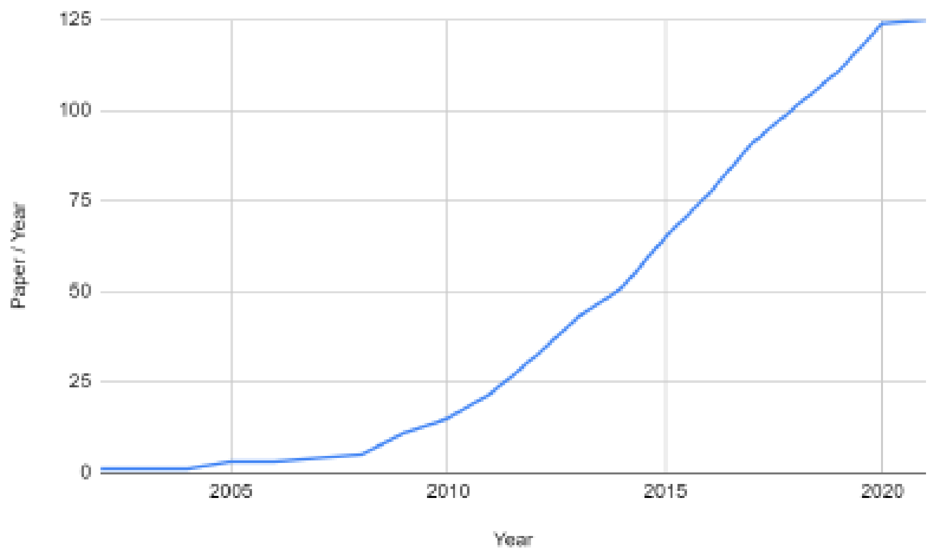

Figure 1. Counting evolution of the papers that mention or treat RL processes or activities in the literature.

The most-cited activities in the period were Collection, Proper Disposal, and Remanufacturing. Notably, other activities with a lower citation count, such as Waste Acquisition, Gatekeeping, and Integration, also showed growth within studies since 2009, most likely due to the need to reduce uncertainties associated with the waste supply to enable the structuring of RL processes. Furthermore, a wide variety of terms that converge to RL have been more evident and discussed in the current context of the literature, such as reverse channels [71,72], reverse supply chain [73–75], closed-loop supply chain [75–77], and circular supply chain [72,78].

According to the context presented, it is possible to perceive that reverse logistics guides a large part of the operations of a certain supply chain system involving product returns, promoting reprocessing and remanufacturing [79]. The proper management of reverse logistics is related to a set of different measures to be implemented [79]. Ref. [80] corroborates this understanding when they highlight that the performance of a reverse logistics system in the supply chain depends a lot on the efficient management of returns of used products. Additionally, Ref. [81] emphasizes that due to the complexity of RL management, outsourcing the management of such activity becomes important in achieving results. The authors also emphasize that through such practices, there is the potential to increase the economic profitability of companies and improve their long-term development.

Given the context of the importance of identifying and defining the processes that make up the RL systems, it is also important to highlight their relationships for the future of logistics networks regarding aspects of digitization and sustainability. In light of RL contributions, Ref. [82] highlights the technological complexity of inter-organizational data sharing as well as concerns about data security, being examples of barriers to the implementation of services inherent to RL. These barriers inherent to logistics networks create considerable challenges for organizations, and it is noteworthy that digital transformation can be a source of future competitive advantages [83], and the development and improvement of activities that make up RL processes can demand the digital transformation of organizations. Additionally, analyzing the barriers and development paths for global logistics networks, Ref. [84] highlights that logistics networks face several challenges that hinder the development of efficient operations, and that professionals involved with logistics and supply chain management must align their networks with the market of the future's need.

3. Methodological Procedures

The main research strategy adopted for the development of this study was a survey, with the following procedures: (a) bibliographic survey; (b) research instrument elaboration; (c) survey development; (d) treatment of the data obtained through descriptive analysis of means, calculation of Cronbach's Alpha, and using the multicriteria decision technique TOPSIS; and e) generation of results and associated conclusions.

Initially, a literature review was carried out on the activities developed in the reverse logistics context on the following scientific bases: Science Direct, Scopus, and Web of Science. For a better understanding of the definitions and concepts, as well as the identification of the state of the art on the subject, the following search terms were used: TITLE-ABS-KEY ("Reverse logistics" AND (activities OR processes OR steps OR paths OR procedures OR operations)) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j")). Several articles were identified, and the content of each one was analyzed in detail. A summary of some of these articles is presented in Section 2.

Then, with the results obtained from the literature analysis, it was possible to develop the research instrument used in the survey with professionals in the field of reverse logistics. The research instrument consists of 16 activities identified in the literature as belonging to reverse logistics processes (Table 3). For each of the activities, respondents indicated using a scale from 1 to 5 considering the following criteria: Note 1—this activity certainly does not belong to a reverse logistics process; Note 2—I believe that this activity does not belong to a reverse logistics process; Note 3—not sure about this activity; Note 4—I believe that this activity belongs to a reverse logistics process; and, Note 5—surely this activity belongs to a reverse logistics process. It is noteworthy that before starting data collection, a Research Ethics Committee was asked to approve the research instrument, since this practice in Brazil is necessary for conducting research involving human beings.

Once the Research Ethics Committee approved it, the survey was carried out to collect data from professionals in the field. The questionnaire was sent online by email using the Google Forms platform and was available to respondents for two months. The invitation to respond to the questionnaire was sent purely to professionals specializing in the field of reverse logistics working in Brazil. Such professionals were identified and selected through searches on the Lattes Platform (academic curriculum record used in Brazil) and via the social network LinkedIn. The questionnaire was sent to 300 professionals, and a return rate of 12.66% was obtained. The questionnaire was answered by researchers (20.00%), professors (40.00%), consultants (5.71%), coordinators, and directors of companies that develop LR activities (34.29%). Among the respondents, 28.57% have more than twenty years of experience, 40.00% have between eleven and twenty years of experience, and 31.43% have up to 10 years of experience.

With the results obtained from the survey, data analysis was performed through descriptive analysis of means, the calculation of Cronbach's Alpha, and using the multicriteria decision technique TOPSIS, following the considerations proposed by [78]. According to these authors, TOPSIS allows the ranking of items (activities) considering different analysis criteria. Such criteria can have different weights and, consequently, denote varying degrees of importance, helping to substantiate and make efficient decision making according to the weights assigned to each one. In this study, it was decided to assign different weights to the responses of each activity analyzed considering the length of experience of each respondent, with 50% for those with over 20 years of experience, 30% for those with between 11 and 20 years of experience, and 20% to those with up to 10 years of experience. It is worth mentioning studies with exploratory objectives similar to the one defined in this research that also used the TOPSIS method, for example, in [85], where a ranking of sustainability indicators was generated in logistics systems, and [2], which aimed to identify the degree of comparative importance attributed to route plan performance objectives in the opinion of logistics professionals working in Brazil. Therefore, through the use of TOPSIS, it was also possible to achieve the objective proposed in this study.

According to [86], the first step in carrying out the calculations aimed at carrying out the ordering of the goals is the structuring of the matrix D, where the elements (xij) are identified by an alternative (i) and by an analysis criterion (j). In this study, the alternatives corresponded to the 16 activities considered in the questionnaire, and the criteria corresponded to the three means obtained from each group of respondents for each of the activities. The mathematical representation of the matrix is shown in Figure 2 (Matrix 1). Then, the normalization of matrix D is performed using Equation (1), presented in Figure 2, resulting in a matrix called Matrix R (Matrix 2). The third step consists of weighting the values of the R Matrix using Equation (2), shown in Figure 2, and obtaining a new matrix called Matrix V (Matrix 3 in Figure 2). Subsequently, the determination of positive (vj+) and negative (vj−) ideal solutions are defined. This step is developed by identifying the maximum and minimum values existing in Matrix V for each of the analysis criteria. The fifth step of TOPSIS consists of calculating the positive and negative Euclidean distances of each alternative. Equations (3) and (4) in Figure 2 present the calculation made to find the Euclidean distance from the positive ideal solution and the Euclidean distance from the negative ideal solution, respectively.

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

Matrix 1

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}}$$

Equation (1)

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$$

Matrix 2

$$v_{ij} = w_j r_{ij}$$

Equation (2)

$$V = \begin{bmatrix} v_{11} & v_{12} & \cdots & v_{1n} \\ v_{21} & v_{22} & \cdots & v_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ v_{m1} & v_{m2} & \cdots & v_{mn} \end{bmatrix}$$

Matrix 3

$$s_i^* = \left[\sum_j \left(v_{ij}^* - v_j^+\right)^2\right]^{1/2}$$

Equation (3)

$$s_i' = \left[\sum_j \left(v_{ij}' - v_j^-\right)^2\right]^{1/2}$$

Equation (4)

$$c_i^* = \frac{s_i'}{(s_i^* + s_i')}$$

Equation (5)

Figure 2. Equations and matrices are used in the steps of the TOPSIS technique. Source: Adapted from [86].

Finally, with the values of Euclidean distances, it is possible to calculate the Ci* indicator and, through it, rank the 16 activities analyzed in the survey according to the perception of different professionals in the field of reverse logistics in Brazil. It is noteworthy that the values of Ci* must be between 0 and 1. The calculation of the indicator Ci* was made using Equation (5), presented in Figure 2.

4. Results and Associated Discussions

Initially, the calculation of Cronbach's Alpha was performed following the recommendations proposed by Christmann and Van Aelst [87], obtaining a coefficient value equal to 0.90, demonstrating the reliability of the research instrument used. Then, Figure 3 presents the averages of the answers given by experts for each item according to the time of experience (up to 10 years, between 11 and 20 years, and above 20 years). After a prior understanding of the Brazilian scenario about the activities that make up the reverse logistics processes according to the descriptive analysis of the average opinion of market professionals, the TOPSIS calculations were started, as were discussions of the ordering of the activities considered in this study and the greater robustness of the results achieved.

Considering the averages obtained through the professional's answers with more experience working in the context of RL (over 20 years), and based on a scale from one to five, presented in the methodological procedures section, for only three of the sixteen activities analyzed, their means were equal to or greater than 4.5. Therefore, market professionals with longer experience are almost certain that such activities belong to RL processes, namely: Integration, Collection, and Transport. On the other hand, another point worth mentioning is that most activities analyzed had an average between 3 and 4, which refers to low levels of uncertainty on the part of more experienced professionals when analyzing whether such activities belong to RL processes. Integration, identified in this research with the highest level of uncertainty in the composition of an RL process, is portrayed by [63] but as one of the most important activities of this process, as it is responsible for the management and performance of the entire RL system. The collection is the entry point of reverse supply networks, and as highlighted in some research [42–44], this activity is responsible for consolidating the generated waste, creating a link between points of generation and processing centers. Transport is relevant due to its intense presence in RL processes, as it occurs between the various installations of the reverse network [43].

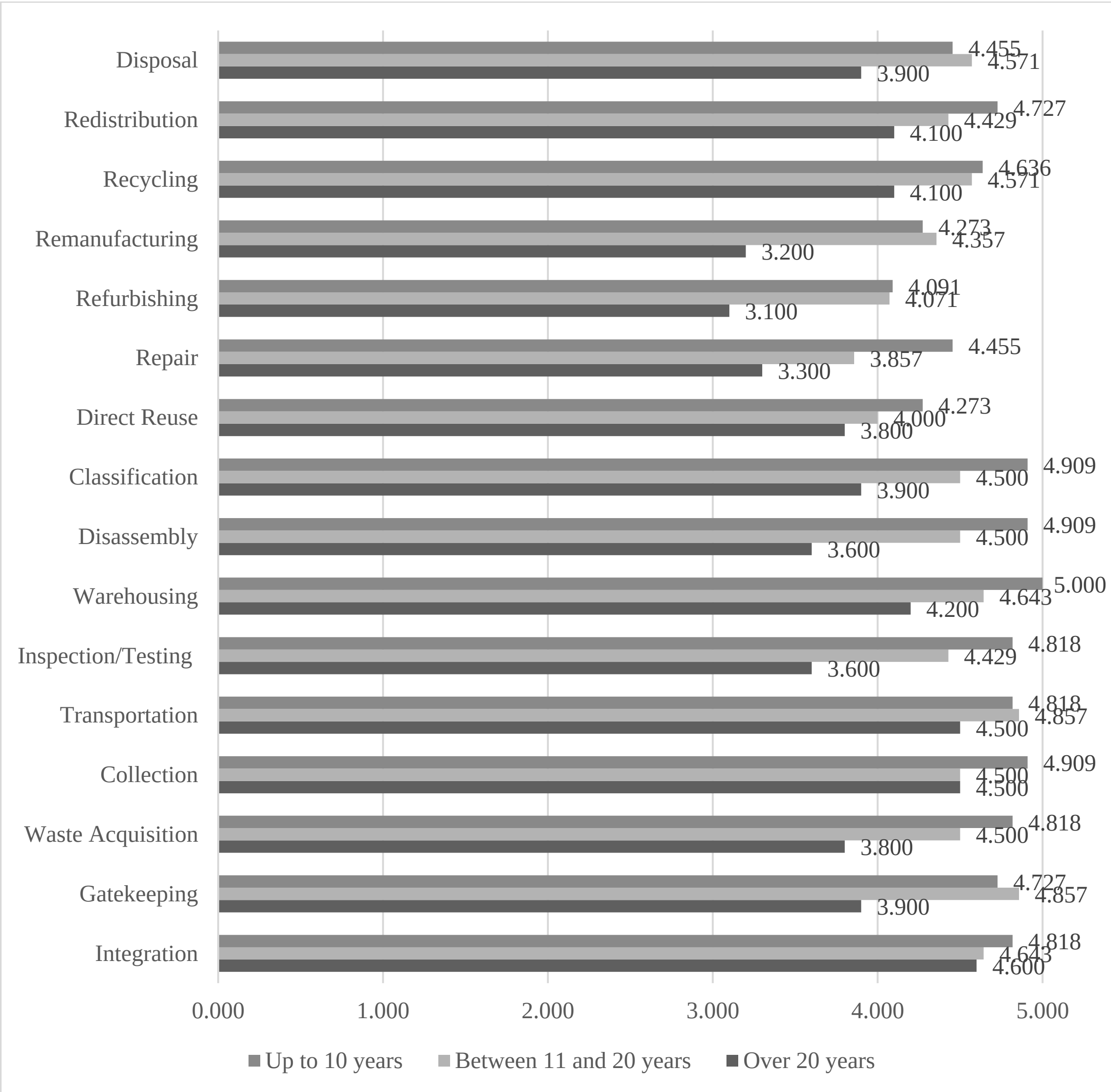

Figure 3. Averages are assigned to each activity by respondents' experience. Source: Authors (2021).

Analyzing the averages based on the opinion of specialists who have between eleven and twenty years of experience, the degree of certainty changes concerning the more experienced responding professionals. Of the sixteen activities analyzed, ten had an average equal to or greater than 4.5. In other words, this group of experts is convinced that the Integration, Gatekeeping, Waste Acquisition, Collection, Transport, Warehousing, Disassembly, Classification, Recycling, and Disposal activities are part of the RL processes.

For the professionals in the sample who have up to 10 years of experience, the scenario presents eleven activities that, in their opinion, are certainly part of the reverse logistics processes, namely: Integration, Gatekeeping, Waste Acquisition, Collection, Transport, Inspection/Test, Warehousing, Disassembly, Classification, Recycling, and Redistribution. Therefore, considering the analysis of means by the class of respondents presented, it is important to analyze and minimize the gaps in understanding among the professionals who work directly with RL processes. According to Quesada [88], RL still has a profusion of different related terms, and the very concept of RL has been changing over time [27], which can contribute to possible doubts (or differences of understanding) among professionals about the inclusion of some activities in the RL processes.

From the results analysis of Figure 3 and aiming at greater results robustness, it was decided to organize the RL activities via TOPSIS to better understand the perception of RL professionals working in Brazil. As presented in the methodological procedures section, the data collected through the survey were divided into three different groups, considering the experience of the respondent experts. Group 1 is characterized by having more than 20 years of experience, group 2 has between 11 and 20 years of experience, and group 3 has up to 10 years of experience. Then, the average of the marks assigned by each group for each goal was calculated, as shown in Table 5.

Table 5. Average of the grades of each group for each item.

Items	Over 20 Years	Between 11 and 20 Years	Up to 10 Years
At_01	4.600	4.643	4.818
At_02	3.900	4.857	4.727
At_03	3.800	4.500	4.818
At_04	4.500	4.500	4.909
At_05	4.500	4.857	4.818
At_06	3.600	4.429	4.818
At_07	4.200	4.643	5.000
At_08	3.600	4.500	4.909
At_09	3.900	4.500	4.909
At_10	3.800	4.000	4.273
At_11	3.300	3.857	4.455
At_12	3.100	4.071	4.091
At_13	3.200	4.357	4.273
At_14	4.100	4.571	4.636
At_15	4.100	4.429	4.727
At_16	3.900	4.571	4.455

Source: Authors (2021).

Then, the normalization of the values in Table 5 was performed using Equation (1), shown in Section 3, resulting in Matrix R (Table 6) with the normalized values. Then, the weights were assigned to each group of respondents considering their length of experience (experts with more than 20 years of experience received a weight of 50%, specialists with experience between 11 and 20 years received a weight of 30%, and specialists with up to 10 years of experience received a weight of 20%), obtaining the Matrix V (Table 7).

Analyzing the calculated averages (not yet considering the weights attributed to each group), it is possible to see that professionals involved with RL processes in Brazil still have many doubts regarding which activities belong to the RL process. The TOPSIS result ranked the activities found in the literature and discussed them as belonging to the RL processes, considering the grades given by the professionals for each activity and the weights attributed to the groups. It is noteworthy that the three activities listed in the last positions (renovation, repair, and remanufacture) are those in which professionals have less uncertainty that they are not part of the RL processes. That is, this does not mean that these activities are not involved in processes of RL in Brazilian industries.

The first three activities listed by TOPSIS, "Transport", "Integration", and "Collection", received coefficients greater than 0.80; that is, in the opinion of the professionals, they are sure that such activities are part of the RL process. According to the literature considered in this study, the activity of "Transport" was observed in 39 articles. Among these, only [43] presented a brief description: "moving secondary assets along the processing stream". In other words, it is an activity solely related to the movement of the material (transportation, uploading/downloading, handling) between facilities or activities in the reverse channels.

Table 6. Matrix R with normalized values.

Items	rij (over 20 Years)	rij (between 11 and 20 Years)	rij (up to 10 Years)
At_01	0.29	0.26	0.26
At_02	0.25	0.27	0.25
At_03	0.24	0.25	0.26
At_04	0.29	0.25	0.26
At_05	0.29	0.27	0.26
At_06	0.23	0.25	0.26
At_07	0.27	0.26	0.27
At_08	0.23	0.25	0.26
At_09	0.25	0.25	0.26
At_10	0.24	0.22	0.23
At_11	0.21	0.22	0.24
At_12	0.20	0.23	0.22
At_13	0.20	0.24	0.23
At_14	0.26	0.26	0.25
At_15	0.26	0.25	0.25
At_16	0.25	0.26	0.24

Source: Authors (2021).

Table 7. Matrix V weighted values.

Items	rij (over 20 Years) × 0.50	rij (between 11 and 20 Years) × 0.30	rij (up to 10 Years) × 0.20
At_01	0.15	0.08	0.05
At_02	0.12	0.08	0.05
At_03	0.12	0.08	0.05
At_04	0.14	0.08	0.05
At_05	0.14	0.08	0.05
At_06	0.12	0.07	0.05
At_07	0.13	0.08	0.05
At_08	0.12	0.08	0.05
At_09	0.12	0.08	0.05
At_10	0.12	0.07	0.05
At_11	0.11	0.06	0.05
At_12	0.10	0.07	0.04
At_13	0.10	0.07	0.05
At_14	0.13	0.08	0.05
At_15	0.13	0.07	0.05
At_16	0.12	0.08	0.05

Source: Authors (2021).

Table 8 presents the positive ideal solution and the negative ideal solution. These data are necessary to calculate the distances from the positive ideal solution, the distance from the negative ideal solution, and the Ci* coefficient (Table 9). Finally, the ordering of the items was carried out based on the values of the coefficient (Ci*) obtained. The result of such ordering is shown in Table 10.

Table 8. Positive ideal solution and negative ideal solution for access to criteria.

Solution Criteria	Over 20 Years	Between 11 and 20 Years	Up to 10 Years
Positive ideal solution (vj+)	0.15	0.08	0.05
Negative ideal solution (vj−)	0.10	0.06	0.04

Source: Authors (2021).

Table 9. Distances from the positive ideal solution, distance from the negative ideal solution, and coefficient Ci*.

Items	Distances from the Positive Ideal Solution (Si+)	Distances from the Negative Ideal Solution (Si−)	Coefficient (Ci*)
At_01	0.00	0.05	0.92
At_02	0.02	0.03	0.58
At_03	0.03	0.03	0.50
At_04	0.01	0.05	0.87
At_05	0.00	0.05	0.93
At_06	0.03	0.02	0.38
At_07	0.01	0.04	0.74
At_08	0.03	0.02	0.39
At_09	0.02	0.03	0.56
At_10	0.03	0.02	0.43
At_11	0.05	0.01	0.14
At_12	0.05	0.00	0.07
At_13	0.05	0.01	0.17
At_14	0.02	0.03	0.67
At_15	0.02	0.03	0.66
At_16	0.02	0.03	0.55

Source: Authors (2021).

Table 10. Ranking of the items.

Position	(Ci*)	Code	Items
1°	0.93	At_05	TRANSPORT
2°	0.92	At_01	INTEGRATION
3°	0.87	At_04	COLLECTION
4°	0.74	At_07	WAREHOUSING
5°	0.67	At_14	RECYCLING
6°	0.66	At_15	REDISTRIBUTION
7°	0.58	At_02	GATEKEEPING
8°	0.56	At_09	SORTING
9°	0.55	At_16	PROPER DISPOSAL
10°	0.50	At_03	WASTE ACQUISITION
11°	0.43	At_10	DIRECT REUSE
12°	0.39	At_08	DISASSEMBLY
13°	0.38	At_06	INSPECTION/TESTING
14°	0.17	At_13	REMANUFATURING
15°	0.14	At_11	REPAIR
16°	0.07	At_12	REFURBISHING

Source: Authors (2021).

Integration, according to [63], is also called Coordinating System, the first and most important key element of the RL process since it is responsible for this system's overall management and performance. It also seeks to integrate the whole RL process's stages by information sharing between all reverse channel members, exactly as a reverse supply chain. In this step, fundamental logistics information still in gross (or aggregated) mode will be made available to support decisions, especially in the starting (Waste Acquisition) and ending (Redistribution) stages of the RL process. Another important point for "Integration is information technology which, according to Gimenez et al. [89] strengthens the relationship between environmental practices and environmental performance.

Thirdly, collecting appears as an activity belonging to the RL process in the professionals' opinion. It constitutes the consolidation of selected waste (based on information from gatekeeping) from generating sources facilities (based on information from waste acquisition) to processing centers, in which the inspection/testing, disassembly, and sorting processes take place. This is the general way in which this process is presented in the literature [42–44]. The intermediate activities in the ranking represent the professionals' uncertainty as to their belonging in the RL process. It can be seen, then, that out of the sixteen analyzed, ten have this classification, which demonstrates a high level of uncertainty by professionals regarding the activities that are a part of the RL process. In other words, there is still a lot of uncertainty about the belonging of most activities considered in the set of processes that make up the RL, which is one of the main findings of this research.

Finally, it is noteworthy that the results presented here, for the most part, do not converge with the results presented in the percentage distribution table of the most-cited RL activities in the literature survey carried out (Table 2). For example, the integration activity, identified by professionals participating in this study as having a low level of uncertainty as to whether it belongs to the LR process, has the lowest occurrence in the articles considered in Table 2.

Enabling the reduction of uncertainties and increasing reliability in the planning, implementation, and control of logistics operations, the reverse channels will likely have the best sustainable performance in the services and products offered. Additionally, Refs. [90–92] emphasizes that through a good definition of logistics processes, both economic and environmental performance can be achieved simultaneously, consequently contributing to the achievement of sustainable goals. Other sustainable contributions arising from a coherent definition of RL processes can be generated through route optimization, packaging optimization, use of recycled packaging, and total reduction of the carbon footprint [93].

According to the results achieved, it is possible to perceive that the correct understanding of the processes and activities that make up certain production systems is essential for achieving sustainable goals [2]. Furthermore, Ref. [94] also highlights that the importance of a systems understanding of sustainability can be affirmed based on the contribution that systems thinking and systems practice can provide to make sustainability deeper if one considers the contributions that a cybernetic insight can bring. Another point to be considered in achieving sustainable goals and objectives is the impacts caused by the COVID-19 pandemic [95], which compromised production systems, supply chains, and logistics networks around the world [96,97].

Additionally, considering the transport, integration, and collection activities (the first in the ranking), it is important to highlight the need to insert concepts of automation in the development of such activities as a future path in logistics networks to enhance the development of such operations in RL systems. Ref. [98] highlights the importance of applications that provide the exchange of information between those involved in the logistics network. Ref. [99] further highlights more specifically that automation includes application area planning, sourcing, material handling, distribution, and also reverse logistics activities.

5. Conclusions

Based on the results presented, it is concluded that the main objective proposed in this study was achieved since it was possible to identify the level of uncertainty about the activities that make up the RL processes in the opinion of professionals working in Brazil. A set of 16 activities was considered to develop a research instrument, and it was used in a survey with 38 professionals in the LR area. Considering the importance of Reverse Logistics (RL) to the fulfillment of the National Solid Waste Policy (NSWP) and the potential RL contributions to the effective development of activities regarded to the Sustainable Development Goals (SDG), especially SDGs 9 and 12, knowing which activities should be part of RL process, especially in specific contexts, is imperative. Considering the results achieved, it is possible to perceive the importance of identifying future challenges of global logistics networks, such as the need to meet sustainable guidelines in the provision of RL services and, in addition, the challenges for the insertion of elements of digitization in logistics processes, such as automation.

The results achieved in this research can contribute to theory and practice in the RL area. From a theoretical point of view, the findings presented here can serve as a basis for the expansion of debates by researchers in the field, since they detail the RL activities that generate greater uncertainty regarding their belonging to RL processes among professionals in the field, thus serving as a basis for the development of studies that aim to mitigate such understandings. From a practical point of view, the results can contribute to managers involved in the RL process and who aim for greater consistency in the definition of activities that are part of the processes in which they are managing. They can use results to help them in planning actions to improve the development and control of their logistics activities in the reverse channels. As a research limitation, its exploratory character stands out, and consequently, its results cannot be generalized to other geographic contexts that are not considered in this study.

As a proposal for future research: (a) apply the study in other geographic contexts; (b) define a training plan for managers in the RL area with the aim to broaden the understanding of activities that belong to the RL processes; and (c) measure the degree of importance attributed by professionals working in the area to each activity belonging to the RL processes.

Author Contributions: Conceptualization, V.W.B.M. and D.R.d.L.N.; Formal analysis, V.W.B.M. and A.C.S.M.; Investigation, A.C.S.M. and D.R.d.L.N.; Methodology, V.W.B.M.; Supervision, R.B. and A.C.S.M.; Validation, V.W.B.M.; Visualization, V.d.M.N.N. and R.B.; Writing—original draft, V.W.B.M. and A.C.S.M.; Writing—review & editing, V.W.B.M. and A.E.B.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted following the Declaration of Helsinki, and approved by the Ethics Committee of Universidade do Estado do Pará, protocol code CAAE: 46004221.2.0000.5174, date of approval on 4 May 2021.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are available at: https://docs.google.com/spread-sheets/d/1tI16FVGkF_auZ8Ado4gFp0ODi6-MWgjF9eDPpjtp6cU/edit?usp=sharing (accessed on 13 September 2021).

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

References

1. Arya, P.; Srivastava, M.K.; Jaiswal, M.P. Modelling environmental and economic sustainability of logistics. *Asia-Pac. J. Bus. Adm.* **2020**, *12*, 73–94. [CrossRef]
2. Nobre, A.V.; Oliveira, C.C.R.; Nunes, D.R.D.L.; Melo, A.C.S.; Guimarães, G.E.; Anholon, R.; Martins, V.W.B. Analysis of Decision Parameters for Route Plans and Their Importance for Sustainability: An Exploratory Study Using the TOPSIS Technique. *Logistics* **2022**, *6*, 32. [CrossRef]
3. Trochu, J.; Chaabane, A.; Ouhimmou, M. A two-stage stochastic optimization model for reverse logistics network design under dynamic suppliers' locations. *Waste Manag.* **2019**, *95*, 569–583. [CrossRef] [PubMed]
4. Morgan, T.R.; Tokman, M.; Richey, R.G.; Defee, C. Resource commitment and sustainability: A reverse logistics performance process model. *Int. J. Phys. Distrib. Logist. Manag.* **2018**, *46*, 293–315. [CrossRef]
5. Pushpamali, N.; Agdas, D.; Rose, T.M. A Review of Reverse Logistics: An Upstream Construction Supply Chain Perspective. *Sustainability* **2019**, *11*, 4143. [CrossRef]
6. Ruiz-Torres, A.J.; Cardoza, G.; Kuula, M.; Oliver, Y.; Rosa-Polanco, H. Logistic services in the Caribbean region: An analysis of collaboration, innovation capabilities and process improvement. *Acad. Rev. Latinoam. Adm.* **2018**, *31*, 534–552. [CrossRef]
7. Agrawal, S.; Singh, R.K.; Murtaza, Q. A literature review and perspectives in reverse logistics. *Resour. Conserv. Recycl.* **2015**, *97*, 76–92. [CrossRef]
8. Morgan, T.R.; Richey, R.G., Jr.; Autry, C.W. Developing a reverse logistics competency. *Int. J. Phys. Distrib. Logist. Manag.* **2016**, *46*, 293–315. [CrossRef]
9. Brandão, R.; Edwards, D.J.; Hosseini, M.R.; Melo, A.C.S.; Macêdo, A.N. Reverse supply chain conceptual model for construction and demolition waste. *Waste Manag. Res.* **2021**, *39*, 1341–1355. [CrossRef]
10. Al-Hakimi, M.A.; Borade, D.B.; Saleh, M.H. The mediating role of innovation between entrepreneurial orientation and supply chain resilience. *Asia-Pac. J. Bus. Adm.* **2021**. [CrossRef]
11. Siew-Phaik, L.; Downe, A.G.; Sambasivan, M. Strategic alliances with suppliers and customers in a manufacturing supply chain: From a manufacturer's perspective. *Asia-Pac. J. Bus. Adm.* **2013**, *5*, 192–214. [CrossRef]
12. Flygansvær, B.; Samuelsen, A.G.; Støyle, R.V. The power of nudging: How adaptations in reverse logistics systems can improve end-consumer recycling behavior. *Int. J. Phys. Distrib. Logist. Manag.* **2021**, *51*, 958–977. [CrossRef]

13. Velasco, N.; Moreno, J.-P.; Rebolledo, C. Logistics practices in healthcare organizations in Bogota. *Acad. Rev. Latinoam. De Adm.* **2018**, *31*, 519–533. [CrossRef]
14. Scarpellini, S.; Portillo-Tarragona, P.; Marin-Vinuesa, L.M. Green patents: A way to guide the eco-innovation success process? *Acad. Rev. Latinoam. Adm.* **2019**, *32*, 225–243. [CrossRef]
15. Govindan, K.; Bouzon, M. From a literature review to a multi-perspective framework for reverse logistics barriers and drivers. *J. Clean. Prod.* **2018**, *187*, 318–337. [CrossRef]
16. Hiruy, K.; Eversole, R. The contribution of research for development to the sustainable development goals: Lessons from fisheries research in Southeast Asia and the Pacific Island countries. *Int. J. Sustain. Dev. World Ecol.* **2019**, *27*, 153–166. [CrossRef]
17. Pärli, R.; Fischer, M. Implementing the Agenda 2030—What is the role of forums? *Int. J. Sustain. Dev. World Ecol.* **2020**, *27*, 443–457. [CrossRef]
18. Khalid, A.M.; Sharma, S.; Dubey, A.K. Concerns of developing countries and the sustainable development goals: Case for India. *Int. J. Sustain. Dev. World Ecol.* **2020**, *28*, 303–315. [CrossRef]
19. Brasil. *Lei n. 12.305, de 2 de agosto de 2010, que Institui a Política Nacional de Resíduos Sólidos; altera a Lei n° 9.605, de 12 de Fevereiro de 1998; e dá Outras Providências; e Legislação Correlata*, 3rd ed.; Câmara dos Deputados: Brasilia, Brasil, 2016; p. 77.
20. Dowlatshahi, S. Developing a theory of reverse logistics. *INFORMS J. Appl. Anal.* **2000**, *30*, 143–155. [CrossRef]
21. Fleischmann, M.; Bloemhof-Ruwaard, J.M.; Dekker, R.; van der Laan, E.; van Nunen, J.A.; Van Wassenhove, L.N. Quantitative models for reverse logistics: A review. *Eur. J. Oper. Res.* **1997**, *103*, 1–17. [CrossRef]
22. Fleischmann, M.; Beullens, P.; Bloemhof-Ruwaard, J.M.; VAN Wassenhove, L.N. The impact of product recovery on logistics network design. *Prod. Oper. Manag.* **2001**, *10*, 156–173. [CrossRef]
23. de Brito, M.P.; Dekker, R. A Framework for Reverse Logistics. In *Reverse Logistics*; Springer: Berlin/Heidelberg, Germany, 2004; pp. 3–27. [CrossRef]
24. Cline, A.; Lemay, S.; Helms, M.M. A framework for reverse logistics: The case of post-consumer carpet in the US. *Int. J. Commer. Manag.* **2015**, *25*, 466–489. [CrossRef]
25. Shi, X.; Li, L.X.; Yang, L.; Li, Z.; Choi, J.Y. Information flow in reverse logistics: An industrial information integration study. *Inf. Technol. Manag.* **2012**, *13*, 217–232. [CrossRef]
26. Chan, F.T.; Chan, H.K.; Jain, V. A framework of reverse logistics for the automobile industry. *Int. J. Prod. Res.* **2012**, *50*, 1318–1331. [CrossRef]
27. Rubio, S.; Jiménez-Parra, B. Reverse logistics: Concept, evolution and marketing challenges. In *Optimization and Decision Support Systems for Supply Chains*; Springer: Cham, Switzerland, 2017; pp. 41–61. [CrossRef]
28. Stević, Z.; Nunić, D.; Badi, I.; Karabašević, D. Evaluation of dimensions of SERVQUAL model for determining quality of processes in reverse logistics using a Delphi–Fuzzy PIPRECIA model. *Rom. J. Econ. Forecast.* **2022**, *25*, 139–159.
29. Stević, Ž.; Tanackov, I.; Puška, A.; Jovanov, G.; Vasiljević, J.; Lojaničić, D. Development of Modified SERVQUAL–MCDM Model for Quality Determination in Reverse Logistics. *Sustainability* **2021**, *13*, 5734. [CrossRef]
30. Fazlollahtabar, H. Operations and inspection Cost minimization for a reverse supply chain. *Oper. Res. Eng. Sci. Theory Appl.* **2019**, *1*, 91–107. [CrossRef]
31. Bienstock, C.C.; Amini, M.; Roberts, D.R. Reengineering a reverse supply chain for product returns services. *Int. J. Bus. Perform. Supply Chain Model.* **2011**, *3*, 335. [CrossRef]
32. Abdessalem, M.; Alouane, A.B.H.; Riopel, D. Decision modelling of reverse logistics systems: Selection of recovery operations for end-of-life products. *Int. J. Logist. Syst. Manag.* **2012**, *13*, 139. [CrossRef]
33. Škapa, R.; Klapalová, A. Reverse logistics in Czech companies: Increasing interest in performance measurement. *Manag. Res. Rev.* **2012**, *35*, 676–692. [CrossRef]
34. Ravi, V. Reverse Logistics Operations in Automobile Industry: A Case Study Using SAP-LAP Approach. *Glob. J. Flex. Syst. Manag.* **2014**, *15*, 295–303. [CrossRef]
35. Peretti, U.; Tatham, P.; Wu, Y.; Sgarbossa, F. Reverse logistics in humanitarian operations: Challenges and opportunities. *J. Humanit. Logist. Supply Chain Manag.* **2015**, *5*, 253–274. [CrossRef]
36. Pal, R. Value creation through reverse logistics in used clothing networks. *Int. J. Logist. Manag.* **2017**, *28*, 864–906. [CrossRef]
37. Fernandes, S.M.; Rodriguez, C.M.T.; Bornia, A.C.; Trierweiller, A.C.; Da Silva, S.M.; Freire, P.D.S. Systematic literature review on the ways of measuring the of reverse logistics performance. *Gestão Produção* **2017**, *25*, 175–190. [CrossRef]
38. Borges, L.C.; Macedo, V.B.H.; Celestino, O.J.D.S. Reverse logistics in são Sebastião and Ilha Bela handmade breweries: Advantages and challenges. *Indep. J. Manag. Prod.* **2020**, *11*, 1708–1723. [CrossRef]
39. Agrawal, S.; Singh, R.K.; Murtaza, Q. Disposition decisions in reverse logistics by using AHP-fuzzy TOPSIS approach. *J. Model. Manag.* **2016**, *11*, 932–948. [CrossRef]
40. Godichaud, M.; Tchangani, A.; Pérès, F.; Iung, B. Sustainable management of end-of-life systems. *Prod. Plan. Control* **2011**, *23*, 216–236. [CrossRef]
41. Bai, C.; Sarkis, J. Flexibility in reverse logistics: A framework and evaluation approach. *J. Clean. Prod.* **2013**, *47*, 306–318. [CrossRef]
42. Bai, C.; Sarkis, J. Integrating and extending data and decision tools for sustainable third-party reverse logistics provider selection. *Comput. Oper. Res.* **2019**, *110*, 188–207. [CrossRef]
43. Zouari, A. Relationships between eco-design, resources commitment and reverse logistics: Conceptual framework. *J. Adv. Mech. Des. Syst. Manuf.* **2019**, *13*, JAMDSM0039. [CrossRef]

44. Alshamsi, A.; Diabat, A. A Genetic Algorithm for Reverse Logistics network design: A case study from the GCC. *J. Clean. Prod.* **2017**, *151*, 652–669. [CrossRef]
45. Conti, M.; Orcioni, S. Cloud-based sustainable management of electrical and electronic equipment from production to end-of-life. *Int. J. Qual. Reliab. Manag.* **2019**, *36*, 98–119. [CrossRef]
46. Meyer, A.; Niemann, W.; Mackenzie, J.; Lombaard, J. Drivers and barriers of reverse logistics practices: A study of large grocery retailers in South Africa. *J. Transp. Supply Chain Manag.* **2017**, *11*, 1–16. [CrossRef]
47. Santana, J.C.C.; Guerhardt, F.; Franzini, C.E.; Ho, L.L.; Júnior, S.E.R.R.; Cânovas, G.; Yamamura, C.L.K.; Vanalle, R.M.; Berssaneti, F.T. Refurbishing and recycling of cell phones as a sustainable process of reverse logistics: A case study in Brazil. *J. Clean. Prod.* **2020**, *283*, 124585. [CrossRef]
48. Uriarte-Miranda, M.-L.; Caballero-Morales, S.-O.; Martinez-Flores, J.-L.; Cano-Olivos, P.; Akulova, A.-A. Reverse Logistic Strategy for the Management of Tire Waste in Mexico and Russia: Review and Conceptual Model. *Sustainability* **2018**, *10*, 3398. [CrossRef]
49. Agrawal, S.; Singh, R.K.; Murtaza, Q. Disposition decisions in reverse logistics: Graph theory and matrix approach. *J. Clean. Prod.* **2016**, *137*, 93–104. [CrossRef]
50. Eltayeb, T.K.; Suhaiza, Z. Drivers on the reverse logistics: Evidence from Malaysian certified companies Tarig Khidir Eltayeb and Suhaiza Hanim Mohamad Zailani. *Int. J. Logist. Syst. Manag.* **2011**, *10*, 375–397.
51. Fagundes, L.D.; Amorim, E.S.; Lima, R.D.S. Action Research in Reverse Logistics for End-Of-Life Tire Recycling. *Syst. Pract. Action Res.* **2017**, *30*, 553–568. [CrossRef]
52. Tsoulfas, G.T.; Pappis, C.P.; Minner, S. An environmental analysis of the reverse supply chain of SLI batteries. *Resour. Conserv. Recycl.* **2002**, *36*, 135–154. [CrossRef]
53. Xia, W.-H.; Jia, D.-Y.; He, Y.-Y. The remanufacturing reverse logistics management based on Closed-loop supply chain management processes. *Procedia Environ. Sci.* **2011**, *11*, 351–354. [CrossRef]
54. Gayialis, S.P.; Kechagias, E.P.; Konstantakopoulos, G.D.; Papadopoulos, G.A. A Predictive Maintenance System for Reverse Supply Chain Operations. *Logistics* **2022**, *6*, 4. [CrossRef]
55. Gonçalves, M.; Pereira, N.; Terence, M.C. Application of reverse logistics for the recycling of polypropylene waste and oyster shell. *Defect Diffus. Forum* **2019**, *391*, 101–105. [CrossRef]
56. Ang, A.; Tan, A. Designing reverse logistics network in an omnichannel environment in Asia. *LogForum* **2018**, *14*, 519–533. [CrossRef]
57. Macedo, P.B.; Alem, D.; Santos, M.; Junior, M.L.; Moreno, A. Hybrid manufacturing and remanufacturing lot-sizing problem with stochastic demand, return, and setup costs. *Int. J. Adv. Manuf. Technol.* **2015**, *82*, 1241–1257. [CrossRef]
58. Sellitto, M.A. Reverse logistics activities in three companies of the process industry. *J. Clean. Prod.* **2018**, *187*, 923–931. [CrossRef]
59. Akdoğan, M.; Coşkun, A. Drivers of Reverse Logistics Activities: An Empirical Investigation. *Procedia-Soc. Behav. Sci.* **2012**, *58*, 1640–1649. [CrossRef]
60. Chen, H.-K.; Chou, H.-W.; Chiu, Y.-C. On the modeling and solution algorithm for the reverse logistics recycling flow equilibrium problem. *Transp. Res. Part C Emerg. Technol.* **2007**, *15*, 218–234. [CrossRef]
61. Sangwan, K.S. Key activities, decision variables and performance indicators of reverse logistics. *Procedia CIRP* **2017**, *61*, 257–262. [CrossRef]
62. Turcu, V.A. The opportunity to evaluate performance indicators when implementing the quality management system within reverse logistics organizational activities. *Qual.-Access Success* **2017**, *18*, 96–98.
63. Chaves, G.D.L.D.; Giuriatto, N.T.; Ferreira, K.A. Reverse logistics performance measures: A survey of Brazilian companies. *Braz. J. Oper. Prod. Manag.* **2020**, *17*, 1–18. [CrossRef]
64. Nel, J.D.; Badenhorst, A. A conceptual framework for reverse logistics challenges in e-commerce. *Int. J. Bus. Perform. Manag.* **2020**, *21*, 114. [CrossRef]
65. Starostka-Patyk, M. Defective products management with reverse logistics processes in the furniture production companies. *Pol. J. Manag. Stud.* **2019**, *20*, 502–515. [CrossRef]
66. Brix-Asala, C.; Hahn, R.; Seuring, S. Reverse logistics and informal valorisation at the Base of the Pyramid: A case study on sustainability synergies and trade-offs. *Eur. Manag. J.* **2016**, *34*, 414–423. [CrossRef]
67. Kazancoglu, I.; Kazancoglu, Y.; Yarimoglu, E.; Kahraman, A. A conceptual framework for barriers of circular supply chains for sustainability in the textile industry. *Sustain. Dev.* **2020**, *28*, 1477–1492. [CrossRef]
68. Tsai, W.-H.; Hung, S.-J. Treatment and recycling system optimisation with activity-based costing in WEEE reverse logistics management: An environmental supply chain perspective. *Int. J. Prod. Res.* **2009**, *47*, 5391–5420. [CrossRef]
69. Razik, M.; Radi, B.; Okar, C. Critical Success Factors for Warehousing Performance Improve- ment in Moroccan Companies. *Int. J. Bus. Manag. Invent.* **2016**, *5*, 32–40.
70. Agrawal, S.; Singh, R.; Murtaza, Q. Outsourcing decisions in reverse logistics: Sustainable balanced scorecard and graph theoretic approach. *Resour. Conserv. Recycl.* **2016**, *108*, 41–53. [CrossRef]
71. Sahebi, H.; Ranjbar, S.; Teymouri, A. Investigating different reverse channels in a closed-loop supply chain: A power perspective. *Oper. Res.* **2021**, *22*, 1939–1985. [CrossRef]
72. Liu, Y.; Wood, L.C.; Venkatesh, V.; Zhang, A.; Farooque, M. Barriers to sustainable food consumption and production in China: A fuzzy DEMATEL analysis from a circular economy perspective. *Sustain. Prod. Consum.* **2021**, *28*, 1114–1129. [CrossRef]

73. Su, Y.; Chen, J.; Si, H.; Wu, G.; Zhang, R.; Lei, W. Decision-making interaction among stakeholders regarding construction and demolition waste recycling under different power structures. *Waste Manag.* **2021**, *131*, 491–502. [CrossRef] [PubMed]
74. Rau, H.; Budiman, S.D.; Monteiro, C.N. Improving the sustainability of a reverse supply chain system under demand uncertainty by using postponement strategies. *Waste Manag.* **2021**, *131*, 72–87. [CrossRef] [PubMed]
75. Wu, C.-H. A dynamic perspective of government intervention in a competitive closed-loop supply chain. *Eur. J. Oper. Res.* **2021**, *294*, 122–137. [CrossRef]
76. Fu, R.; Qiang, Q.P.; Ke, K.; Huang, Z. Closed-loop supply chain network with interaction of forward and reverse logistics. *Sustain. Prod. Consum.* **2021**, *27*, 737–752. [CrossRef]
77. Golpîra, H.; Javanmardan, A. Decentralized Decision System for Closed-Loop Supply Chain: A Bi-Level Multi-Objective Risk-Based Robust Optimization Approach. *Comput. Chem. Eng.* **2021**, *154*, 107472. [CrossRef]
78. Nag, U.; Sharma, S.K.; Govindan, K. Investigating drivers of circular supply chain with product-service system in automotive firms of an emerging economy. *J. Clean. Prod.* **2021**, *319*, 128629. [CrossRef]
79. Guo, S.; Shen, B.; Choi, T.-M.; Jung, S. A review on supply chain contracts in reverse logistics: Supply chain structures and channel leaderships. *J. Clean. Prod.* **2017**, *144*, 387–402. [CrossRef]
80. Hosseini-Motlagh, S.-M.; Nematollahi, M.; Johari, M.; Choi, T.-M. Reverse supply chain systems coordination across multiple links with duopolistic third party collectors. *IEEE Trans. Syst. Man Cybern. Syst.* **2019**, *50*, 4882–4893. [CrossRef]
81. Chen, Z.-S.; Zhang, X.; Govindan, K.; Wang, X.-J.; Chin, K.-S. Third-party reverse logistics provider selection: A computational semantic analysis-based multi-perspective multi-attribute decision-making approach. *Expert Syst. Appl.* **2020**, *166*, 114051. [CrossRef]
82. Straube, F.; Junge, A.L.; Verhoeven, P.; Mansfeld, M.; Reipert, J. *Pathway of Digital Transformation in Logistics: Best Practice Concepts and Future Developments*; Technische Universität Berlin: Berlin, Germany, 2019.
83. Gerlach, B.; Zarnitz, S.; Nitsche, B.; Straube, F. Digital supply chain Twins—Conceptual clarification, use cases and benefits. *Logistics* **2021**, *5*, 86. [CrossRef]
84. Nitsche, B. Decrypting the Belt and Road Initiative: Barriers and Development Paths for Global Logistics Networks. *Sustainability* **2020**, *12*, 9110. [CrossRef]
85. Martins, V.W.B.; Anholon, R.; Sanchez-Rodrigues, V.; Filho, W.L.; Quelhas, O.L.G. Brazilian logistics practitioners' perceptions on sustainability: An exploratory study. *Int. J. Logist. Manag.* **2020**, *32*, 190–213. [CrossRef]
86. Singh, R.K.; Gupta, A.; Kumar, A.; Khan, T.A. Ranking of barriers for effective maintenance by using TOPSIS approach. *J. Qual. Maint. Eng.* **2016**, *22*, 18–34. [CrossRef]
87. Christmann, A.; Van Aelst, S. Robust estimation of Cronbach's alpha. *J. Multivar. Anal.* **2006**, *97*, 1660–1674. [CrossRef]
88. Quesada, I.F. The concept of reverse logistics: A review of literature the concept of reverse logistics. In Proceedings of the Annual Conference for Nordic Researchers in Logistics, Oulu, Finland, 21 June 2003; pp. 464–478.
89. Gimenez, C.; Sierra, V.; Rodon, J.; Rodriguez, J.A. The role of information technology in the environmental performance of the firm: The interaction effect between information technology and environmental practices on environmental performance. *Acad. Rev. Latinoam. Adm.* **2015**, *28*, 273–291. [CrossRef]
90. Abdussalam, O.; Trochu, J.; Fello, N.; Chaabane, A. Recent advances and opportunities in planning green petroleum supply chains: A model-oriented review. *Int. J. Sustain. Dev. World Ecol.* **2021**, *28*, 524–539. [CrossRef]
91. Guarnieri, P.; e Silva, L.C.; Vieira, B. How to Assess Reverse Logistics of e-Waste Considering a Multicriteria Perspective? A Model Proposition. *Logistics* **2020**, *4*, 25. [CrossRef]
92. Ali, A.; Melkonyan, A.; Noche, B.; Gruchmann, T. Developing a Sustainable Logistics Service Quality Scale for Logistics Service Providers in Egypt. *Logistics* **2021**, *5*, 21. [CrossRef]
93. Somsuk, N.; Laosirihongthong, T. Prioritization of applicable drivers for green supply chain management implementation toward sustainability in Thailand. *Int. J. Sustain. Dev. World Ecol.* **2016**, *24*, 175–191. [CrossRef]
94. Donaires, O.S.; Cezarino, L.; Caldana, A.C.F.; Liboni, L. Sustainable development Goals—An analysis of outcomes. *Kybernetes* **2019**, *48*, 183–207. [CrossRef]
95. Anholon, R.; Rampasso, I.S.; Martins, V.W.B.; Serafim, M.P.; Filho, W.L.; Quelhas, O.L.G. COVID-19 and the targets of SDG 8: Reflections on Brazilian scenario. *Kybernetes* **2021**, *50*, 1679–1686. [CrossRef]
96. Heydari, J.; Mirzajani, Z. Supply chain coordination under nonlinear cap and trade carbon emission function and demand uncertainty. *Kybernetes* **2020**, *50*, 284–308. [CrossRef]
97. Sawangwong, A.; Chaopaisarn, P. The impact of applying knowledge in the technological pillars of Industry 4.0 on supply chain performance. *Kybernetes* **2021**. [CrossRef]
98. Nitsche, B.; Straube, F.; Wirth, M. Application areas and antecedents of automation in logistics and supply chain management: A conceptual framework. *Supply Chain Forum. Int. J.* **2021**, *22*, 223–239. [CrossRef]
99. Nitsche, B. Exploring the Potentials of Automation in Logistics and Supply Chain Management: Paving the Way for Autonomous Supply Chains. *Logistics* **2021**, *5*, 51. [CrossRef]

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Review

Analyzing the Implementation of Digital Twins in the Agri-Food Supply Chain

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Abstract: *Background*: Digital twins have the potential to significantly improve the efficiency and sustainability of the agri-food supply chain by providing visibility, reducing bottlenecks, planning for contingencies, and improving existing processes and resources. Additionally, they can add value to businesses by lowering costs and boosting customer satisfaction. This study is aimed at responding to common scientific questions on the application of digital twins in the agri-food supply chain, focusing on the benefits, types, integration levels, key elements, implementation steps, and challenges. *Methods*: This article conducts a systematic literature review of recent works on agri-food supply chain digital twins, using a list of peer-reviewed studies to analyze concepts using precise and well-defined criteria. Thus, 50 papers were selected based on inclusion and exclusion criteria, and descriptive and content-wise analysis was conducted to answer the research questions. *Conclusions*: The implementation of digital twins has shown promising advancements in addressing global challenges in the agri-food supply chain. Despite encouraging signs of progress in the sector, the real-world application of this solution is still in its early stages. This article intends to provide firms, experts, and researchers with insights into future research directions, implications, and challenges on the topic.

Keywords: digital twin; agri-food supply chain; contributions; integration level; challenges

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Citation: Melesse, T.Y.; Franciosi, C.; Di Pasquale, V.; Riemma, S. Analyzing the Implementation of Digital Twins in the Agri-Food Supply Chain. *Logistics* **2023**, *7*, 33. https://doi.org/10.3390/logistics7020033

Academic Editors: Benjamin Nitsche and Frank Straube

Received: 6 April 2023
Revised: 26 May 2023
Accepted: 31 May 2023
Published: 12 June 2023

1. Introduction

In recent decades, various technologies have been implemented to improve the efficiency of the agri-food supply chain. New challenges are arising that require the use of innovative solutions due to evolving market demands, regulations, and cost-effectiveness. As a result, increasing efficiency through effective, integrated smart technologies and approaches like digital twins (DTs) has been actively addressed in recent years. A DT is a new notion that has emerged alongside the advancement of Industry 4.0. It provides virtual representations of physical systems during their lifecycle using real-time data from sensors, thereby enhancing decision-making processes. The DT can represent both living and non-living objects, as well as processes that can be analyzed and simulated to interfere with the course of evolution [1]. The use of reliable DTs could be one of the most crucial techniques for monitoring supply chain processes in a real-time. As a result, the ability to simulate multiple operations and predict critical situations in advance enables rapid response and process modification, as well as enhancing resilience.

A DT is a virtual copy of a physical system, including its environment and processes, that is kept up to date by sharing information between the physical and virtual systems. It is a tool that has a continuous link between its physical and virtual counterparts (the twin) [1,2]. It consists of three components: a digital definition of its counterpart derived from CAD, Product Lifecycle Management (PLM), etc.; operational and experiential data of its counterpart gathered primarily using Internet of Things (IoT) data and real-time telemetry; and information model (dashboards, HMIs, etc.) that corresponds to and displays the information to facilitate decision-making. A DT is continuously learning and updating itself by using sensor data or external entities. All aspects of human activity, including the livestock sector, logistics, the petrochemical industry, and manufacturing, can profit greatly from DT systems [3]. The design, management, maintenance, development, and all industrial aspects related to goods, services, equipment, operations, and activities, as well as human resource management, can all be optimized with the use of these tools. Moreover, it enables users to remotely manage and control components and systems, as well as assess and predict resource- and process-related changes through "what if" analysis. Thus, firms would be able to assess information regarding service quality, new product development [4], and timely delivery. Furthermore, the DT is used to aid in the identification of control parameters to meet target KPIs and enhance the existing operation in terms of increasing energy efficiency and savings, reducing the number of off-target end products, improving process consistency, and reducing downtimes during maintenance [5].

In the context of the supply chain, the DT is a simulation model of an actual supply chain that forecasts supply chain dynamics using real-time data and snapshots [6] and that can send and receive data in both directions in real-time [7]. Supply chain DTs differ from conventional simulation models in terms of update frequency, powerful analytics capability, and simulation capability, allowing for deep synchronization and dynamic interaction between the physical and virtual worlds [8]. Supply chain analysts can use its output to assess supply chain activity, predict unforeseen events, and implement corrective measures. It is also used to monitor and forecast real-time changes in orders, supply, demand, approvals, and so on. As a result, firms can effectively evaluate their supply chain and adapt to changes more swiftly.

Despite the importance of DTs in improving agri-food supply chain activities, from the literature review conducted, it has emerged that the scientific community does not have a common understanding of the concept. As a result, DTs have been presented in a variety of ways in the articles. In certain cases, distinguishing DTs from digital models and digital shadows has become more challenging [9–14].

The adoption of DTs in agri-food supply chains is crucial because it enables the early detection of risks and the quality monitoring of food items using statistical, data-driven, or physics-based models [15]. Given the rising concerns about monitoring real-time activities, the agri-food supply chain continues to struggle with assuring traceability.

Despite promising advances in the field, DTs are still in their early stages of use in agri-food supply chains [16–18]. This is due to issues such as education (which causes management change and knowledge transfer), accurate representation, data quality, costs, intellectual property protection (data ownership concerns, identity assurance methods, and user access control), digital security, and interoperability [19], as well as ethical concerns and potential societal and safety consequences [1].

Currently, DT applications are more focused on sectors such as the manufacturing, construction, automotive, and aerospace industries [3]. Only a few studies have focused on DT applications in food and agriculture. In this case, there is an initial trend toward the implementation of DTs, and more clarity and insights are needed for the scientific community and industries interested in the implementation of this technology. To the best of our knowledge, despite being a hot topic that has caught the interest of many businesses and academics, DT implementation in the agri-food supply chain is still not well investigated, and no detailed study analyzing the current state of the art has been found. In particular, the benefits, types, levels of integration, key aspects, implementation processes, and challenges related to the adoption of DTs in the agri-food supply chain remain unclear. Therefore, this study aims to provide a first contribution to the topic by responding to the following research questions (RQs): how does the use of DT applications contribute to the agri-food supply chain? (RQ1); what are the key elements of implementing a DT? (RQ2); what types and levels of integration exist within the DT in the agri-food supply chain? (RQ3); what are the steps for implementation? (RQ4); and how challenging is it to adopt DTs in the agri-food supply chain? (RQ5).

The remaining sections are arranged as follows: the background is described in Section 2, and the method used in the study is described in Section 3. The fourth section of the paper goes into detail about the descriptive analysis and discussion of research questions. Finally, the summary, implications, and limitations of the study are stated in Section 5.

2. Theoretical Background

2.1. Challenges in the Agri-Food Supply Chain

The agri-food supply chain is a complex network of stakeholders who share common goals such as ensuring food quality, food security, food safety, and sustainability. It is subject to greater uncertainty and risk than other supply chains, raising serious issues concerning its impact on the environment, society, and the economy [20]. Additionally, unprecedented occurrences such as the COVID-19 pandemic and Ukraine's prolonged war, as well as economic sanctions, have highlighted the vulnerabilities of global supply networks [21,22]. These factors can result in problems related to unexpected delays, cost management, collaboration, data synchronization, rising freight charges, demand forecasting, digital transformation, port congestion, and the perishable nature of products [23].

The agri-food supply chain is one of the sectors that use advanced tools to evolve into a data-driven, intelligent, agile, and autonomously connected system [4]. Recent technology breakthroughs in cloud computing, IoT, big data, blockchain, robotics, and AI provide smart connected systems [20], allowing for the automation of this industry. Automation approaches are essential for developing supply chain DTs, which can lead to scalable and sustainable growth in the industry.

2.2. Supply Chain DTs

A DT is a dynamic, real-time depiction of the different agents in the supply chain network that forecasts supply chain dynamics using real-time data and snapshots. In logistics, the supply chain DT maps the data, state, relationships, and behavior of the system, mimicking its behavior using dynamic simulation capabilities [21,24]. Four areas of DT application have been identified in the supply chain, including network level (network management and transportation), site, manufacturing, warehousing, and cargo handling [24]. Network management is concerned with managing and monitoring valuable networks, while the transportation domain includes use cases involving the network-level transportation of products and commodities. Manufacturing is the most common application area on the site level, involving tasks related to the production of goods. Warehousing covers applications related to facilities that store, ship, and return goods and materials.

Supply chain optimization through DTs adds value to businesses by lowering costs and boosting customer satisfaction [25]. To do this, all aspects of the supply chain must be upgraded, including material flows, financial flows, and information flows. By simulating alternative scenarios and identifying risks and opportunities, DTs enable businesses to optimize levels of inventory, reduce costs, enhance collaborations, and improve supply chain efficiency [26,27]. Additionally, supply chain management based on DTs does not require physical proximity, meaning that actual product movement from source to the consumer is no longer dependent on the location of the parties performing control and collaboration [28].

DTs are becoming increasingly popular in the agri-food supply chain due to their benefits, such as improved product quality, resource utilization, maintenance, production planning, reduced losses, improved logistics, energy savings, and increased visibility [18,19,22,29–31]. They enable supply chain actors to control demand, understand demand patterns, monitor food quality and marketability, track goods during transportation, ensure traceability, and monitor environmental conditions [26,32,33]. In agriculture, the use of such tools can provide information on fertilizers, chemicals, seeds, irrigation management techniques, environmental protection, pests, climate, crop monitoring management solutions, market demands, and business changes [34]. In general, DTs in the agri-food supply chain provide simulation and optimization, livestock tracking and health management [2,35–37], collaborative planning and collaboration [8], crop monitoring and management [38,39], supply chain visibility and traceability [40,41], and predictive analytics and decision support [42] to help farmers and supply chain managers identify patterns and generate actionable insights.

3. Methodology

This study used a systematic literature review (SLR), which uses a list of peer-reviewed research to identify, evaluate, and synthesize ideas using strict and well-defined criteria. SLR seeks to address RQs, test hypotheses, and theories, or produce new arguments [43]. SLR was chosen for this study because of its ability to reduce bias and improve the accuracy of exploring and analyzing related studies. Thus, the methodology ensures a detailed analysis of relevant works, thereby offering a key foundation for the evolution of traceable information.

3.1. Data Sources and Keywords Definition

In this review, the Scopus and Web of Science databases have been used as a data source with the keywords (“digital twin” OR “digital model” OR “digital shadow” OR “simulation model”) AND (“post-harvest” OR “agri food” OR “agrifood” OR “agri-food”). Because many publications on this topic have been published without consistent use of terms, the search was carried out with considerable care, using a wide range of keyword combinations. When choosing keywords, several elements related to digitization in the agriculture and food supply chain were considered.

Since this review aims to investigate how DTs have been used in recent years in the agri-food supply chain, the search includes published papers from 1 January 2019 to 20 August 2022. After eliminating duplicates, the authors evaluated each article to determine whether it met the inclusion criteria.

3.2. Screening and Eligibility Check

Only works that have been peer-reviewed and published in journals, conferences, and book chapters were considered during the preliminary screening stage. All the articles collected from the two databases (Scopus and Web of Science) were checked for duplication using the reference management tool (Mendeley), followed by reading the abstracts and full texts of the selected articles.

The final screening and eligibility assessment were done based on the following criteria.

Screening Exclusion Criteria (SEC):

- SEC1—Is it a peer-reviewed journal article, a book chapter, a review, or a conference paper?
- SEC2—Does the document illustrate the use of DTs in the agri-food supply chain?

Eligibility Exclusion Criteria (EEC):

- EEC1—Is the full document available for reading?
- EEC2—Does the paper discuss digital models, digital shadows, or DTs in the agri-food supply chain?
- EEC3—Does the paper answer at least one of the research questions that have already been set?

4. Analysis and Discussion

4.1. Descriptive Analysis of Selected Studies

Following the initial screening and checks to ensure eligibility, 50 papers were selected for further analysis (Figure 1). This descriptive analysis began by examining the current trend of research development in the agri-food supply chain.

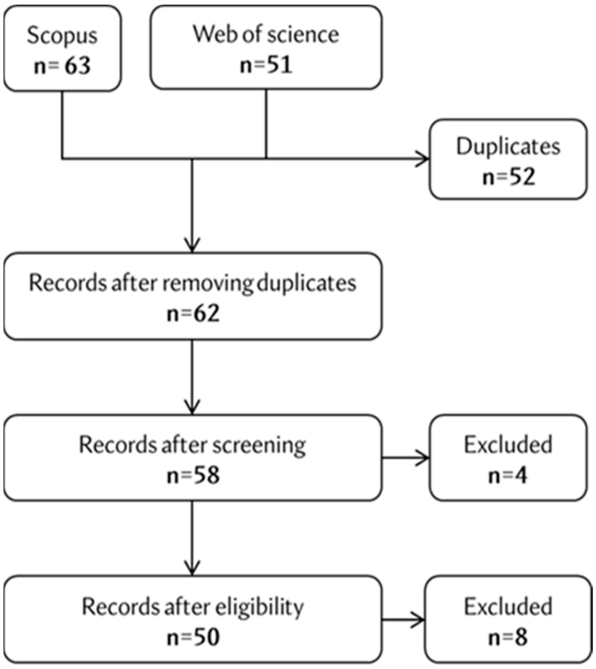

Figure 1. Stages for literature review.

Accordingly, the research trends on the implementation of DTs in the agri-food supply chain have recently attracted the interest of numerous scholars (Figure 2). The data for 2022 are not complete, and it looks like fewer papers were published in 2022 than in 2021. This is because the study only looked at papers that showed up in the search until 20 August 2022.

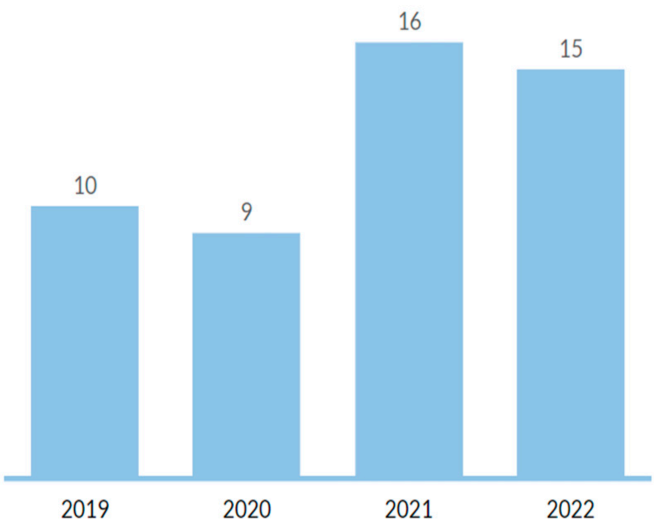

Figure 2. Distribution of papers over the years.

In total, 66% of all contributions are in the form of articles published in peer-reviewed journals. The remaining documents are review articles (6%), conference papers (26%), and book chapters (2%), as shown in Figure 3.

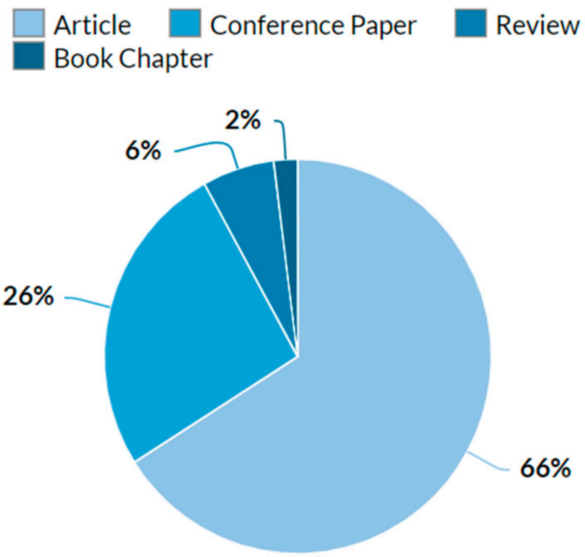

Figure 3. Contribution of selected papers.

The search conducted on Scopus and Web of Science revealed that the publications drew their data from a total of 36 different journals. The International Journal of Production Research got the most citations (229), followed by the IEEE Transactions on Industrial Informatics with 103 citations, Animal Production Science with 51 citations, and the Journal of Resources, Conservation, and Recycling with 51 citations each (Figure 4).

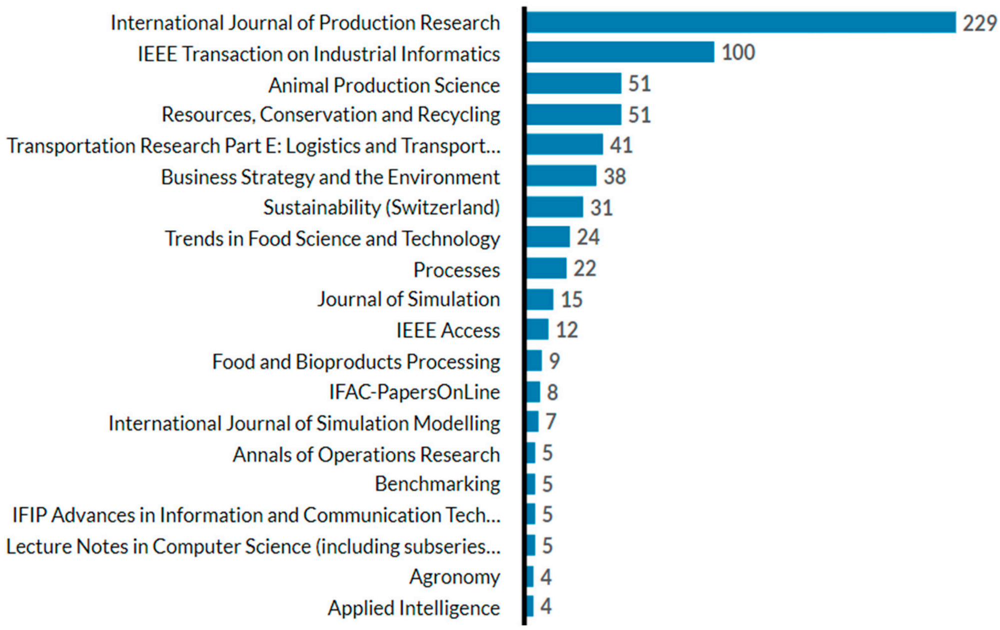

Figure 4. Top 20 journals based on their citations.

The United States contributed 16.7% of the studies that were conducted on the application of DTs in the agri-food supply chain. This was followed by Switzerland, which contributed 15.6% of the studies, and China, which contributed 6.1% of the publications (Figure 5).

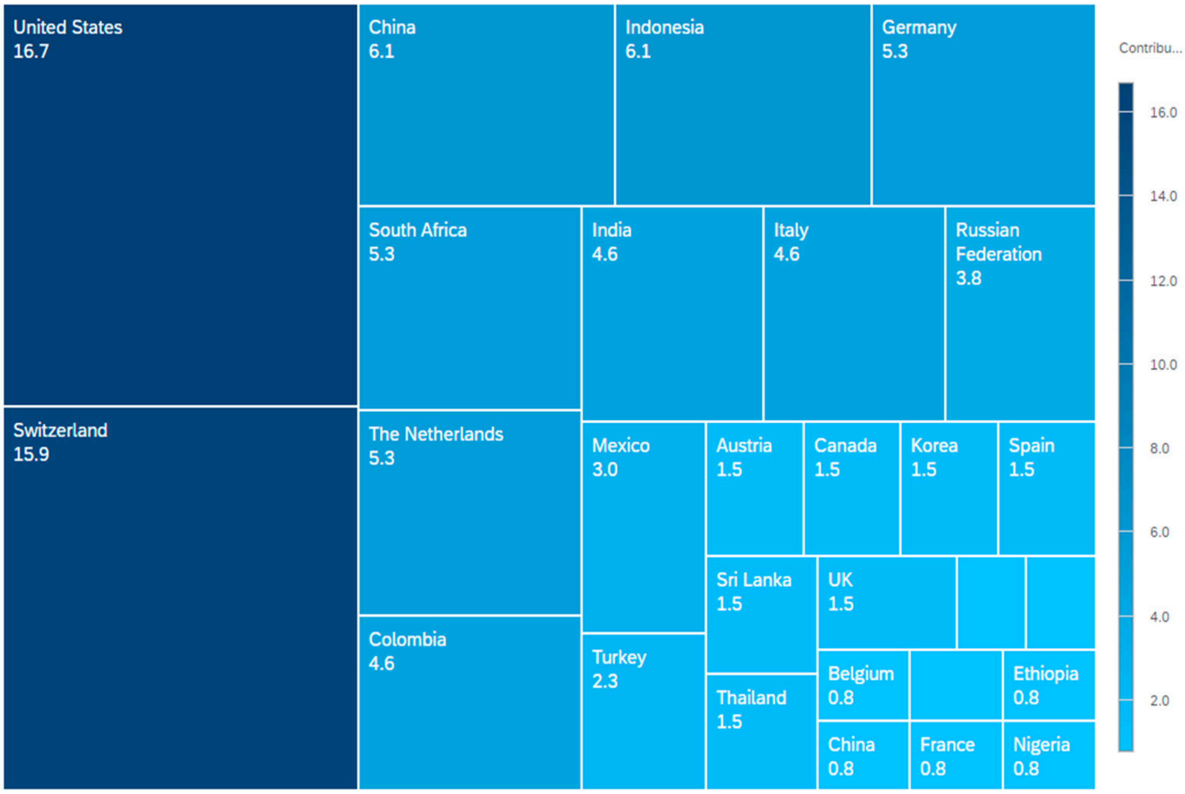

Figure 5. Treemap of contributing countries.

This analysis demonstrates the increasing interest among researchers from all over the world. In the coming years, there may be an increase in the number of publications that explore the contexts in which DTs might be leveraged in the agri-food supply chain due to the increasing need to digitalize the sector.

4.2. Discussion of Results with Respect to the Research Questions

Based on the framework shown in Figure 6, this section highlights recent scientific studies on DT applications in the agri-food supply chain, with an emphasis on the benefits (RQ1), key aspects of implementation processes (RQ2), types, integration levels (RQ3), implementation steps (RQ4), and challenges (RQ5).

4.2.1. Contributions of DTs to the Agri-Food Supply Chain (RQ1)

Several researchers contend that the adoption of digital technology had a significant impact on the supply chain's visibility, and the monitoring of processes [19,22,29–31]. Visibility is transparency in real-time over the entire transport network, including information on available capacity, interruptions, and operational status [7].

Due to the short shelf life of many agri-food products in the supply chain, excellent forecasting and monitoring tools are needed to eliminate the mismatch between shortages and surpluses [26]. A DT continuously controls demand, can better comprehend demand patterns, and allows for the connection of sensor data in a real-time to monitor the quality of food and marketability [44]. Furthermore, it has significant potential for use in determining food quality and the design of personalized foods [16,30]. Retailers might use this tool to assess how the temperature difference between the packhouse and their store impacts the overall quality of their products [45,46]. Similarly, the use of DTs for tracking goods, traceability, and monitoring the environmental conditions, weight loss, and overall quality loss in the postharvest supply chain has also attracted the interest of the food industry [32,33,47]. This would enhance system integration and product or system visibility and knowledge, as well as help predictive capabilities, perform scenario analysis, and continuous improvement. Table 1 summarizes case studies of agri-food DTs.

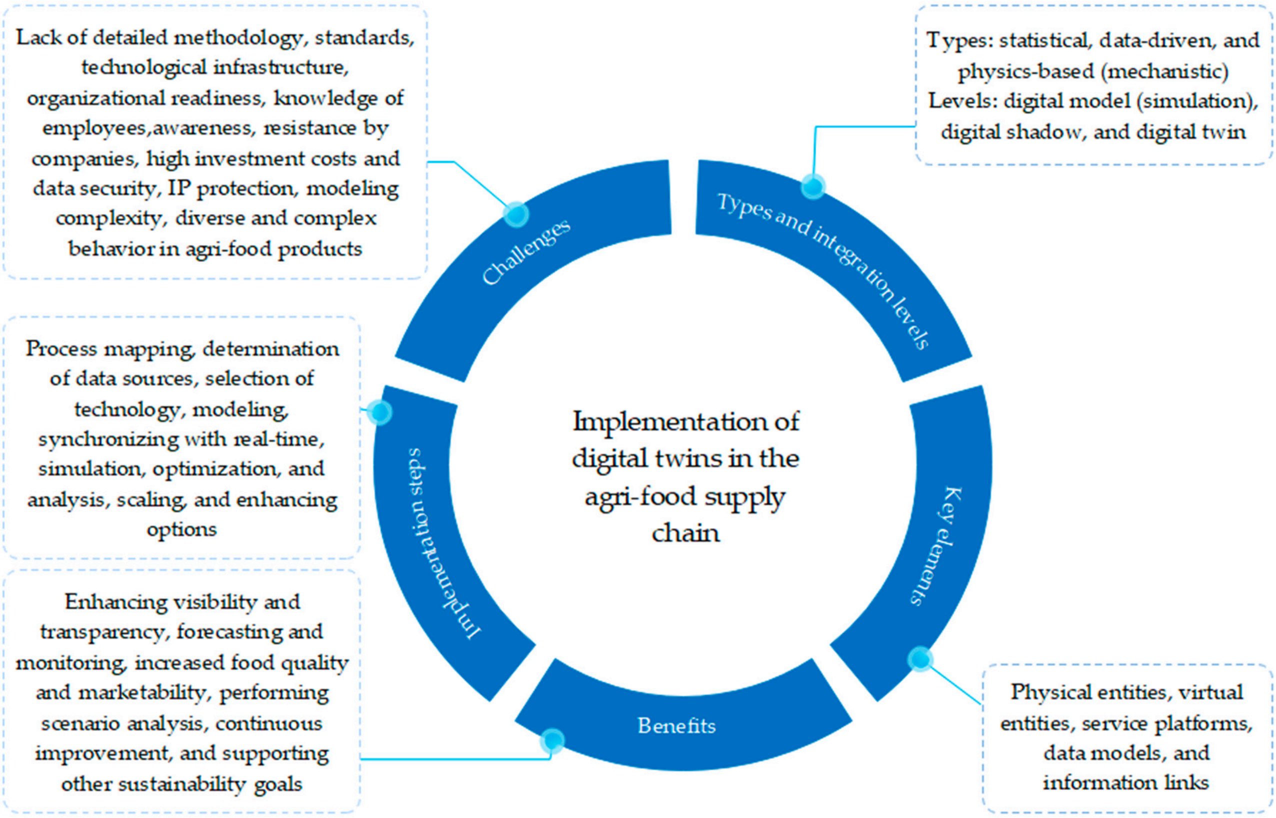

Figure 6. Highlights of the results discussed in the paper.

Table 1. Identified use cases of agri-food supply chain DTs.

Application Area	Implementation Purpose of DT	References
Transportation and storage of fruit	To provide insights regarding the thermophysical behavior of fruit	[48]
Food retail supply chains	To enhance end-to-end visibility and resilient management of demand, inventory, and capacity	[22]
Postharvest supply chains	To provide insight with actionable data and aid in detecting and predicting supply chain issues	[15]
Refrigerated transport and cold storage	To optimize the cooling process for a variety of fruits and vegetables with complex shapes and compositions	[46]
Cold chain	For cold chain optimizations in the design process	[45]
Food industry	To enhance food quality and traceability, and design personalized foods	[16]
Refrigerated supply chain	For monitoring food quality and marketability	[44]
Fruit retail	For monitoring the quality of fruit during storage	[31]
Food supply chain	To replicate the dynamic evolution of a system over time	[49]
Agriculture	To collect and analyze fruiting body growth in farming	[50]
Meat and livestock	To replicate the value chain	[51]
Smart farm	To enhance farm management	[52]
Food processing plant	To enhance pasteurization and predict processing conditions in beverage processing	[53,54]

Recently, agricultural sectors such as controlled environment agriculture, open-field agriculture, and animal farming have started using DTs [48,55,56]. As the next phase of the digitization paradigm, DT technologies can help farmers by enabling continuous and real-time monitoring of the physical world (the farm) and updating the status of the virtual environment [57]. Digital farming methods can supply information regarding the use of fertilizers, chemicals, seeds, irrigation management techniques, environmental protection, pests, climate, crop monitoring management solutions, market demands, and business changes [34]. In addition, it can be used to monitor greenhouse activity and predict crop growth [1]. Besides this, these systems allow growers to monitor the health of their crops and receive real-time notifications regarding pests, diseases, and climate change. This helps farms decide what to do with the actual crop and how to use fertilizers, as well as determine the effects of these activities.

4.2.2. Key Elements in DT Implementation (RQ2)

More broadly, the top five essential components of DTs have been identified in physical entities, virtual entities, service platforms, data models, and information links [16,58]. The identification of physical entities is the first essential component of DT implementation. The physical entity is a relative term that refers to the actual product or system that a virtual DT mimics in the real world. This may include "vehicle", "component", "product", "system", "artifact", etc. For instance, in the agri-food supply chain, it is common to find the DTs of fruits, farms, and supply chain networks. To build a virtual entity, one must create a digital model with the same appearance, properties, behaviors, and rules as the real entity. In addition, service platforms are essential components for the execution of models. Additionally, the virtual entity needs to have access to cloud applications, data, and knowledge for it to work properly. In the supply chain DT development, experts are increasingly seeking real-time data such as demographic data collected from various supply chain participants or stakeholders that can be used to get information regarding the location of truck routes, fulfillment centers, retail outlets, consumers, etc., to better understand logistics. These data can be directly entered into databases like the Enterprise Resource Planning (ERP) database and the production system to build a DT with a simulation tool [59]. Furthermore, DTs can utilize data from transportation management systems (TMS) and customer relationship management systems (CMS) [7]. It is also possible to combine internal data from the systems of the actors with external data sources (e.g., weather, traffic, competitors' prices). These lay the groundwork for the DTs of the supply chain to construct a model that is as realistic and accurate as possible to conduct analysis and simulations based on high data quality. Smart analysis and the quality, quantity, and integration of data are fundamental requirements for the optimal usage of supply chain DTs. In addition, basic requirements for supply chain DT adoption include visibility and transparency, update frequency, data collection, data analysis, simulation capabilities, decision support capabilities for planning, and the ability to handle disruptions.

4.2.3. Types and Levels of DT Integration (RQ3)

In the agri-food supply chain, DT models can be statistical, data-driven, or physics-based (mechanistic) [15,44,45,47,55]. Multiphysics modeling and simulation are used in physics-based approaches to model and simulate the relevant physical, biochemical, microbiological, and physiological processes, including the CAD geometry of the fruit, material property data, and the physical model's beginning and boundary conditions [45,46,48]. This is accomplished by employing a mathematical definition of the relevant biological processes, such as biochemical processes, that affect fruit quality parameters [48]. In the case of a data-driven model, AI techniques, including machine learning, are utilized for model building, calibration, verification, and validation. Machine learning models can be trained in a variety of ways, including through supervised and unsupervised learning. The model training data could include horticultural-product storage conditions as well as the measured biological response of fresh horticulture products over time.

Recent applications of DTs in the agri-food supply chain, mostly in the fruit supply chain, have emphasized physics-based DTs [15,16,29,30,44,45,47,48,55,60,61]. Because of advancements in prediction accuracy and computational performance, the adoption of a physics-based DT is growing rapidly [5]. Using mechanistic models (e.g., heat and mass transfer) and kinetic models (quality deterioration), a DT can forecast when food will change its quality over time, including during storage and shipment. With such models, more emphasis has been placed on monitoring fresh fruits and vegetables, contributing to product loss, particularly during transcontinental shipments.

In comparison to statistical and data-driven DTs, which determine how fresh horticultural products end up losing their quality by looking for patterns in the data, physics-based twins provide a better description of the physiological, biochemical, microbiological, and physiological processes that are taking place, which explains why this quality loss occurs [15]. In response to specific temperatures and other environmental conditions, they can assist horticulture items in communicating their history as they move from the field to the consumer. By connecting real-world products to sensors, DTs help determine how the quality of products changes over time. Similarly, machine learning-based techniques are used to build biophysical DTs comprising process and raw material data to replicate a food product and process [16].

The scientific community has described DTs in a variety of ways in the literature. In some circumstances, it has become more difficult to distinguish DTs from digital models and digital shadows [9–14]. To precisely define a digital model, there must be no automated data exchange between the physical and virtual twins. These kinds of models are used by the industry to determine how a change to a digital entity's counterpart might be affected if implemented. A digital shadow is a unidirectional exchange between a physical and a digital object—not vice versa, whereby a change in a physical object creates a change in its digital counterpart. In this instance, data flow is automatic from the physical asset to its digital replica, but manual from the digital asset to its physical counterpart. It is typically employed for data collection and subsequent analysis [29]. The model is referred to as a "DT" if data flow between a physical object and a digital entity is entirely integrated in both directions. In other words, any modifications made to the digital item are mirrored instantaneously in its physical counterpart, and vice versa. The autonomy of the model is the primary distinction between digital shadows and DTs [62]. In the DT, interventions could be automatic, whereas, in the digital shadow, they must be deliberate (human-supported) decisions. A digital model (simulation) depicts what could happen to an item or supply chain system, but a DT depicts what is already happening. Table 2 presents the category of selected papers based on the level of integration.

Table 2. Category of selected papers based on the level of integration.

Level of Integration	References
Digital model (simulation)	[46–57]
Digital shadow	[56,63–67]
DT	[15,16,22,30,31,44–46,48–55,68,69]

4.2.4. Implementation Steps (RQ4)

The implementation of a DT entails several steps, including process mapping, determination of data sources, selection of technology, modeling, synchronizing into real-time, simulation, optimization, and analysis, as well as scaling and enhancing options [26] (Figure 7).

Compared to implementation in manufacturing or a piece of machinery, a supply chain DT requires the modeling of the entire supply chain supported by real-time or near-real-time operational parameters [70]. Various modeling methods can be used to manage the growing complexity and unpredictability of the agri-food supply chain. In the selected papers, modeling techniques such as agent-based modeling [71,72], system [63,73–75] discrete event simulation [30,56,66,76–80], and hybrid simulation [30,81,82] are commonly used. The application of these methods will provide answers to planning-related questions, such as the amount to be purchased, delivered, or produced. During the modeling process, the DT should be constructed with long-term plans in mind. Moreover, the framework should enable the modeling and analysis of alternative processes, asset performance optimization, and event forecasting.

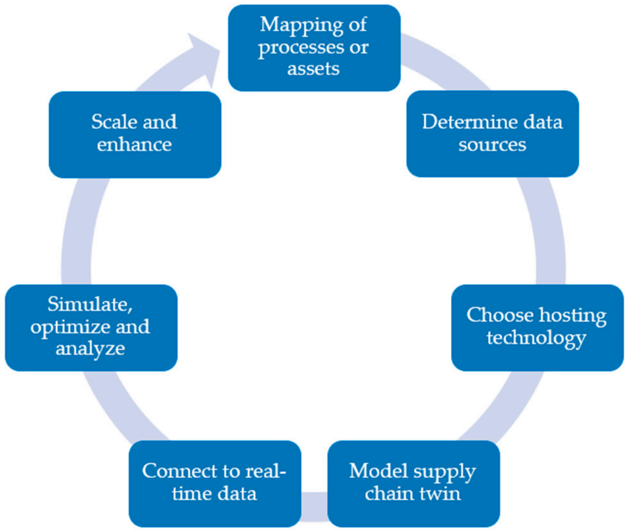

Figure 7. Steps to implement the supply chain DT.

Connecting to real-time data is yet another vital step for the agri-food supply chain's DT deployment. Although the time scale is goal-oriented, real-time data are essential for the use of DTs [26]. For instance, distributed control systems, predictive control models, online optimization, and process scheduling use seconds, minutes, hours, days, or weeks as time scales. Sensors are frequently linked to the IoT, which is unquestionably a requirement for DTs since real-time data collection is made possible by wireless connectivity between many objects located in the same or distinct physical areas. Sensor technology is available to monitor the agri-food supply chain; however, it is still challenging to apply in commercial supply chains [45]. Various types of sensors have been installed in the agri-food supply chain to date to execute DT scenarios. In the case of post-harvest activities, for instance, temperature and gas sensors are reported to be used to monitor the status of a fresh product during the logistics and storage phases [15,45,46,48,55,56,83], as well as to depict inventory and grain quality as it flows across a plant [30]. Citrus shipments also employ sensors for temperature measurements [44]. Infrared thermal cameras are also proven to be an effective tool for detecting physiological changes in fruits [31,84–88]. In the case of DT-based smart farms, several sensors can be utilized to monitor the plant's nutrients, growth, and environmental conditions [52]. Among the sensors are environmental sensors that measure temperature, chemicals, light humidity, air velocity, lighting, ventilation, and movement, which allows for reporting their behavior, health, and condition [89]. Temperature and pressure sensors have been indicated for use in the proposed DT models in food processing [53,54]. Sensors and indicators time-temperature indicators, freshness indicators, gas indicators, and integrity indicators) are used in smart packaging to detect biological, chemical, or gaseous changes in packaged fresh produce [90]. Sensor-based RFID tags can detect corresponding attributes and chemical changes in fresh fruits and vegetables throughout the post-harvest supply chain [32].

Another key stage in developing a DT for the supply chain is the capacity to simulate, optimize, and analyze. Possibilities for applying prescriptive, predictive, and advanced analytics to influence decision-making through digital supply chain twins vary from strategic to operational [89]. Once integrated with models, operations, and assets can be simulated or optimized to obtain insights, test possible scenarios, or adapt to disturbances. The outcomes should be communicated throughout the enterprise to inform plans of action at all levels. The simulation module offered by cloud computing can predict future conditions of the real-world supply chain by applying different parameters to its DT. The DT's outputs could help optimize, monitor, or forecast supply chain behavior [30,45,48,52,55].

Ultimately, DTs should be scalable across enterprises to enhance end-to-end visibility across supply chains. They can even connect with suppliers and consumers outside of the enterprise. More real-time data points from internal sources, third parties, and industry groups can enhance the DT's performance.

4.2.5. Challenges for the DT Implementation (RQ5)

The adoption of DTs in the agri-food industry remains difficult [91]. For instance, deploying IoT-based agricultural systems still faces significant challenges due to the demand for continuous power supplies to operate. Although alternative energy sources such as solar and wind can be used to meet the energy demand, this will greatly increase the cost. In the countryside and village areas, the lack of a reliable internet connection is another challenge. The connection needs to have enough broadband to deliver data as needed by the service. In addition, farmers need instruction in using basic computers and tablets, as well as knowledge of how the IoT works.

In practice, mapping and obtaining a detailed real-time snapshot of the supply chain is challenging. The simultaneous validation of all model-output parameters is an additional barrier to the use of DTs in supply chain applications [44]. Moreover, the stakeholders in the cold chain, such as retailers, require specific evidence to demonstrate the benefits in shelf life that may be obtained with certain digital solutions. Unfortunately, pilot studies to derive such validations are sometimes costly and time-consuming. Further implementation issues include a lack of detailed methodology and standards, a lack of clear data governance, and difficulties gathering and storing massive datasets [20,92–94]. For instance, the lack of modeling standards for DT can lead to compatibility issues during the integration of models created separately [95]. Developing a data acquisition system, synchronization problems, the modeling of a complex system, lack of awareness, companies' resistance to adopting the technology [96], as well as difficulties in developing, understanding, controlling, and simulating real-time changes in the system, all pose challenges.

Combining multidisciplinary knowledge and providing enough data are the two most difficult aspects of implementing DTs [16]. Similarly, education (which causes management changes and knowledge transfers), accurate representation, data quality, costs, IP protection (data ownership concerns, identity assurance procedures, and user access control), digital security, and interoperability [19,97] can be considered obstacles to the implementation. Moreover, in agriculture, the implementation of the DT is hindered due to ethical concerns, as well as potential societal and safety consequences [1]. Due to product complexity and operational challenges, the deployment of DTs at the industry level remains difficult [5,47]. However, some recent studies show promising signs of progress [17,18,29].

5. Conclusions

This study explored the state of the art in the implementation of DTs in the agri-food supply chain and provides insight into the roles of the DT in improving supply chain performance, optimizing resources, facilitating collaboration, and sharing information. The benefits, types, integration levels, key elements, and implementation steps of a DT in the reviewed area, as well as the challenges to its implementation, were discussed. In this regard, DTs can improve efficiency and sustainability in the agri-food supply chain by providing visibility, minimizing bottlenecks, planning for contingencies, and improving existing processes and resources. However, the scientific community lacks a common comprehension of the DT concept, making it impossible to distinguish between a DT, a digital model, and a digital shadow. Furthermore, research advances and real-world implementations of DTs in agri-food are still in the early stages of development.

The findings of this study are intended to help researchers, policymakers, and the agri-food sector understand the potential and future possibilities of using DTs, including meeting sustainability goals. As a result, the current study could give researchers a clear understanding of the benefits of DTs in supporting the agri-food industry, as well as details on the current pattern of DT utilization. This research will further assist academics in identifying the capabilities of the solution along with the requirements during the DT development and implementation phases. Researchers and supply chain actors would benefit the most from an in-depth analysis of DTs to gain a common awareness of this emerging tool.

The literature search was conducted using the Web of Science and Scopus databases, which are commonly used data sources for literature analysis. Despite their large citations, these databases have limitations in terms of document availability and coverage. Many reports regarding the progress of DT implementation by the companies are documented in white papers and other publications that are not included in both databases. Despite our best efforts to assure inclusiveness, our study is limited to publications that have undergone peer review. So, additional related work that has been published in other databases or languages other than English might be missed during our analysis. As a result, scholars interested in DT applications in the supply chain could consult additional sources. Researchers might also focus on evaluating the solution's effectiveness in terms of sustainability and feasibility, which will boost confidence in industries within the agri-food supply chain to incorporate this technology into their business processes. Furthermore, studies might be directed toward the development of tools and standards for the use of DTs to ease implementation efforts. Future research should focus on practical applications and proving the technical and economic benefits of DTs, as well as exploring their deployment and operation from a technical and economic standpoint.

Author Contributions: Conceptualization, T.Y.M., C.F., V.D.P. and S.R.; methodology, T.Y.M. and C.F.; writing—original draft preparation, T.Y.M.; writing—review and editing, T.Y.M. and C.F.; supervision, V.D.P. and S.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

References

1. Van der Burg, S.; Kloppenburg, S.; Kok, E.J.; van der Voort, M. Digital Twins in Agri-Food: Societal and Ethical Themes and Questions for Further Research. *NJAS Impact Agric. Life Sci.* **2021**, *93*, 98–125. [CrossRef]
2. Neethirajan, S.; Kemp, B. Digital Twins in Livestock Farming. *Animals* **2021**, *11*, 1008. [CrossRef] [PubMed]
3. Melesse, T.Y.; Di Pasquale, V.; Riemma, S. Digital Twin Models in Industrial Operations: State-of-the-Art and Future Research Directions. *IET Collab. Intell. Manuf.* **2021**, *3*, 37–47. [CrossRef]
4. Koulouris, A.; Misailidis, N.; Petrides, D. Applications of Process and Digital Twin Models for Production Simulation and Scheduling in the Manufacturing of Food Ingredients and Products. *Food Bioprod. Process.* **2021**, *126*, 317–333. [CrossRef]
5. Eppinger, T.; Longwell, G.; Mas, P.; Goodheart, K. Increase Food Production Efficiency Using the Executable Digital Twin (XDT). *Chem. Eng. Trans.* **2021**, *87*, 37–42. [CrossRef]
6. Supply Chain Digital Twins: Definition, the Problems They Solve, and How to Develop Them. Available online: https://www.anylogistix.com/features/supply-chain-digital-twins/ (accessed on 27 December 2022).
7. Busse, A.; Gerlach, B.; Lengeling, J.C.; Poschmann, P.; Werner, J.; Zarnitz, S. Towards Digital Twins of Multimodal Supply Chains. *Logistics* **2021**, *5*, 25. [CrossRef]
8. Wang, Y.; Wang, X.; Liu, A. Digital Twin-Driven Supply Chain Planning. *Procedia CIRP* **2020**, *93*, 198–203. [CrossRef]
9. Fuller, A.; Fan, Z.; Day, C.; Barlow, C. Digital Twin: Enabling Technologies, Challenges and Open Research. *IEEE Access* **2020**, *8*, 108952–108971. [CrossRef]
10. Stecken, J.; Ebel, M.; Bartelt, M.; Poeppelbuss, J.; Kuhlenkötter, B. Digital Shadow Platform as an Innovative Business Model. *Procedia CIRP* **2019**, *83*, 204–209. [CrossRef]
11. Tseng, G.W.G.; Chen, C.Q.G.; Erkorkmaz, K.; Engin, S. Digital Shadow Identification from Feed Drive Structures for Virtual Process Planning. *CIRP J. Manuf. Sci. Technol.* **2019**, *24*, 55–65. [CrossRef]

12. Vogt, A.; Schmidt, P.H.; Mayer, S.; Stark, R. Production in the Loop-the Interoperability of Digital Twins of the Product and the Production System. *Procedia CIRP* **2021**, *99*, 561–566. [CrossRef]
13. Bamunuarachchi, D.; Georgakopoulos, D.; Banerjee, A.; Jayaraman, P.P. Digital Twins Supporting Efficient Digital Industrial Transformation. *Sensors* **2021**, *21*, 6829. [CrossRef]
14. Kalaboukas, K.; Rožanec, J.; Košmerlj, A.; Kiritsis, D.; Arampatzis, G. Implementation of Cognitive Digital Twins in Connected and Agile Supply Networks-an Operational Model. *Appl. Sci.* **2021**, *11*, 4103. [CrossRef]
15. Defraeye, T.; Shrivastava, C.; Berry, T.; Verboven, P.; Onwude, D.; Schudel, S.; Bühlmann, A.; Cronje, P.; Rossi, R.M. Digital Twins Are Coming: Will We Need Them in Supply Chains of Fresh Horticultural Produce? *Trends Food Sci. Technol.* **2021**, *109*, 245–258. [CrossRef]
16. Henrichs, E.; Noack, T.; Krupitzer, C.; María, A.; Piedrahita, P.; Salem, M.A.; Stolz, J. Can a Byte Improve Our Bite? An Analysis of Digital Twins in the Food Industry. *Sensors* **2021**, *22*, 115. [CrossRef] [PubMed]
17. Pylianidis, C.; Osinga, S.; Athanasiadis, I.N. Introducing Digital Twins to Agriculture. *Comput. Electron. Agric.* **2021**, *184*, 105942. [CrossRef]
18. Verboven, P.; Defraeye, T.; Datta, A.K.; Nicolai, B. Digital Twins of Food Process Operations: The next Step for Food Process Models? *Curr. Opin. Food Sci.* **2020**, *35*, 79–87. [CrossRef]
19. Moshood, T.D.; Nawanir, G.; Sorooshian, S.; Okfalisa, O. Digital Twins Driven Supply Chain Visibility within Logistics: A New Paradigm for Future Logistics. *Appl. Syst. Innov.* **2021**, *4*, 29. [CrossRef]
20. Lezoche, M.; Panetto, H.; Kacprzyk, J.; Hernandez, J.E.; Alemany Díaz, M.M.E. Agri-Food 4.0: A Survey of the Supply Chains and Technologies for the Future Agriculture. *Comput. Ind.* **2020**, *117*, 103187. [CrossRef]
21. Zarnitz, S.; Straube, F.; Nitsche, B. *Digital Supply Chain Twins for Sustainable Planning of a Logistics System*; Springer International Publishing: Berlin/Heidelberg, Germany, 2023; ISBN 9783031288395.
22. Burgos, D.; Ivanov, D. Food Retail Supply Chain Resilience and the COVID-19 Pandemic: A Digital Twin-Based Impact Analysis and Improvement Directions. *Transp. Res. Part E Logist. Transp. Rev.* **2021**, *152*, 102412. [CrossRef]
23. Violi, A.; De Maio, A.; Fattoruso, G.; Olivieri, M.G. An Age-Based Dynamic Approach for Distribution of Perishable Commodities with Stochastic Demands. *Soft Comput.* **2023**, *27*, 7039–7050. [CrossRef]
24. Gerlach, B.; Zarnitz, S.; Nitsche, B.; Straube, F. Digital supply chain Twins—Conceptual clarification, use cases and benefits. *Logistics* **2021**, *5*, 86. [CrossRef]
25. Perez, H.D.; Amaran, S.; Erisen, E.; Wassick, J.M.; Grossmann, I.E. A Digital Twin Framework for Business Transactional Processes in Supply Chains. *Comput. Aided Chem. Eng.* **2021**, *50*, 1755–1760.
26. Melesse, T.Y.; Bollo, M.; Di Pasquale, V.; Riemma, S. Digital Twin for Inventory Planning of Fresh Produce. *IFAC-Pap.* **2022**, *55*, 2743–2748. [CrossRef]
27. Attaran, M.; Celik, B.G. Digital Twin: Benefits, Use Cases, Challenges, and Opportunities. *Decis. Anal. J.* **2023**, *6*, 100165. [CrossRef]
28. Verdouw, C.N.; Wolfert, J.; Beulens, A.J.M.; Rialland, A. Virtualization of Food Supply Chains with the Internet of Things. *J. Food Eng.* **2016**, *176*, 128–136. [CrossRef]
29. Agrawal, T.K.; Kalaiarasan, R.; Olhager, J.; Wiktorsson, M. Understanding Supply Chain Visibility Through Experts' Perspective: A Delphi Based Approach. In *Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems, Proceedings of the IFIP WG 5.7 International Conference, APMS 2021, Nantes, France, 5–9 September 2021*; Springer: Cham, Switzerland, 2021; Volume 633, ISBN 9783030859091.
30. Dyck, G.; Hawley, E.; Hildebrand, K.; Paliwal, J. Digital Twins: A Novel Traceability Concept for Post-Harvest Handling. *Smart Agric. Technol.* **2023**, *3*, 100079. [CrossRef]
31. Melesse, T.Y.; Bollo, M.; Di Pasquale, V.; Centro, F.; Riemma, S. Machine Learning-Based Digital Twin for Monitoring Fruit Quality Evolution. *Procedia Comput. Sci.* **2022**, *200*, 13–20. [CrossRef]
32. Zou, Z.; Chen, Q.; Uysal, I.; Zheng, L. Radio Frequency Identification Enabled Wireless Sensing for Intelligent Food Logistics. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2014**, *372*, 20130313. [CrossRef] [PubMed]
33. Jedermann, R.; Nicometo, M.; Uysal, I.; Lang, W. Reducing Food Losses by Intelligent Food Logistics. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2014**, *372*, 20130302. [CrossRef]
34. Chergui, N.; Kechadi, M.T.; McDonnell, M. The Impact of Data Analytics in Digital Agriculture: A Review. In Proceedings of the International Multi-Conference on Organization of Knowledge and Advanced Technologies, OCTA 2020, Tunis, Tunisia, 6–8 February 2020. [CrossRef]
35. Jo, S.K.; Park, D.H.; Park, H.; Kim, S.H. Smart Livestock Farms Using Digital Twin: Feasibility Study. In Proceedings of the 2018 International Conference on Information and Communication Technology Convergence (ICTC), Jeju Island, Republic of Korea, 17–19 October 2018; pp. 1461–1463. [CrossRef]
36. Mishra, S.; Sharma, S.K. Advanced Contribution of IoT in Agricultural Production for the Development of Smart Livestock Environments. *Internet Things* **2023**, *22*, 100724. [CrossRef]
37. Verdouw, C.; Tekinerdogan, B.; Beulens, A.; Wolfert, S. Digital Twins in Smart Farming. *Agric. Syst.* **2021**, *189*, 103046. [CrossRef]
38. Purcell, W.; Neubauer, T. Digital Twins in Agriculture: A State-of-the-Art Review. *Smart Agric. Technol.* **2023**, *3*, 100094. [CrossRef]
39. Ariesen-Verschuur, N.; Verdouw, C.; Tekinerdogan, B. Digital Twins in Greenhouse Horticulture: A Review. *Comput. Electron. Agric.* **2022**, *199*, 107183. [CrossRef]

40. Torres-Sánchez, R.; Martínez-Zafra, M.T.; Castillejo, N.; Guillamón-Frutos, A.; Artés-Hernández, F. Real-Time Monitoring System for Shelf Life Estimation of Fruit and Vegetables. *Sensors* **2020**, *20*, 1860. [CrossRef]
41. Haji, M.; Kerbache, L.; Muhammad, M.; Al-Ansari, T. Roles of Technology in Improving Perishable Food Supply Chains. *Logistics* **2020**, *4*, 33. [CrossRef]
42. Ghandar, A.; Ahmed, A.; Zulfiqar, S.; Hua, Z.; Hanai, M.; Theodoropoulos, G. A Decision Support System for Urban Agriculture Using Digital Twin: A Case Study with Aquaponics. *IEEE Access* **2021**, *9*, 35691–35708. [CrossRef]
43. Thomé, A.M.T.; Scavarda, L.F.; Scavarda, A.J. Conducting Systematic Literature Review in Operations Management. *Prod. Plan. Control* **2016**, *27*, 408–420. [CrossRef]
44. Shrivastava, C.; Berry, T.; Cronje, P.; Schudel, S.; Defraeye, T. Digital Twins Enable the Quantification of the Trade-Offs in Maintaining Citrus Quality and Marketability in the Refrigerated Supply Chain. *Nat. Food* **2022**, *3*, 413–427. [CrossRef]
45. Shoji, K.; Schudel, S.; Onwude, D.; Shrivastava, C.; Defraeye, T. Mapping the Postharvest Life of Imported Fruits from Packhouse to Retail Stores Using Physics-Based Digital Twins. *Resour. Conserv. Recycl.* **2022**, *176*, 105914. [CrossRef]
46. Tagliavini, G.; Defraeye, T.; Carmeliet, J. Multiphysics Modeling of Convective Cooling of Non-Spherical, Multi-Material Fruit to Unveil Its Quality Evolution throughout the Cold Chain. *Food Bioprod. Process.* **2019**, *117*, 310–320. [CrossRef]
47. Krupitzer, C.; Noack, T.; Borsum, C. Digital Food Twins Combining Data Science and Food Science: System Model, Applications, and Challenges. *Processes* **2022**, *10*, 1781. [CrossRef]
48. Defraeye, T.; Tagliavini, G.; Wu, W.; Prawiranto, K.; Schudel, S.; Assefa, M.; Verboven, P.; Bühlmann, A.; Assefa Kerisima, M.; Verboven, P.; et al. Digital Twins Probe into Food Cooling and Biochemical Quality Changes for Reducing Losses in Refrigerated Supply Chains. *Resour. Conserv. Recycl.* **2019**, *149*, 778–794. [CrossRef]
49. Vallejo, M.E.; Larios, V.M.; Magallanes, V.G.; Cobian, C.; De La Luz Guzman Castaneda, M.; Tellez, G.B. Creating Resilience for Climate Change in Smart Cities Based on the Local Food Supply Chain. In Proceedings of the 2021 IEEE International Smart Cities Conference (ISC2), Online, 7–10 September 2021. [CrossRef]
50. Wang, L.; Li, L.; Zhou, Q. Established Digital Model of Fruit Body Growth of Agrocybe Cylindracea Based on Network Programming. *Discret. Dyn. Nat. Soc.* **2021**, *2021*, 6643273. [CrossRef]
51. Keates, O. The Design and Validation of a Process Data Analytics Methodology for Improving Meat and Livestock Value Chains. In Proceedings of the 17th International Conference on Business Process Management (BPM 2019), Vienna, Austria, 1–6 September 2019; Volume 2420.
52. Sung, Y.M.; Kim, T. Smart Farm Realization Based on Digital Twin. *ICIC Express Lett. Part B Appl.* **2022**, *13*, 421–427. [CrossRef]
53. Bottani, E.; Vignali, G.; Carlo Tancredi, G.P. A Digital Twin Model of a Pasteurization System for Food Beverages: Tools and Architecture. In Proceedings of the IEEE International Conference on Engineering, Technology, and Innovation, ICE/ITMC 2020, Virtual Conference, 15–17 June 2020; pp. 1–3. [CrossRef]
54. Vignali, G.; Bottani, E. A Tube-in-Tube Food Pasteurizer Modelling for a Digital Twin Application. In Proceedings of the 6th International Food Operations and Processing Simulation Workshop (FoodOPS 2020), Online, 16–18 September 2020; pp. 30–36. [CrossRef]
55. Shoji, K.; Schudel, S.; Shrivastava, C.; Onwude, D.; Defraeye, T. Optimizing the Postharvest Supply Chain of Imported Fresh Produce with Physics-Based Digital Twins. *J. Food Eng.* **2022**, *329*, 111077. [CrossRef]
56. Leithner, M.; Fikar, C. A Simulation Model to Investigate Impacts of Facilitating Quality Data within Organic Fresh Food Supply Chains. *Ann. Oper. Res.* **2019**, *314*, 529–550. [CrossRef]
57. Nasirahmadi, A.; Hensel, O. Toward the Next Generation of Digitalization in Agriculture Based on Digital Twin Paradigm. *Sensors* **2022**, *22*, 498. [CrossRef] [PubMed]
58. Qi, Q.; Tao, F.; Hu, T.; Anwer, N.; Liu, A.; Wei, Y.; Wang, L.; Nee, A.Y.C.C. Enabling Technologies and Tools for Digital Twin. *J. Manuf. Syst.* **2021**, *58*, 3–21. [CrossRef]
59. Abideen, A.Z.; Sundram, V.P.K.; Pyeman, J.; Othman, A.K.; Sorooshian, S. Digital Twin Integrated Reinforced Learning in Supply Chain and Logistics. *Logistics* **2021**, *5*, 84. [CrossRef]
60. Onwude, D.I.; Chen, G.; Eke-Emezie, N.; Kabutey, A.; Khaled, A.Y.; Sturm, B. Recent Advances in Reducing Food Losses in the Supply Chain of Fresh Agricultural Produce. *Processes* **2020**, *8*, 1431. [CrossRef]
61. Sanchez-Londono, D.; Barbieri, G.; Fumagalli, L. Smart Retrofitting in Maintenance: A Systematic Literature Review. *J. Intell. Manuf.* **2022**, *34*, 1–19. [CrossRef]
62. Marquardt, T.; Cleophas, C.; Morgan, L. Indolence Is Fatal: Research Opportunities in Designing Digital Shadows and Twins for Decision Support. In Proceedings of the 2021 Winter Simulation Conference, Brussels, Belgium, 10–13 December 2021. [CrossRef]
63. Jayalath, M.M.; Perera, H.N. Mapping Post-Harvest Waste in Perishable Supply Chains through System Dynamics: A Sri Lankan Case Study. *J. Agric. Sci.-Sri Lanka* **2021**, *16*, 526–543. [CrossRef]
64. Veerakachen, W.; Raksapatcharawong, M. RiceSAP: An Efficient Satellite-Based AquaCrop Platform for Rice Crop Monitoring and Yield Prediction on a Farm—To Regional-Scale. *Agronomy* **2020**, *10*, 858. [CrossRef]
65. Zou, G.; Tang, J.; Yilmaz, L.; Kong, X. Online Food Ordering Delivery Strategies Based on Deep Reinforcement Learning. *Appl. Intell.* **2022**, *52*, 6853–6865. [CrossRef]
66. Sarjoughian, H.S. DEVS-scripting: A black-box test frame for DEVS models. In Proceedings of the 2020 Winter Simulation Conference, Orlando, FL, USA, 14–18 December 2020.

67. Cai, X.; Zhang, H.; Li, Q. Analysis and Design of Smart Cold Chain Logistics Simulation Model Based on Internet of Things Technology. In Proceedings of the 2022 IEEE Asia-Pacific Conference on Image Processing, Electronics and Computers (IPEC2022), Dalian, China, 14–16 April 2022; pp. 1352–1356. [CrossRef]
68. Tebaldi, L.; Vignali, G.; Bottani, E. Digital Twin in the Agri-Food Supply Chain: A Literature Review. In *Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems, Proceedings of the IFIP WG 5.7 International Conference, APMS 2021, Nantes, France, 5–9 September 2021*; Springer International Publishing: Cham, Switzerland, 2021; Volume 633, ISBN 9783030859091.
69. Sharma, A.; Zanotti, P.; Musunur, L.P. Drive through Robotics: Robotic Automation for Last Mile Distribution of Food and Essentials during Pandemics. *IEEE Access* **2020**, *8*, 127190–127219. [CrossRef]
70. Ivanov, D.; Dolgui, A. A Digital Supply Chain Twin for Managing the Disruption Risks and Resilience in the Era of Industry 4.0. *Prod. Plan. Control* **2021**, *32*, 775–788. [CrossRef]
71. Rahman, M.M.; Nguyen, R.; Lu, L. Multi-Level Impacts of Climate Change and Supply Disruption Events on a Potato Supply Chain: An Agent-Based Modeling Approach. *Agric. Syst.* **2022**, *201*, 103469. [CrossRef]
72. Perdana, T.; Chaerani, D.; Achmad, A.L.H. Supporting Data for the Integrated Agent-Based Modelling and Robust Optimization on Food Supply Network Design in COVID-19 Pandemic. *Data Br.* **2022**, *40*, 107809. [CrossRef] [PubMed]
73. Kazancoglu, Y.; Ekinci, E.; Mangla, S.K.; Sezer, M.D.; Kayikci, Y. Performance Evaluation of Reverse Logistics in Food Supply Chains in a Circular Economy Using System Dynamics. *Bus. Strateg. Environ.* **2021**, *30*, 71–91. [CrossRef]
74. Hernández, J.M.; Pedroza-Gutiérrez, C. Estimating the Influence of the Network Topology on the Agility of Food Supply Chains. *PLoS ONE* **2019**, *14*, e0218958. [CrossRef]
75. Herrera, M.M.; Orjuela-Castro, J. An Appraisal of Traceability Systems for Food Supply Chains in Colombia. *Int. J. Food Syst. Dyn.* **2021**, *12*, 37–50. [CrossRef]
76. Singh, S.; Kumar, R.; Panchal, R.; Tiwari, M.K. Impact of COVID-19 on Logistics Systems and Disruptions in Food Supply Chain. *Int. J. Prod. Res.* **2021**, *59*, 1993–2008. [CrossRef]
77. Suryani, E.; Hendrawan, R.A.; Muhandhis, I.; Indraswari, R. A Simulation Model to Improve the Value of Rice Supply Chain (A Case Study in East Java–Indonesia). *J. Simul.* **2022**, *16*, 392–414. [CrossRef]
78. Zhu, Q.; Krikke, H. Managing a Sustainable and Resilient Perishable Food Supply Chain (PFSC) after an Outbreak. *Sustainability* **2020**, *12*, 5004. [CrossRef]
79. Yuan, Y.; Viet, N.; Behdani, B. The Impact of Information Sharing on the Performance of Horizontal Logistics Collaboration: A Simulation Study in an Agri-Food Supply Chain. *IFAC-Pap.* **2019**, *52*, 2722–2727. [CrossRef]
80. Ambekar, S.; Kapoor, R. Optimization of Inventory Policies of Food Grain Distribution Stage in Public Distribution System. *Benchmarking* **2019**, *26*, 692–713. [CrossRef]
81. Mittal, A.; Krejci, C.C. A Hybrid Simulation Modeling Framework for Regional Food Hubs. *J. Simul.* **2019**, *13*, 28–43. [CrossRef]
82. Almeder, C.; Preusser, M. A Hybrid Simulation Optimization Approach for Supply Chains. *Congr. Model. Simul.* **2007**, *2007*, 9–13.
83. Ortúzar, J.E.; Dogan, O.B.; Sotomayor, G.; Jiménez, C.; Clarke, J.; Flores, R.A.; Gray, G.M.; Rupnow, J.H.; Wang, B. Quantitative Assessment of Microbial Quality and Safety Risk: A Preliminary Case Study of Strengthening Raspberry Supply System in Chile. *Food Control* **2020**, *113*, 107166. [CrossRef]
84. Feng, J.; Zeng, L.; He, L. Apple Fruit Recognition Algorithm Based on Multi-Spectral Dynamic Image Analysis. *Sensors* **2019**, *19*, 949. [CrossRef] [PubMed]
85. Gurupatham, S.; Fahad, F.; Hudlow, A. *Improving Shelf-Life of Fruits Using Thermography*; Kennesaw State University: Kennesaw, GA, USA, 2018; pp. 1–6.
86. Manickavasagan, A.; White, N.D.G. Applications of Thermal Imaging in Agriculture—A Review. *Can. Soc. Eng. Agric. Food Biol. Syst.* **2005**, 1–11.
87. Ferreira, D.S. Thermal Imaging as a Tool in Food Analysis. *J. Spectr. Imaging* **2020**, *9*, a7. [CrossRef]
88. Jiao, L.Z.; Wu, W.B.; Zheng, W.G.; Dong, D.M. The Infrared Thermal Image-Based Monitoring Process of Peach Decay under Uncontrolled Temperature Conditions. *J. Anim. Plant Sci.* **2015**, *25*, 202–207.
89. Smith, M.J. Getting Value from Artificial Intelligence in Agriculture. *Anim. Prod. Sci.* **2019**, *60*, 46–54. [CrossRef]
90. Pal, A.; Kant, K. Smart Sensing, Communication, and Control in Perishable Food Supply Chain. *ACM Trans. Sens. Netw.* **2020**, *16*, 1–41. [CrossRef]
91. Rehman, A.; Saba, T.; Kashif, M.; Fati, S.M.; Bahaj, S.A.; Chaudhry, H. A Revisit of Internet of Things Technologies for Monitoring and Control Strategies in Smart Agriculture. *Agronomy* **2022**, *12*, 127. [CrossRef]
92. Purcell, W.; Neubauer, T.; Mallinger, K. Digital Twins in Agriculture: Challenges and Opportunities for Environmental Sustainability. *Curr. Opin. Environ. Sustain.* **2023**, *61*, 101252. [CrossRef]
93. Wanasinghe, T.R.; Wroblewski, L.; Petersen, B.K.; Gosine, R.G.; James, L.A.; De Silva, O.; Mann, G.K.I.; Warrian, P.J. Digital Twin for the Oil and Gas Industry: Overview, Research Trends, Opportunities, and Challenges. *IEEE Access* **2020**, *8*, 104175–104197. [CrossRef]
94. Schleich, B.; Anwer, N.; Mathieu, L.; Wartzack, S. Shaping the Digital Twin for Design and Production Engineering. *CIRP Ann.-Manuf. Technol.* **2017**, *66*, 141–144. [CrossRef]
95. Tzachor, A.; Richards, C.E.; Jeen, S. Transforming Agrifood Production Systems and Supply Chains with Digital Twins. *Npj Sci. Food* **2022**, *6*, 47. [CrossRef] [PubMed]

96. Lohtander, M.; Garcia, E.; Lanz, M.; Volotinen, J.; Ratava, J.; Kaakkunen, J. Micro Manufacturing Unit—Creating Digital Twin Objects with Common Engineering Software. *Procedia Manuf.* **2018**, *17*, 468–475. [CrossRef]
97. Kamble, S.S.; Gunasekaran, A.; Parekh, H.; Mani, V.; Belhadi, A.; Sharma, R. Digital Twin for Sustainable Manufacturing Supply Chains: Current Trends, Future Perspectives, and an Implementation Framework. *Technol. Forecast. Soc. Chang.* **2022**, *176*, 121448. [CrossRef]

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Systematic Review

Warehouse Management Systems for Social and Environmental Sustainability: A Systematic Literature Review and Bibliometric Analysis

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Abstract: *Background*: With the continuing growth of warehouses globally, there is an increasing need for sustainable logistics solutions in warehousing, but research linking warehouse management systems (WMS) and sustainability is lacking. *Methods:* A systematic literature review and bibliometric analysis were conducted in Scopus and Web of Science databases from 2006 to 2022 to investigate academic knowledge of WMS contributing to warehouses' social and environmental sustainability. *Results*: Findings revealed only 12 topic-relevant articles from 2013 to 2022, primarily published recently. More recent articles have received more citations than earlier published works. The articles were from multiple research fields, such as business economics, engineering, computer science, and social sciences, with only one article on environmentally sustainable technologies. The top keywords were "warehouse management system", "internet of things", "industry 4.0" and "supply chain". Only six articles had environmental sustainability terms in the keywords. Findings show more discussions about social rather than environmental sustainability. Most studies suggest integrating WMS with other systems to support sustainability efforts in warehousing. *Conclusions*: The study addressed a gap in academic literature regarding WMS and sustainability. Research findings added knowledge of practical activities to achieve warehouse operations and performance sustainability and proactively reduce warehouse operations' environmental and social impacts.

Keywords: warehouse management system; wms; social; environment; sustainability; systematic literature review; bibliometric analysis; PRISMA; digitalization

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Citation: Minashkina, D.; Happonen, A. Warehouse Management Systems for Social and Environmental Sustainability: A Systematic Literature Review and Bibliometric Analysis. *Logistics* **2023**, *7*, 40. https://doi.org/10.3390/logistics7030040

Academic Editors: Benjamin Nitsche, Frank Straube and Robert Handfield

Received: 20 March 2023
Revised: 30 May 2023
Accepted: 26 June 2023
Published: 7 July 2023

1. Introduction

The need for environmentally friendly logistics solutions is growing as circumstances dictate large-scale actions to reduce global emissions, natural resource consumption, and waste generation. Global greenhouse gas (GHG) emissions keep scaling up, despite the most significant CO_2 emission drop (8.8%) in history [1] because of the COVID-19 pandemic. As the pandemic compelled people to stay home from work and education and restricted access to shops, the volume of materials in supply chains (SCs) has significantly increased. Simultaneously, companies are transitioning from asset producers to service solutions and digitalization experts, reducing physical asset output [2]. Several countries have already pledged to achieve carbon neutrality in the near future, reducing GHG emissions and combating global warming [3,4]. In the target of reducing global emissions, any wide-scale improvements, performance enhancement [5], and application of green management practices [6] on the sustainability front inside SC and logistics can directly affect the global reduction of CO_2 emissions [7]. According to ref. [8], SCs are often responsible for over 75% of GHG emissions. Half of global GHG is from the top eight global SCs in fast-moving consumer goods, food, fashion, electronics, professional services, construction, automotive, and freight [9]. Research by the World Economic Forum and Boston Consulting Group found that SC decarbonization offers a game-changing opportunity for companies to fight against climate change [9]. Technology is the most popular tool business companies use to improve sustainability performance [10]. Moreover, rapid technological progress presents a chance to harness the power of digitalization and technologization to tackle sustainability challenges [11] and actively pursue a transition toward sustainability [12].

The positive intersection of Industry 4.0 technologies and sustainable warehousing is a topic of research interest [13] to contribute to achieving the Sustainable Development Goals (SDGs) set by the United Nations (UN) [14]. A warehouse, being an indispensable part of the SC and playing a vital strategic role in logistics, generates significant sustainability impacts by consuming energy and resources [15]. Logistics buildings alone account for approximately 10% of total CO_2 emissions in the logistics and transport sectors (2800 CO_2 megatons) [16]. To reduce carbon intensity, ref. [17] addresses the development of GHG assessment and allocation methods in a logistics facility in the form of environmental performance indicators. The International Warehouse Logistics Association, together with the Sustainable Supply Chain Foundation, introduces sustainable initiatives and standards development for the warehousing industry to enhance real SC sustainability [18]. Ref. [19] research a warehouse's more profoundly environmental performance indicators and assign them to primary warehouse operations (receiving/shipping, put-away/storage/picking, cross-docking/sorting, and others) and provide examples of such CO_2 emissions. Analyzing warehouse emission scenarios, ref. [20] points out that the research in warehousing pays only scarce attention to the environmental impact of warehousing operations. Ref. [13] also concludes that both warehouse equipment technologies, together with the usage of greener energy sources, can reduce or even prevent the increase in CO_2. Ref. [21] shows how inner transportation in a warehouse can optimize sustainability to decrease nearly 60% of warehouse waste (such as redundant forklift driving and operations). Ref. [22] design and weigh the importance of 30 sustainable warehouse key performance indicators (KPIs) in economic, environmental, and social dimensions for sustainable warehousing. One of the technologies that can decarbonize warehouse activities is a warehouse management system (WMS) [23].

A warehouse management system (WMS) is an IT software solution for handling and optimizing warehouse logistics activities and supporting warehouse process automation. According to VDI guideline 3601, published by The Association of German Engineers [24], WMS is: "management, control, and optimization of storage and distribution using a software system (including storage and storage management, as well as the management and administration of the equipment), with extensive methods and means for checking the system conditions and with a selection of operational and optimization strategies to manage and optimize in-house storage and transport systems". Drawing a simple analogy, WMS does the same for warehousing as ERP does for a company in operations and asset management. Thus, WMS plays a significant role in the planning and operations of warehouse logistics [25]. Furthermore, as an information system, WMS supports specific warehouse management operations [26]. Even though the concept of sustainability in warehousing has shown signs of increasing academic attention, the actual role of WMS as a tool to bring sustainability to warehouse activities is still not a well-studied field. Ref. [27] defined KPIs for a sustainable WMS by mapping indicators of warehouse management according to the triple-bottom-line approach.

This research offers a structured and comprehensive overview of area-specific research and warehouse sustainability in the academic literature to understand and map the current status of research. As a limitation, the financial benefits of WMS for warehouse operators, WMS definition, environmentally friendly materials for warehouse building construction, and renewable energy utilization in warehouses lie beyond the scope of this research. Our findings help researchers and practitioners identify research gaps in WMS and sustainability and reveal ways academic research has shown directions to utilize WMS for positive sustainability contributions.

This research addresses the following research questions based on the literature.

RQ1: What are current academic research directions and focus areas on WMS and sustainability?
RQ2: What is the current state of the art in WMS and sustainability-related literature?

The research data collection and analysis undertaken in the study are based on a mixed methodology of systematic literature review (SLR) and bibliometric analysis. These research methods are used to cover the research gap by conducting SLR with biometric analysis concerning the research area of WMS and sustainability. SLR helps to answer the first RQ, while bibliometric analysis is conducted to answer the second RQ.

2. Research Design

To answer the set RQ, the choice of SLR over a formal literature review was based on a need to remove potential biases caused by the author's subjectivity and guarantee good baseline work for further research replications [28]. According to [29], SLR helps to identify, evaluate, and interpret all available literature related to the research topic, being at the top of the hierarchy of research evidence [30–32]. Providing a rigorous process of theoretical synthesis of already published literature on the topic, SLR can advance both academic and practitioner communities in pragmatic management research [33]. To ensure transparency and repetitiveness of the research, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was applied [34].

Following the SLR guidance by [35], the first step of defining the research purpose and research-specific questions was covered in the introduction and research methodology sections. In the second stage, the research implementation states inclusion and exclusion criteria. Ref. [33] also emphasizes the importance of a review protocol to provide a transparent and high-quality research process. This study focused purely on peer-reviewed academic journal articles written in English. A preference was expressed for peer-reviewed articles because of their high-quality contributions and rigorous research validation practices. This decision was supported by [28,36], who strongly recommend focusing on peer-reviewed articles in SLRs to avoid the use of gray literature sources (such as some working papers, conference proceedings, books, etc.).

For the timeframe, articles from 2006 to 2023 were included. Even though the oft-quoted "sustainable development" terminology was already introduced in the 1980s [37], there are reasons for setting timeframes. For example, ref. [38] proposes a 22-criteria concept model to assess warehouse sustainability based on the analyzed literature on sustainable warehouses dating from the earliest study in 2008. In an in-depth analysis of the literature on green warehousing, ref. [39] emphasizes the trend to publish studies on this topic in 2006. Thus, for this research, literature was gathered by searching the databases at set time points until the 8th of May 2023 to withdraw all possible recent mentions of WMS bringing sustainability. So, the publication timespan for this research was set from 2006 to June 2022.

The third step addressed database selection and defining/building keyword groups. In this research, the Web of Science (Core Collection) and Scopus (Elsevier) were used as online electronic databases to extract academic literature. According to ref. [40], these databases are recognized as academic search systems for systematic reviews, allowing evidence synthesis. Besides, these two databases were chosen for the search because of their multidisciplinary nature and essential common measures supporting the comparison of the academic results. Their data extraction features allow a proper bibliometric analysis [36]. Additionally, the Web of Science database has the most extensive systematic history of citation indexes. In contrast, the Scopus index has the most significant number of journals in all the different fields [41]. The results data was exported in CSV format files from databases and tabulated in Microsoft Excel for further data analysis, pairing, interpretation, and graph and figure visualizations.

Following the academic guidance for SLR, the focus was turned to determining keywords to collect the literature from the databases. With a proper selection of keywords, it is possible to include studies strongly contributing to the search results [33,42]. We started the keyword selection based on area-specific research to get a wide starting point. After an overview of WMS and warehousing-related publications, previous SLR studies on similar topics were briefly reviewed. Their keywords for collecting the literature were used to build our search baseline. The keywords were prioritized and grouped in a manner supporting a collection of research-specific relevant literature for future analysis steps.

Following the previous publications and the set of research questions, two main groups of keywords were developed: Group A ("warehouse management system"—1 keyword) and Group B (sustainability-related—33 keywords).

Table 1 presents the utilized keywords. The following parts of this publication explain a comprehensive description of the steps that resulted in this set of keywords. By combining keywords from Group A and B, all word combinations were considered to match them in databases for studies' titles, abstracts, or publications keywords. When possible, an asterisk (*) was applied to words to give more variations and scope in the literature-gathering phase.

Table 1. Group A ("warehouse management system"), Group B (words related to sustainability).

Group A	Group B		
"warehouse management system"	carbon	health*	resource*
	CO_2	"life cycle"	responsib*
	control*	renewabl*	revers*
	clean*	repair*	pollut*
	degrad*	reus*	prevent*
	eco	recover*	minimis*
	emission	recycl*	minimiz*
	energ*	reduc*	safe*
	environment*	regenerat*	social*
	ethic*	remanufactur*	sustain*
	green	report*	waste*

To map the current academic literature on WMS and sustainability, WMS is a core keyword component of the keywords set. In trial searches, it was found that using just the abbreviation "WMS" alone, without any explication connected to warehousing, tended to include a considerable number of non-related publications. The three-letter acronym "WMS" is widely used in academic literature and has multiple meanings, such as waste/water/workload management system, or wildlife/weather monitoring system, etc. For consistent and warehousing-connected results, we included only "warehouse management system" as a keyword in the main Group A to use in a follow-up search. To comprise sustainability keywords in Group B, we built keywords from a recent study by [39] on systematic analyses of green warehousing as comprehensive research and a summary of key knowledge of the green warehousing theme in literature. Plus, to enrich sustainability keyword selection and ensure complete coverage of sustainability terms, we extracted keywords from the study [43] on the classification of sustainability-oriented principles, approaches, and sub-systems to characterize sustainable development. More illustrations of the logic of building the 33 sustainability-related keywords from different academic works for Group B can be found in Appendix A. Appendix B presents the final keyword set combination used to collect literature from Scopus (Elsevier) and Web of Science (Core Collection) as a full-fledged query into the databases with field tags (searching matches in titles, abstracts, and keywords) and Booleans operators. After running selected keyword-based searches and filtering all results, we retrieved 133 and 73 journal articles written in English that were published in the period from the start of 2006 until the 8th of May 2023 in Scopus and Web of Science, respectively. These results were merged, leading to 206 studies without the removal of duplicates (Table 2).

Table 2. Publications search process in Scopus and Web of Science.

	Total	Eng	Journal Articles	2006–2022	Combined
SCOPUS	524	509	196	133	206
WoS	212	208	81	73	

After exporting results from Scopus and Web of Science databases, the PRISMA flow diagram was used to record further article analysis for review (Figure 1).

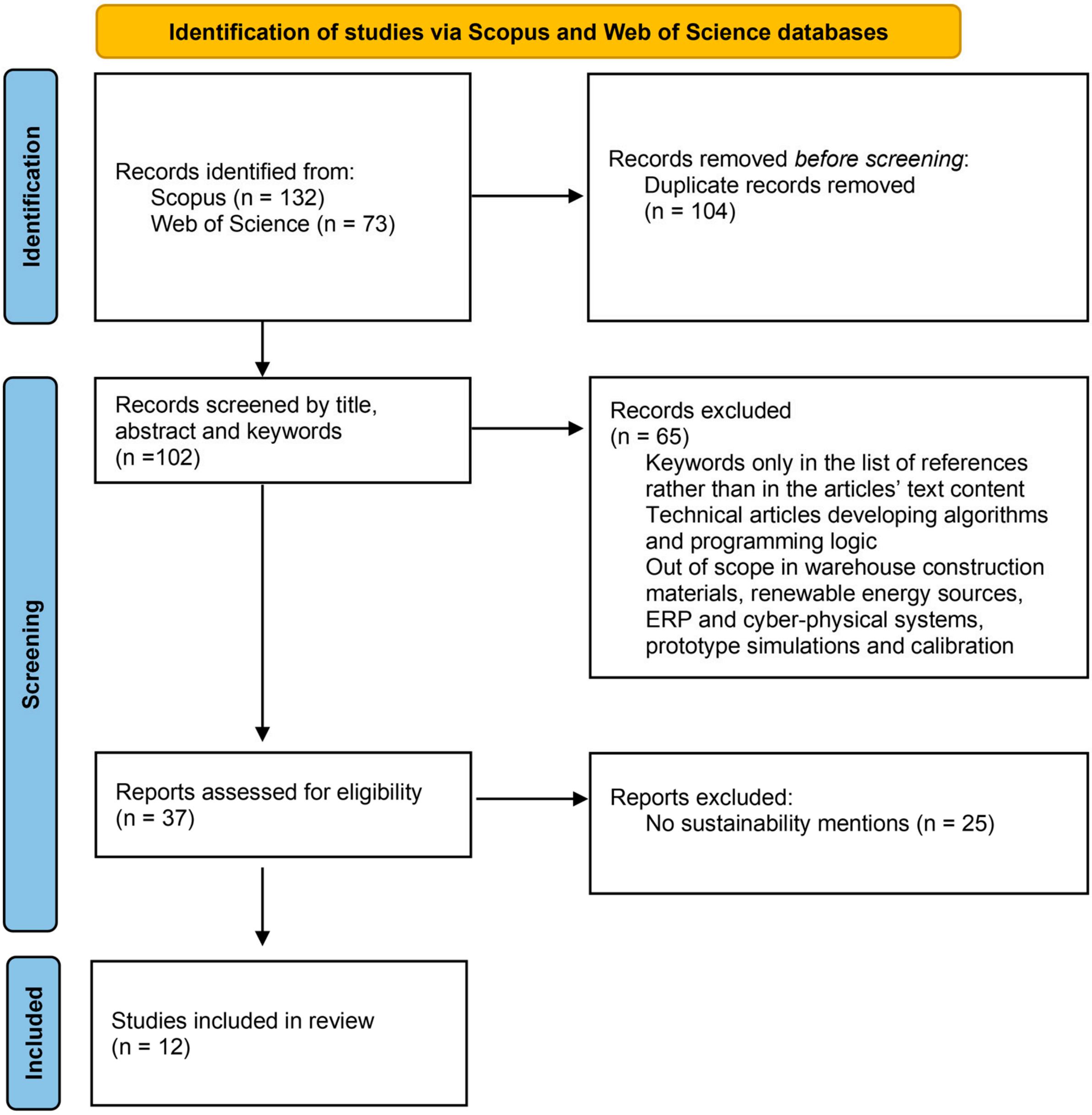

Figure 1. PRISMA 2020 flow diagram, adapted from [34].

Following the literature collection, the articles' relevance was determined by their titles and abstracts. If an article was not excluded based on its title, its abstract was analyzed to verify its WMS-specific contribution. Some articles were excluded because they appeared in the search results, having defined keywords only in the list of references rather than in the body of the article. This way, articles about ERP systems, information systems, cyber-physical systems, network optimization, prototype calibration, and dynamic simulations were excluded due to a lack of relevance. The same was true of too technical articles discussing, e.g., fuzzy analysis, data quality problems, integer programming, and generic algorithms. After passing all these review rounds, the remaining articles were comprehensively studied as the final phase of the article selection process. We verified that the article's content matched the set goals and research questions, which could help build a connection between WMS and sustainability. During this check, more than half of the articles had to be excluded from the final article list due to the absence of any exact sustainability mentions. Some articles discuss close topics to warehousing sustainability, for example, perishable products' shelf life and labor capacity, but only from the perspective of economic and operational efficiency. Thus, a working sample of 12 articles was obtained for descriptive content analysis.

3. Results

This section is divided into the descriptive and content analysis of 12 found articles shedding light on the topic of WMS and social and environmental sustainability. The descriptive analysis allows for describing the found dataset in a measurable form, while the content analysis synthesizes literature findings.

3.1. Descriptive Results

Table 3 shows main articles' details (authors, titles, published years) as well as reference citation numbers. Articles are sorted in the table in alphabetical order according to authors' names. Additionally, articles were assigned Roman index numbers from I to XII to ease the representation of a reference to one of the 12 articles in the follow-up tables and figures illustrations. Appendix C gathers the entire article's information.

Table 3. Brief 12 articles information and index numbers.

Index Number	Reference	Authors	Title	Year
I	[44]	Andelkovic A.; Radosavljevic M.	Improving Order-picking Process Through Implementation of Warehouse Management System	2018
II	[45]	Goomas D.T.; Yeow P.H.P.	IT-assisted equipment safety checks system to improve compliance: A case study at a distribution center	2013
III	[46]	Halawa F.; Dauod H.; Lee I.G.; Li Y.; Yoon S.W.; Chung S.H.	Introduction of a real time location system to enhance the warehouse safety and operational efficiency	2020
IV	[47]	Mostafa N.; Hamdy W.; Alawady H.	Impacts of internet of things on supply chains: A framework for warehousing	2019
V	[48]	Murauer N.; Pflanz N.	A full shift field study to evaluate user-and process-oriented aspects of smart glasses in automotive order-picking processes	2018
VI	[49]	Passalacqua M.; Léger P.-M.; Nacke L.E.; Fredette M.; Labonté-Lemoyne É.; Lin X.; Caprioli T.; Sénécal S.	Playing in the backstore: interface gamification increases warehousing workforce engagement	2020

Table 3. *Cont.*

Index Number	Reference	Authors	Title	Year
VII	[50]	Periša M.; Kuljanić T.M.; Cvitić I.; Kolarovszki P.	Conceptual model for informing user with innovative smart wearable device in industry 4.0	2019
VIII	[27]	Torabizadeh M.; Yusof N.M.; Ma'aram A.; Shaharoun A.M.	Identifying sustainable warehouse management system indicators and proposing new weighting method	2020
IX	[51]	Trab S.; Bajic E.; Zouinkhi A.; Thomas A.; Abdelkrim M.N.; Chekir H.; Ltaief R.H.	A communicating object's approach for smart logistics and safety issues in warehouses	2017
X	[52]	Trab S.; Zouinkhi A.; Bajic E.; Abdelkrim M.N.; Chekir H.	IoT-based risk monitoring system for safety management in warehouses	2018
XI	[53]	Hamdy W.; Al-Awamry A.; Mostafa N.	Warehousing 4.0: A proposed system of using node-red for applying internet of things in warehousing	2022
XII	[54]	Likhouzova T.; Demianova Y.	Robot path optimization in warehouse management system	2022

3.1.1. Analysis of Publishing Years

Even though the publications' timespan covered studies from 2006, the first relevant paper found was from 2013 (Figure 2), followed by a few years of publishing gaps. However, 2017 and the next three years received numerous research contributions. There was only one publication in 2021 and the first half of 2022. Given the standard lengthy academic publishing processes, it would be expected to see more contributions later in 2023. In short, most found publications were from 2018 to 2020, indicating the topic's freshness.

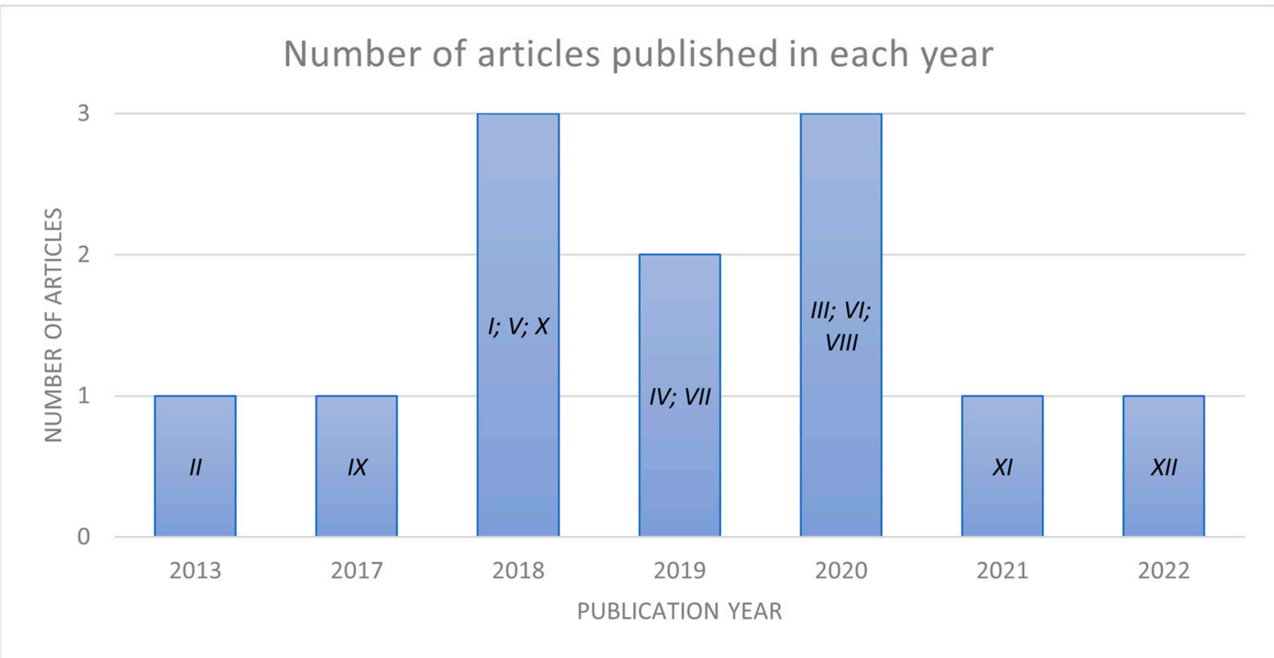

Figure 2. The number of publications discussing WMS and sustainability topics per year.

3.1.2. Research Areas and Subjects

Using the data tools from both Scopus and Web of Science, we were able to get ready-made base classification lists for the selected publications' research and subject areas. Figure 3 illustrates a pie chart of general research areas covered in 12 articles extracted from both databases indexing subjects. In addition, the pie chart provides indicators of what articles and how many were identified in a particular research category. One article could be identified in multiple research fields. Among the most significant shares came from the business economics and management field (seven articles).

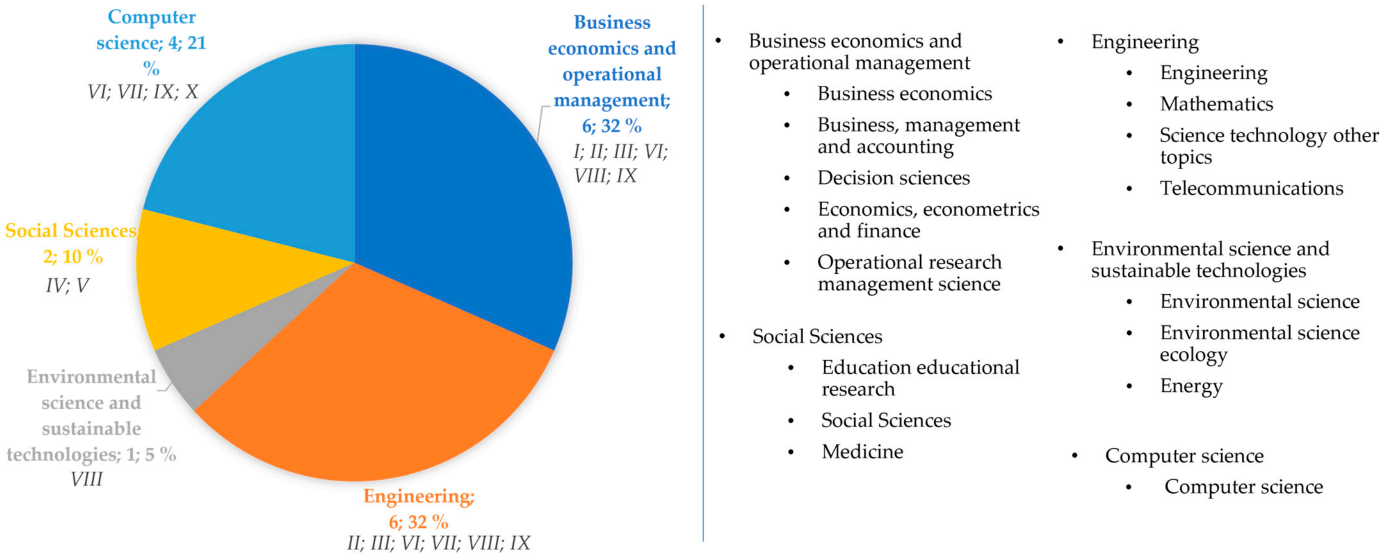

Figure 3. Selected articles research areas in the form of the pie chart (**left**) and precise research categorization (**right**).

Similarly, seven articles discussed engineering solutions for warehouse operations. Five articles focused on computer science. In a few articles in this research context, social science aspects were not yet touched on too much. Only one article was found to discuss environmentally sustainable technologies.

3.1.3. Research Methods Classification

To open up articles' material and identify what research methods best reflect their content, we identified and summarized research methodologies. Table 4 shows the research methods in each selected article based on five research methodologies (Table 5).

Table 4. Description of research methods adapted from [55–57].

Research Method	Description
Theoretical and conceptual literature review	development of a conceptual framework based on theory, standalone literature review, formulation of hypothesis, and practical applications are often lacking
Case study	examination of a phenomenon within its real-life context, investigating and verifying results in practice
Survey and interviews	questionnaires, interviews, collection of factual data about a subject, a research subject

Table 4. *Cont.*

Research Method	Description
Quantitative/mathematical/analytical model	simple numeric analysis (e.g., mean, percentage, and standard deviation, etc.), as well as more sophisticated analysis (e.g., linear regression, analytical model, simulation), are used
Simulation	experiments on the reaction of a model, software programs, and techniques

Table 5. Research methods classification of 12 articles adapted from [55–57].

Article's Index Number	Theoretical and Conceptual Literature Review	Case Study	Survey & Interviews	Quantitative/Mathematical/Analytical Model
I	X		X	
II	X	X	X	X
III	X	X		X
IV	X			
V	X	X	X	X
VI	X	X	X	X
VII	X			
VIII	X		X	X
IX	X			
X	X	X		
XI	X	X		X
XII	X			X

An article could be classified into multiple methodology categories depending on its characteristics. For example, the article [27] comprised only a theory review and model development. All articles had a literature review of their research topic. Five articles verified that their conceptual model developed in a real-life context. Likewise, studies tested their research hypothesis or theory by conducting interviews; half of the articles described software simulations, and seven included mathematical calculations.

3.1.4. Publication Channels

As an inclusion criterion, only articles published in journals were considered. Table 6 gathers journals' titles and the number of published articles in particular journals. There was no single published journal touching on both WMS and sustainability in more than one article. All journals were equal in the number of published articles (one per each). Based on the titles' scope, these journals generally focus on industrial engineering and management, sustainability, and social and computer sciences. Remarkably, there were no journals on the list with an emphasis on warehousing logistics, or WMS. Besides, most of the journals had a technical and business management focus.

Table 6. The list of journals and articles number published on the topic.

Articles' Index Number	Publication Journal	Number of Article(s)
IX	Concurrent Engineering Research and Applications	1
XII	Evolutionary Intelligence	1
VI	Industrial Management and Data Systems	1
V	Interaction Design and Architecture	1
X	International Journal of Information and Communication Technology	1
III	International Journal of Production Economics	1
VIII	Journal of Cleaner Production	1
XI	Sustainable Futures	1
II	Safety Science	1
IV	Social Sciences	1
I	Strategic Management	1
VII	Wireless Networks	1

3.1.5. Authorship Collaboration

In total, 41 authors contributed to the found publications set. Table 7 presents the list of these authors and the number of co-authorized publications. Only seven authors (grey-colored cells) contributed to two different articles. Other authors published/co-authored only one article.

Table 7. The full list of authors and numbers of co-authored publications.

Author	Article(s) Authorship	Author	Article(s) Authorship
Abdelkrim M.N.	2	Lee I.G.	1
Bajic E.	2	Léger P.-M.	1
Chekir H.	2	Li Y.	1
Hamdy W.	2	Likhouzova T.	1
Mostafa N.	2	Lin X.	1
Trab S.	2	Ltaief R.H.	1
Zouinkhi A.	2	Ma'aram A.	1
Alawady H.	1	Murauer N.	1
Al-Awamry, A.	1	Nacke L.E.	1
Andelkovic A.	1	Passalacqua M.	1
Caprioli T.	1	Periša M.	1
Chung S.H.	1	Pflanz N.	1
Cvitić I.	1	Radosavljevic M.	1
Dauod H.	1	Sénécal S.	1
Demianova Y.	1	Shaharoun A.M.	1
Fredette M.	1	Thomas A.	1
Goomas D.T.	1	Torabizadeh M.	1
Halawa F.	1	Yeow P.H.P.	1
Kolarovszki P.	1	Yoon S.W.	1
Kuljanić T.M.	1	Yusof N.M.	1
Labonté-Lemoyne É.	1		

Table 8 reports the number of authors per article and shows that most papers (33%) were written by two authors, followed by a collaboration of three and four authors (17% each). For the rest of the papers, there was no notable similarity in the number of co-authorships. None of the articles were written by a single author. The collaborations of more authors might be motivated by the increased number of researchers interested in the sustainability of warehousing operations using information management technologies such as WMSs.

Table 8. Authorship per publication.

Number of Authors per Article	Number of Articles	Percent
Two authors	4	33%
Three authors	2	17%
Four authors	2	17%
Five authors	1	8%
Seven authors	1	8%
Six authors	1	8%
Eight authors	1	8%

3.1.6. Countries of Faculties Where Authors Did the Contributing Research

Table 9 presents the list of 11 separate countries, including all academic faculties to which the authors contributed. Only five countries seemed to be more than a bit productive in this research direction. The United States is the first on the list, which can be just the correlative reality of the fact that the USA has more than a few of the largest warehouses in the world [58].

Table 9. The list of countries interested in WMS and sustainability topic search.

Countries	Article(s)	Percent
United States	3	25%
Egypt	2	17%
Malaysia	2	17%
France	2	17%
Tunisia	2	17%
Croatia	1	8%
Canada	1	8%
Germany	1	8%
Slovakia	1	8%
Saudi Arabia	1	8%
Ukraine	1	8%

3.1.7. Keywords Analysis

The keywords are expected to capture the main focus of the study [59]. The number of accepted keywords might be defined by the journals too. Table 10 reports the number of keywords per article. Nearly half of the articles had five keywords, one-fourth of the articles had four keywords, and an equal number of articles had seven keywords and six keywords, respectively.

Table 10. Keywords count among articles.

Keywords	Number of Articles	Percent
Five keywords	5	42%
Four keywords	3	25%
Seven keywords	2	17%
Six keywords	2	17%

The frequency of the keywords was accounted for to see the most commonly used keywords. Table 11 depicts the list of 49 unique keywords and their occurrences. There were three top keywords, "warehouse management system", "internet of things", "industry 4.0 and "supply chain", heading the list. Thus, WMS words and technologies were at the top, and others were used only once.

Table 11. The list of authors' keywords and their occurrence among articles' keywords.

Keyword	Counts	Keyword	Counts
warehouse management system	8	process	1
internet of things	5	real-time location system	1
industry 4.0	3	intelligent product	1
supply chain	2	safety	1
augmented reality	1	interaction mechanisms	1
safety management	1	smart environment	1
compliance behavior	1	smart logistics	1
computer technology	1	communicating object	1
sustainability key performance indicators (kpis)	1	structural equation modeling (sem)	1
controlled experiment	1	iot	1
wms	1	sustainable warehousing (sw)	1
data analytics	1	logistics	1
risk monitoring system	1	warehouse	1
employee engagement	1	modeling	1
smart glasses	1	warehouse management system (wms)	1
equipment safety checks	1	multi-criteria analysis	1
ultra-wide band	1	wireless sensor network	1
full shift usage	1	neurois	1
weighting	1	assistive technology	1
gamification	1	occupational safety and health act (osha)	1
order picking processes	1	node-red	1
order-picking	1	mongodb	1
ant colony optimization	1	EVIN	1
control system	1	neural network	1
robotic device	1		

Analyzing keywords' semantics, we divided all the keywords into seven most prominent content-related groups (Figure 4). The number of keywords in groups varied from three to 12. The main focus group was on WMS-related keywords (WMS abbreviation and warehouse management system). The most prominent groups contained sustainability-related terminology keywords (sustainable warehousing and performance indexes, safety management) and employees' motivation (gamification and engagement). Another keyword group was about technologies simplifying storage and assisting in picking (smart glasses, wristbands, and other location systems). The technologies-related group contained smart technologies and similar concepts (industry 4.0, smart, and intelligent storage). The other two small groups include supply chain, logistic, and warehouse process terms. Interestingly, three articles did not mention "warehouse management system" or "wms" in their list of keywords. Similarly, only half of the articles had environmental sustainability terms in the keywords (Appendix C).

WAREHOUSE MANAGEMENT SYSTEM
warehouse management system
warehouse management system (wms)
wms

SKU HANDLING, PICKING AND STORING RELATED
order picking processes
order-picking
process

SUPPORTIVE TECHNOLOGIES FOR WAREHOUSE OPERATIONS
assistive technology
computer technology
real-time location system
smart glasses
ultra-wide band
wireless sensor network
node-red
mongodb
control system
robotic device

DECISION MAKING STATISTICS & ANALYSIS
modeling
multi-criteria analysis
controlled experiment
data analytics
structural equation modeling (sem)
weighting

SUSTAINABILITY, SAFETY AND EMPLOYEES' MOTIVATION
communicating object
compliance behavior
employee engagement
equipment safety checks
full shift usage
gamification
occupational safety and health act (osha)
risk monitoring system
safety
safety management
sustainability key performance indicators (kpis)
sustainable warehousing (sw)

SMART TECHNOLOGY CONCEPTS
augmented reality
industry 4.0
intelligent product
interaction mechanisms
internet of things
iot
neurois
smart environment
smart logistics
EVIN
neural network
ant colony optimization

SUPPLY CHAIN & LOGISTICS
logistics
supply chain
warehouse

Figure 4. Grouping selected articles' keywords in themantic areas.

3.1.8. Citation Analysis

From the 12 articles retrieved from Scopus and Web of Science, only a few were available in both databases. All articles' citation counts collected from Scopus and Web of Science were presented in Appendix C. The Google Scholar index was utilized to study the global interest in citing these studies. Figure 5 depicts articles by publishing year (horizontal axis) and citation count (vertical axis). Blue dots with Roman numerals indicate the articles. As an interesting note, the more recent articles have received more citations than the earlier published works, except XI and XII, which were published in 2022. However, it was expected that older articles would collect more citations. Noticeably, IV has been cited much more than other articles.

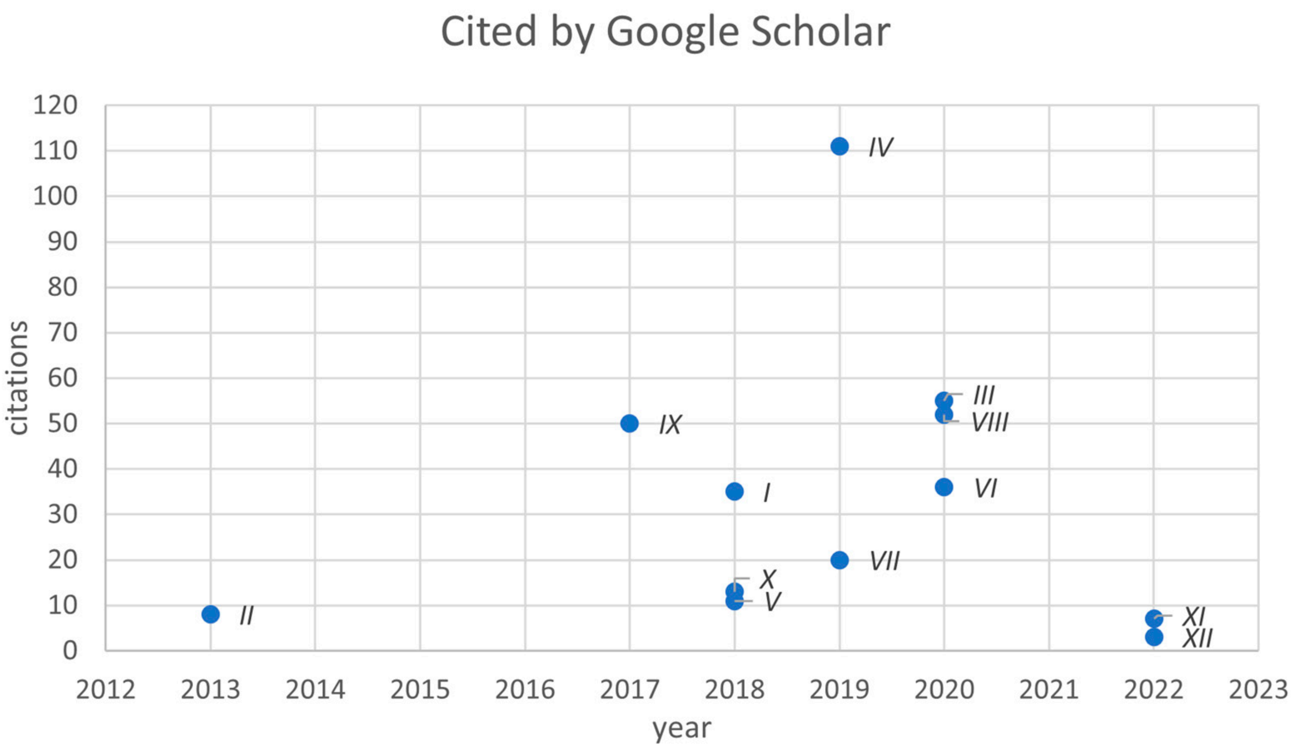

Figure 5. Articles' publication years and a number of Google Scholar citations.

3.2. Content Analysis

To access WMS and sustainability connection, all 12 articles were read, and their content was analyzed to understand their research aims (Table 12).

Table 12. The research aims of 12 articles.

Article's Index Number	AIM
I	to demonstrate the importance of implementing WMS to improve the order-picking process
II	to develop a framework for an IT-assisted/computerized equipment checks system (using WMS and barcode readers) to improve the safety check compliance of motorized vehicles (forklifts and pallet jacks)
III	to demonstrate how real-time location technology (RTLS) technology can be leveraged to enhance warehouse safety and operational efficiency via a real warehouse case study
IV	to propose a theoretical framework for implementing IoT in a warehouse
V	to conduct a field study on the impact of a full shift usage of smart glasses in order picking processes on workers and picking process

Table 12. *Cont.*

Article's Index Number	AIM
VI	to present a laboratory experiment in which two gamification elements, goal setting and feedback, are implemented in a wearable WMS interface to examine their effect on user engagement and performance in picking task
VII	to present a way to raise the quality of life for people with disabilities using assistive technology (implementing smart wristbands)
VIII	to develop a list of 33 key performance indicators (KPIs) for a sustainable warehouse management system
IX	to propose a concept "IoT-controlled Safe Area" for communicating objects in smart logistics
X	to implement the concepts and architecture of IoT using ZigBee wireless sensor network platform and LabView software to design a risk monitoring system for a warehouse with hazardous products
XI	to demonstrate the IoT value for WMS using Node-RED and MongoDB software tools based on the real warehouse data
XII	to develop a control system of the Evolutionary Intelligence to manage robots during the order-picking process in a warehouse with WMS

Figure 6 shows an overview of articles' focus on adding value to the environmental and social sustainability sides of WMS. We marked with green colors if an article discussed WMS and sustainability from both social and environmental sides or only one. In addition, the darker green indicates that a certain aspect is one of the article's core aspects. In contrast, aspects marked with the light green are not a primary focus of the paper and are partly discussed and slightly mentioned, e.g., in theory, as can be seen from the table, 10 out of 12 articles built some social sustainability connections with WMS. In comparison, only five articles contributed to WMS and environmental content. Nearly half of the articles (four) covered social and environmental sustainability associated with WMS usage and implementation.

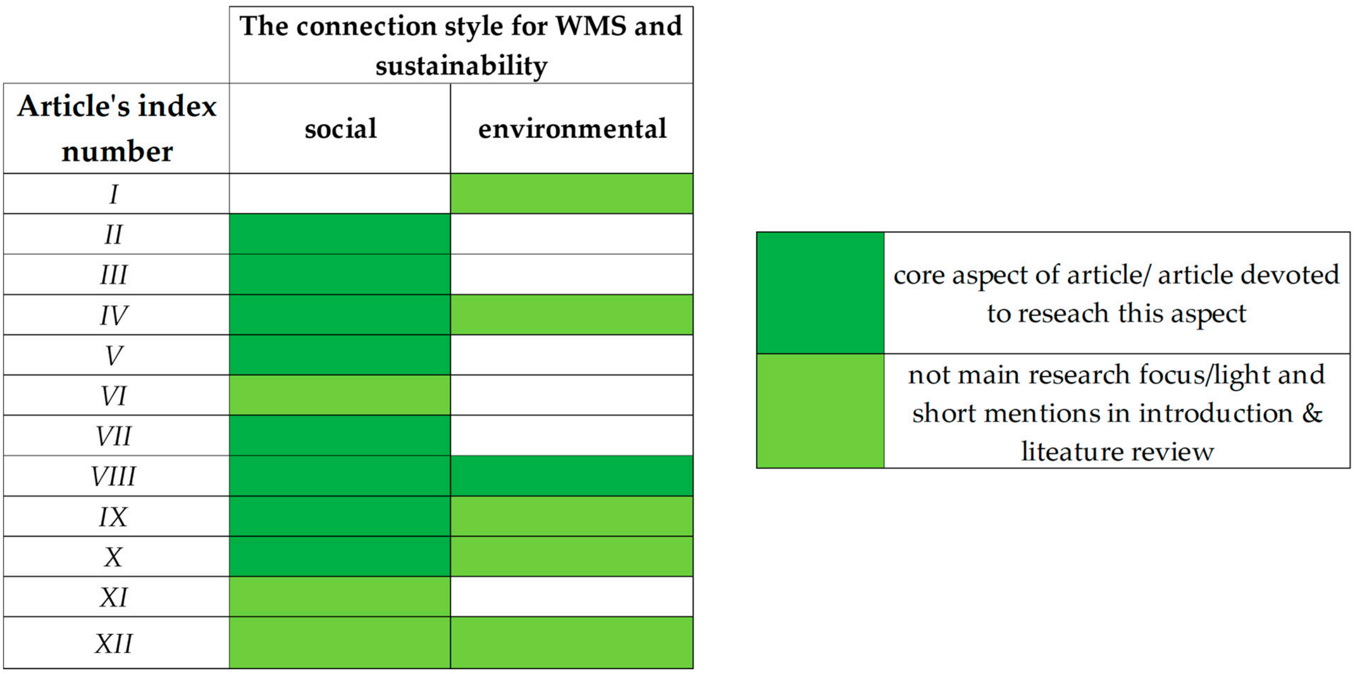

Figure 6. The colored connection style for WMS and social and environmental sustainability in the 12 articles with color identification description.

Together with the social or environmental sustainability focus in articles, all articles were assessed based on the technology interface with WMS. The evaluation was completed, as WMS integration into other systems had the technological capability to add a new level of sustainability to warehouse operations. Figure 7 gathers two tables about the assessment of technologies discussed in 12 selected articles. The left table identifies whether WMS alone or any additional technologies used with WMS contribute to environmental or social sustainability, where matches are marked with "X". At the same time, the right table has a detailed description of any other technologies used with WMS. In most papers (nine out of 12), assistive technology was integrated with WMS to work in tandem.

	WMS itself alone	*WMS integration with other technologies*
I	x	
II	x	
III		x
IV		x
V		x
VI		x
VII		x
VIII	x	
IX		x
X		x
XI		x

	ARE THERE ANY OTHER TECHNOLOGIES DISCUSSED WITH WMS OR NOT?
I	only WMS discussion for better order-picking
II	discssion of WMS modules and OSHA safety checklist to be shons in computerised system
III	main discussion of real time locatopns system integrated with WMS and FFMS
IV	implementing IoT network in a warehouse and , in turn, all the data captured from readers and sensors are transferred to the WMS that processes the data and converts it into useful information and actions
V	two visualization devices monitor and smart glasses interacted with WMS
VI	investigate the effects of the gamification of a wearable WMS interface for order pickers.
VII	using smart wristband equipped with appropriate sensor technologies for efficient use of workers time in smart warehouses. By using IoT and web technologies it is possible to integrate
VIII	just discussion of KPIs for sustainable WMS
IX	WMS is a part of IoT safety architecture network
X	IoT-based risk monitoring system (WMS is a part) with ZigBee wireless sensor network platform and LabView software
XI	a system using IoT software package technologies Node-RED and MongoDB

Figure 7. Mentioned technologies working with WMS in 12 selected studies, the left table—identification of technologies used or not with WMS in a warehouse, the right table—a description of technologies in a warehouse.

Analyzing the found publications from a sustainability point of view, the article with the strongest contribution, connecting both social and environmental sustainability with WMS was written by ref. [27]. The authors devised 33 KPIs for WMS in all three sustainability pillars (economic, environmental, and social) derived from sustainability reporting guidance and literature and interviews with Malaysian automotive warehouse managers in 2004 (Figure 8). This study was also the only one discussing the sustainability performance of WMS. However, since the authors did not disclose the exact interview question list, it was hard to judge on the questions asked: were these questions related to warehouse performance, WMS functions, or the dashboard of WMS. Nevertheless, this research has made a good step towards researching and stating such metrics for policymakers and the government to push sustainability through warehousing operations to make them more sustainable. Developing sustainability indicators, ref. [27] did not say how WMS could contribute to reaching them or how these indicators affect warehousing operations. For the model's environmental group of indicators, the authors defined warehouse resources (consumption of recyclable materials, energy, water, impact on biodiversity and habitat), emission waste, and environmental commitment (emission and waste reduction, environmental laws violations, green investing). The authors identified labor practice, decent work, product responsibility, and society as social indicator groups. Besides, after analyzing interviews, the authors concluded that some indicators have a higher contribution among their own group indicators and sustainable warehousing. For example, the percentage of products sold with recyclable packaging material had the highest weight to form sustainable warehousing using WMS, and the total number of new employees hired by age, gender, and religion had the highest contribution to sustainable warehousing.

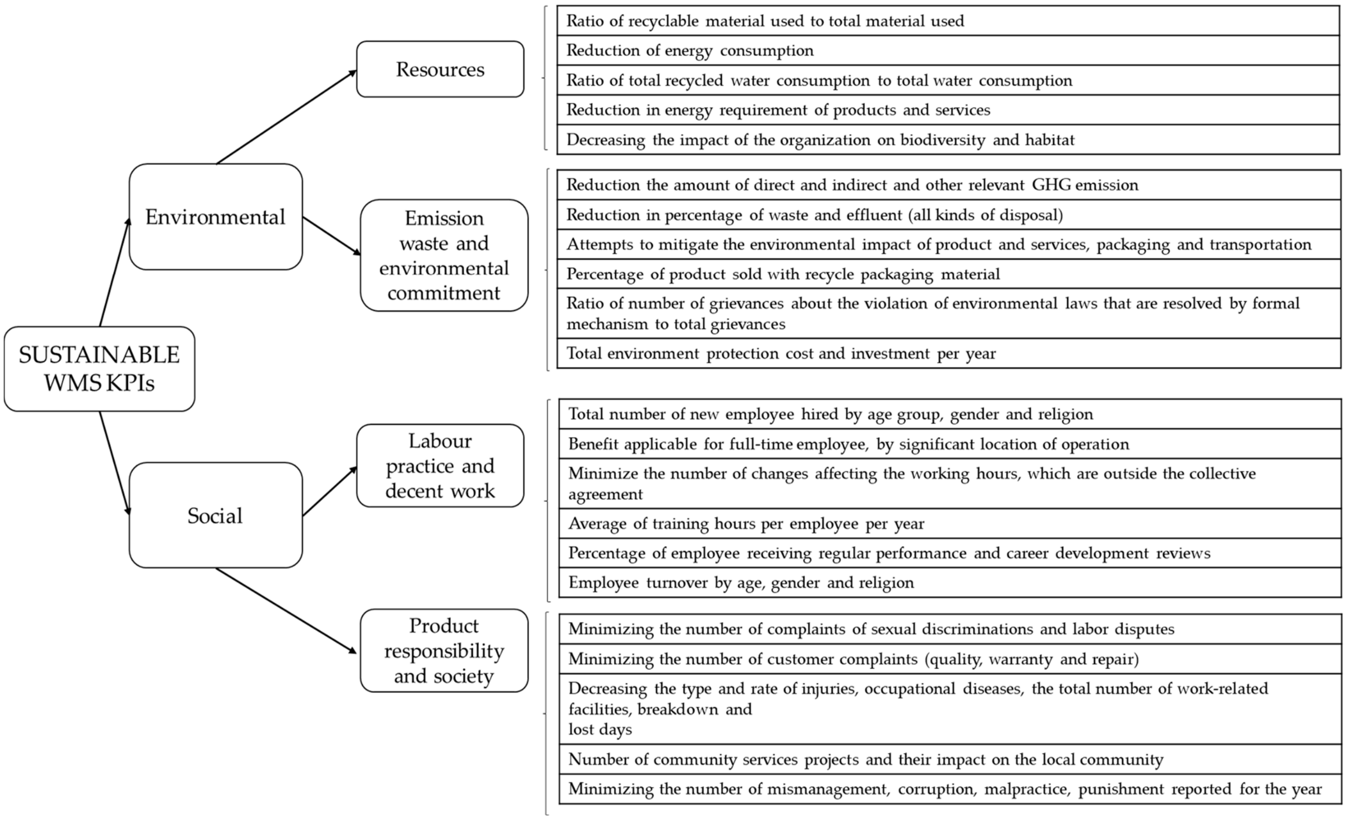

Figure 8. Environmental and sustainable KPIs of sustainable WMS adapted from [27].

The research of ref. [27] indicated a lack of theory in the field of KPIs for sustainable warehousing with WMS. This article was also the closest to the current core research connecting WMS to sustainability matters. The authors validated these KPIs with industry experts but did not align the defined KPIs with the actual scope of WMS activities, keeping the discussion at a general level. Thus, these KPIs cover general warehousing activities rather than activities that lie within the scope of WMS. Another group of three articles [47,51,52] with similar contribution weights to environmental and social sustainability and WMS discussed more social issues than environmental warehouse issues. Ref. [47] strongly emphasized the role of IoT implementation in warehousing. Namely, WMS received all the data captured from readers attached to gates, forklifts, products' tags, and shelves' sensors (product's location, product type, expiry date, storage, and picking confirmation) and converted this data into useful information and a set of actions providing real-time visibility of inventory levels and preventing stock-outs. Plus, the HVAC system got the data required to optimize energy consumption and assure product quality and warehouse safety. Controlled and reported actions in order picking helped to update the inventory level automatically, make immediate order fulfillment more efficient, easier, and accurate, and prevent counterfeiting. The authors' proposed IoT framework decreased human interventions and consequently led to more safety for warehouse workers and products, reduced accidents, decreased counterfeiting and fraud, and decreased theft. The other two articles shared the same research idea of bringing up social (mainly) and environmental sustainability in developing warehouse operations [51] and implementing [52] an IoT-controlled Safe Area. Ref. [51] implemented an IoT-controlled safety area to ensure safety control of all warehouse operations related to hazardous products, shelves, forklifts, and human labor. This study used WMS with highly autonomous components supporting a communicating object concept, RFID readers, and tags. In the paper of ref. [51], WMS and an IoT-architecture reference model generated safety-based scenarios with an IoT-controlled Safe Area improving warehousing operations of hazardous products by using safety mechanisms for detecting and pretending all potential conflictual and risky situations, environmental disturbances, and disasters (e.g., the absence of a product due to a theft or a human error in storing, the existence of an empty or damaged product, the lack of warehouse workers' safety protection equipment). Ref. [52] added safety to a WMS with the help of a smart product IoT-based risk monitoring system (ZigBee wireless sensor network platform and LabView software) to safely manage goods and people in a warehouse with hazardous chemical products (warehousing operations control, intelligence, and decision-making support, control sensors for storing products in different temperate sections, detection of environmental disturbances, and risky and conflictual situations). Furthermore, this article discussed warehouse safety issues (harmful forklift accidents, storage and transportation of dangerous goods, etc.) as a part of the literature review. Both papers revealed the importance of warehousing safety, overcoming safety problems in a warehouse, and investigating a lack of automated safety control during WMS operations with the smart product concept.

Even though an article by [44] was not about sustainability, there is a description of WMS facilitating sustainability in a warehouse by reducing paperwork/paper consumption and decreasing CO_2 emissions level and energy consumption with optimized utilization of transportation equipment (the last is mentioned in the literature review only). The primary article focused on the importance of implementing a WMS for improving the order-picking process as a warehouse activity.

Another article that concentrated more on developing control system algorithms for robot path optimization in the order-picking process than on social and environmental sustainability aspects belongs to [54]. In this article, the authors minimized the number of robots needed for order-picking, optimized their travel paths, and reduced the risks of robot collisions, which, in turn, resulted in increased control, safety, and energy consumption in a warehouse using WMS.

In the recently published article [53], the primary focus was not strongly on social sustainability. The article primarily demonstrates IoT benefits for SC if software such as Node-RED and MongoDB can enhance a WMS. However, the authors summed up the positive impacts of integrating this software with WMS to gain more control of warehouse operations with IoT, decrease fraud, theft, and counterweighting, and avoid warehouse accidents because of more accurate online data, analysis, and reporting.

Discussing the social sustainability of warehouse operations, Ref. [45] only brought up the issue of reducing forklift accidents in a warehouse by using an equipment safe module in WMS for vehicle checks (visual inspection and operational equipment checks like wheels, forks, battery, seat, etc.). This article compared a computerized system against a simple paper instruction check. Another article lighting the social sustainability of warehousing operations belongs to [48]. These authors reported studying augmented reality devices such as visualization device monitors and smart glasses integrated with a WMS. In the following way, they analyzed health-oriented aspects as well as the task completion time and the error frequency for an entire shift of eight hours of usage of smart glasses in order picking processes. One of the negative consequences of such long glass shifts is that participants experience headaches, pain in or around the eyeball, and difficulty focusing. Summing up, the pickers' opinions about the full-shift usage of smart glasses in combination with a ProGlove as an interaction device are quite different. Some employees enjoyed working with the glasses. Most of them liked the user interface and the colors, especially the series of numbers, with which they had a better overview. Providing for error feedback is appreciated and leads to nearly error-free picking'. The higher working speed is viewed as advantageous because it is caused by visualization in their field of view and the avoidance of head- and body movements. Wireless working without a power bank prevented entanglement. One picker described the tasks as robot work, where a worker only performed the work without thinking. Some other negative aspects were the weight of the glasses, the inflexible and narrow temples, and left imprints left by the nose clips. The headache at the back of the head was caused by the design of the temples. Another challenge was to refocus from objects to visualization in the glasses and the limited field of view. Few pickers perceived the display as blinding. This experiment resulted in a decrease in the mean task completion time. While the sub-values of 'mental demand', 'performance', and 'frustration' were higher after using smart glasses as visualization devices, the sub-values of physical demand', 'temporal demand', and 'effort' were higher using the monitor.

In addition to the warehouse safety topic, ref. [46] discussed social sustainability in a warehouse, in literature and case studies. The authors investigated primarily the introduction of real-time location technology (RTLS) integrated with WMS to enhance safety and operational efficiency. The RTLS uses actual data obtained from WMS and the forklift fleet management system to optimize driving routing and identify unsafe driving behaviors like overspeeding or harshness in braking. As a result, the zones with safety concerns can be visualized with the help of warehouse performance heat maps concerning speed, braking, impacts, and routing policy compliance. An algorithm utilizing both WMS and RTLS was developed to mitigate the noise issue. Thus, data-driven decision support systems could assist in accurate and efficient vehicle management.

For social sustainability in warehousing, Ref. [50] suggested increasing the quality of the working lives of people with disabilities in a warehouse with the help of assistive technologies integrated with WMS. The wireless sensor network and cloud computing technology are used in the Industry 4.0 concept. The authors suggest using smart wristbands with sensor technologies for efficient workers' usage. In the following manner, all relevant data from logistic processes can be integrated into WMS with the help of IoT and web technologies. Ref. [49] presents an interesting study where wearable devices are used with a WMS interface to motivate warehouse workers' pathways using gamification that positively affects workers' engagement and performance.

4. Discussion

This study has collected the current literature on WMS and sustainability-related research together. Primarily, this study has searched for evidence of WMS contributing to social and environmental sustainability. Based on the found literature, this is the first SLR to address WMS and sustainability together. Additionally, as part of the goal to seek an answer to what the current state of the art and scale on topic-specific academic research, we were able to show this research topic is still in its early phases and quite narrow in scale. Figure 9 gathers a synthesis of findings with references to the articles in Roman numbers and presents the list of actions WMS can take to bring social and environmental sustainability into warehouse operations.

Only 12 articles described the effect of WMS on sustainability in warehousing. From the found literature, the study most focused explicitly on this matter belongs to [27], who defined KPIs for a sustainable WMS. However, this study misses instructions on how exactly WMS could contribute to reaching these KPIs. The research on achieving social and/or environmental sustainability with WMS functions or through utilizing WMS as a part of operations management is missing from the current literature, indicating a clear research gap. Based on this finding, we suggest additional research on warehouse information systems utilization, social sustainability, and operations continuous improvement context. One should fit continuous improvement and employees' participation levels properly with the level of centralization of authority [60]. The fitment is essential for WMS utilization level studies and experiments when, e.g., action research and employee engagement-based development activities are studied.

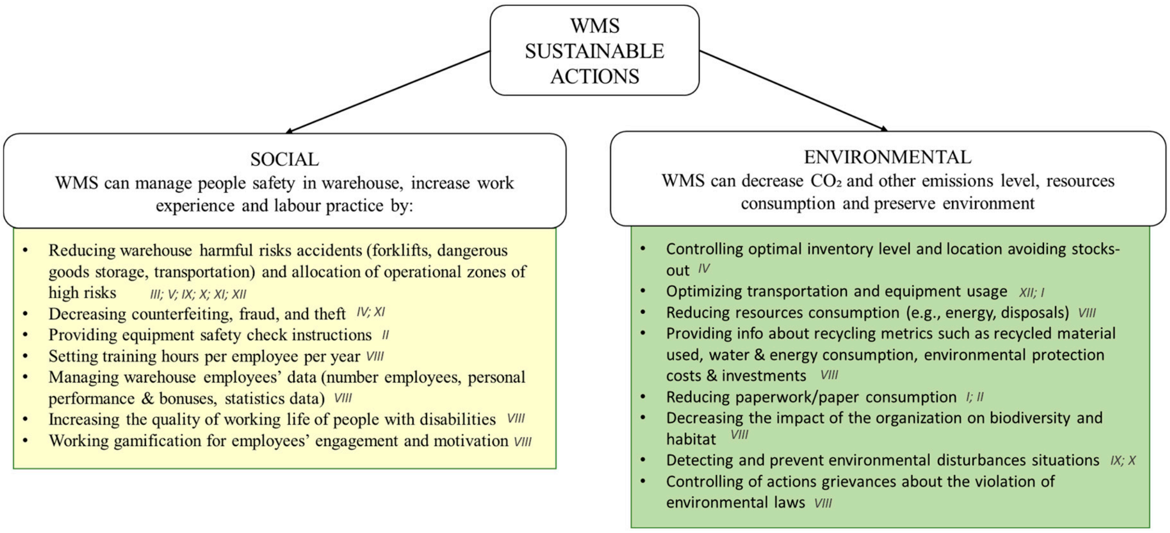

Figure 9. The list of WMS's social and environmental sustainability activities was gathered from literature findings.

Additionally, even though the sustainability goals achievement studies with WMS connected manner are lacking, there is increasing research attention to studies of reducing GHG in warehousing. Ref. [17] addressed the development of the assessment and allocation method of GHG in a logistics facility, as well as [19], which developed environmental performance indicators for main warehouse activities. Furthermore, ref. [39] indicated a growing research interest in sustainable warehousing in general. Moreover, companies need to achieve shorter delivery times, increase the speed of deliveries, and find ways to win the tight competition in warehousing performance levels worldwide [61]. In the same way, as WMS increases inventory visibility and traces inventory [62], WMS might calculate GHG emissions based on resources consumed in a warehouse, like in the model [19], and collaborate with SC partners to allocate CO_2 [63].

Considering the found publications' focus areas, most generally discussed warehouse operations and focused on social sustainability in a warehousing context, especially workers' safety. This finding aligns well with the view that humans are the key players in both warehouses' physical and non-physical activities [64]. Additionally, from the point of view of business productivity and operations side cost, carelessness on the topic of employee safety has been shown to negatively impact business quality and performance [65], give companies bad publicity, and damage companies' brands.

Considering WMS as a sustainability-enhancing tool, the academic world is still missing the research line addressing the topic of utilizing WMS for warehouse personnel and sustainability management efforts, even though it is known that a WMS can manage warehouse resources (such as inventory, storage, orders, and workforce). However, for the system, this should not be a difficult task; for example, ref. [66] introduced the sustainable warehouse management approach through workforce scheduling for better usage of the workforce, resources, and equipment.

Another significant finding was sustainability, which the literature mainly focused on. The studies were more steered towards social sustainability aspects than environmental sustainability aspects, indicating a research gap on the side of environmental sustainability that could be achieved with WMS. As with any other logistics activity, warehousing sustainability is a part of SC sustainability research. For example, the SLR of the transport sector studies by [67] with a little focus on sustainability topics gave the opposite result of more environmental rather than social sustainability studies. Additionally, the literature analysis on sustainability interactions between SC actors revealed the domination of environmental over social practices in studies and the increasing gap between these two dimensions in the last decade [68]. A study [69] also emphasizes a predominant focus on environmental concerns in designing sustainability methods and tools. Our findings show that the sustainability discussion is ongoing and supports research in the warehousing literature. However, the sustainability focus on warehousing is different from that in logistics sectors. Especially, research on warehouse operations management software like the WMS and their possible contribution towards environmental sustainability is lacking. These systems are top operations management tools in all medium- and large-scale warehouses nowadays, all around the globe.

In most of the analyzed articles on the topic of WMS and social and environmental sustainability, WMS was interfaced with other supporting technologies. Generally speaking, the found literature emphasizes IT utilization's role in warehousing. This issue can be connected with the value of IT-based systems for sustainable SC business activities [70]. For WMS, integration with other systems is always beneficial for efficient and smooth operations [61]. In the list of world trends in warehousing logistics, there are robotization, big data, RFID, EDI, drones, IoT, additive technology, cross-docking, and multi-story warehouses [71]. This correlates with the findings of [72], who conclude that warehousing research after 2011 has evolved to be focused more on highly automated and integrated warehousing systems to boost operations efficiency and effectiveness. Technologies can help identify unsustainable behavior, e.g., forklift over-speeding [46]. The rising interest in pro-environmental behavior will increase the adoption of sustainability norms [73]. Ref. [18] noted that more automation deployed in a warehouse led to higher energy expenditure. In contrast, ref. [74] proposed a model of controllable energy consumption for environmental conservation (reduced pollution and emissions) and increased profit. Several studies have already been dedicated to extending our understanding of how automation technologies can enhance operational energy efficiency [75,76]. The recent SLR validated a similar positive linkage between sustainable warehousing and industry 4.0 technologies [13]. Such an increasing dependence on information technology systems may result in negative consequences from technology disruptions, as discovered in the study of ref. [77] on the link between sustainability and resilience.

Moreover, due to more automation deployed in a warehouse, it is estimated that the warehousing industry will not experience a dramatic loss of jobs—technologies can lower the skill level required for the job and reduce monotonous or highly physical energy-consuming activities [78]. Considering the supply of safety-related publications, issues like gender equality, the UN SDG, the high cost of a talented workforce, and replacing qualified personnel in case of an accident, the present spread of COVID-19 might have pushed research in this particular direction.

It is also surprising that warehouse waste reduction in a warehouse is not brought up in found articles, except for being mentioned by ref. [27] without any further description in one of the tables about WMS KPIs. From 12 articles, ref. [53] also mentioned a waste problem in a warehouse, but in the meaning of impropriate utilization of a warehouse space without any reference to sustainability. Ref. [79] found that pollution prevention and waste management practices positively affected GHG emission reduction. In recent years, sustainability, circularity, and waste reduction have gotten more attention in research communities [80,81]. There can be a circular economy and a sustainable stream of WMS studies in the near future. The social distancing restrictions due to COVID-19 limited warehouse work (rising labor costs because of working restrictions, the need to increase stock levels because of quickly increased demand, and the need to store large inventory volumes because of interrupted SCs) [71]. All of the above can hinder the sustainability research development speed as corporations are forced to focus on the survival of their organizations as their priority.

5. Conclusions

The global markets and social development have put the companies under a pressing need for more sustainable SCs. Meanwhile, turning a widely known paradigm [82] of a SC to be as strong as its weakest link towards sustainability, it can be said that every chain (stop/intermediate/connection point) of a SC should also be sustainable to ensure the overall sustainability of the SC. Maintaining the same sustainability perception, using the PRISMA model, the present research paper was designed to gather evidence from WMS and sustainability discussion from Scopus and Web of Science databases. The current academic literature on this topic appears to be somewhat limited in terms of research. As a result, 12 academic articles within the range from 2013 to 2023 were extracted. The research topic was first discussed in the article published in 2013, then had a few years of publishing gaps, was raised again in 2017, and had two peaks in 2018 and 2020. Next year, the research topic received numerous research contributions.

Regarding the geographical enlargement of research, of the 11 countries, only five countries were more active in their contributions to the research direction. The United States is the most popular, followed by Egypt, Malaysia, France, and Tunisia. From the citation count, surprisingly, recent articles have received more citations than earlier published articles. Based on findings in most cases, WMS is currently integrated with other warehouse sub-systems to bring up the social and environmental sustainability results of warehousing. Interestingly, most articles observe social sustainability and WMS as dominant over environmental sustainability focus. Furthermore, nearly half of the articles contributed to WMS's social and environmental knowledge. Synthesizing knowledge from these 12 articles, we listed activities that WMS could do to foster warehousing operations' social and environmental sustainability.

6. Theoretical Applications

The current research findings have a number of theoretical implications for WMS and social and environmental sustainability research that can be significant in several ways. This research is an addition to the body of knowledge on WMS and sustainability. Another theoretical implication is the potential to enhance understanding of the interplay between technology and sustainable warehousing. Investigating how WMS can contribute to social and environmental sustainability can become a starting point for designing and developing technologies to promote sustainable practices in a warehouse. The research can help to balance social and environmentally sustainable warehousing operations with the economic efficiency of warehousing operations. Moreover, the current research can positively impact the development of a more sustainable supply chain that cares about people and the environment.

7. Managerial Applications

By gaining more knowledge about and control over warehousing operations, companies could reduce the environmental impact of warehousing operations and move closer to achieving the UN SDG [83]. Ban Ki-moon, the Secretary-General of the UN, acknowledged the crucial role of business companies in maximizing efforts toward the SDGs by integrating sustainability across all SC functions [84]. Defining relevant sustainable SCM practices, ref. [85] placed green warehousing into the sustainable practice of the downstream SC. In decarbonizing SC activities, ref. [86] indicated a significant role of third-party logistics in freight transportation and warehousing in implementing a low-carbon strategy. To reach the concept of sustainable warehousing, ref. [87] introduced sustainable warehouse system modeling, and ref. [38] developed criteria for the assessment of warehouse sustainability mentioning the role of warehouse systems and automatization. Ref. [88] reviewed the development of warehousing systems and technologies to contribute to sustainable warehousing. Refs. [89,90] demonstrated a scarcity of research in the WMS context and sustainability-supporting aspects of third-party logistics. As content analysis has shown, the topics of WMS and sustainability are truly missing practical implications.

Companies could reduce the environmental and social impact of their warehousing operations with added knowledge for practical implementation activities to achieve sustainability KPIs and control warehousing operations with respect to sustainability. All this will allow companies to push the surrounding society closer to achieving the set UN Sustainable Development Goals Research 2030 Agenda [91].

8. Future Research Suggestions

We would recommend academics and business owners research more about the topic and collaborate in this direction. The combination of our findings supports the need for further research on utilizing WMS for sustainability activities. WMS are the key systems in warehousing, controlling what happens where and why in a warehouse.

In this context, further research is needed to support companies' proactive approaches to sustainability matters. In this case, if the high demand for sustainable warehousing comes from the government, policymakers, producers, or even end customers, warehousing companies should be prepared and know what to do, why, and when. One potential higher-level integration of automatization optimization in the WMS context could be self-operating autonomous vehicles [92] in the restricted parts of warehouses and their surrounding yards to be controlled by the WMS. In the long term, WMS could be developed to handle larger-scale fleets [93,94], and improve their optimization capabilities in warehouse environments.

To further understand the potential of WMS to achieve and set sustainability goals, studies on utilizing WMS alone for sustainability would be beneficial. This would add to understanding what can be achieved in warehouses with different available resources and tools. For example, in further studies, WMS functional characteristics for sustainability should be considered when discovering purely WMS-based capabilities for sustainability, including sustainability report functions, separated waste streams quantity generation forecasting, mapping and classification of different processes based on their CO_2, and waste production per handled ton. This, in turn, will also lead to incorporating more quantitative and qualitative techniques to investigate this research direction further.

When there is a bigger picture of how WMS can be both socially and environmentally sustainable, it would be important to also be able to identify WMS sustainability contributing development possibilities according to the triple bottom line approach to cover all three pillars of sustainability [95] and overlapping sustainability elements in the same way as completed by ref. [96]. The same call for building WMS and sustainability knowledge came from the 3PL area specialist interviews by ref. [97]. Here, we would suggest also considering the sustainability trade-offs with WMS in warehousing, which is completed by refs. [98,99] in the SC contexts.

9. Limitations

The most important limitation of this research lies in the fact that only 12 studies contributed to the understanding of the environmental and social sustainability of WMS. The current academic literature on the researched WMS and sustainability topic is a bit narrow in availability, so it could not produce wider insights into WMS utilization in the sustainability connection. What makes the generalizability of these results subject to certain limitations.

As only Web of Science (Core Collection) and Scopus (Elsevier) were used as two databases to extract literature for the bibliometric and content analysis, this choice may lead to omitting findings from other databases.

For example, researchers can consider mapping the available knowledge from gray literature sources. It is also crucial to approach the study findings with understanding, as only English-published academic literature was analyzed.

Other limitations come from the main focus of the research on WMS actions towards sustainability rather than, e.g., using eco-friendly materials in warehouse construction or utilizing renewable energy in warehouses. For the same reasons, technical-related studies, e.g., programming and developing algorithms, were not reviewed. The current research has identified ways to utilize WMS for positive social and environmental sustainability contributions.

Despite the abovementioned limitations, we see our work as contributing to a better understanding of the current literature on WMS and sustainability for new in-depth research gap fulfillment efforts.

Author Contributions: Conceptualization, D.M. and A.H.; methodology, D.M.; software, D.M.; validation, D.M. and A.H.; formal analysis, D.M.; investigation, D.M.; resources, D.M.; data curation, D.M.; writing—original draft preparation, D.M.; writing—review and editing, D.M. and A.H.; visualization, D.M.; supervision, A.H.; project administration, A.H.; funding acquisition, A.H. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported and funded by the European Neighborhood instrument Cross-border Cooperation (ENI CBC) funded AWARE project under Grant KS1913.

Data Availability Statement: Data sharing not applicable.

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

Appendix A

Table A1. Keywords Based on [39,43].

Selected Sustainability Keywords	Bartolini—Environmental Sustainability Terms	Glavič & Lukma—Sustainability Principles, Approaches & Sub-Systems
carbon	"carbon"	-
CO_2	"CO_2"	-
control*	-	"pollution control", "integrated pollution prevention and control"
clean*	-	"cleaner production"
degrad*		degradation
eco	"eco"	"eco-design", "eco-efficiency"
emission	"emission"	-
energ*	"energy"	-
environment*	"environment*"	"environmental engineering", "environmental technology", "environmental accounting", "environmental legalisation", "environmental management strategy", "voluntary environmental agreement"
ethic*	-	"ethical investment"
green	"green"	"green chemistry"
health*	-	"safety and health"
"life cycle"	"life cycle"	"life cycle assessment"
renewabl*	-	"renewable resources"
repair*	-	repair
reus*	-	reuse
recover*	-	recovery
recycl*	-	recycling
reduc*	-	"source reduction"
regenerat*	-	regeneration
remanufactur*	-	remanufacturing
report*	-	reporting

Appendix B

Table A2. Combination of Keywords Used in Database Searches.

Database	Keywords Combination
Scopus (Elsevier)	TITLE-ABS-KEY("warehouse management system*") AND TITLE-ABS-KEY(carbon OR CO_2 OR control* OR clean* OR degrad* OR eco OR emission OR energ* OR environment* OR ethic* OR green OR health* OR "life cycle" OR renewabl* OR repair* OR reus* OR recover* OR recycl* OR reduc* OR revers* OR regenerat* OR remanufactur* OR report* OR resourc* OR responsib* OR pollut* OR prevent* OR minimis* OR minimiz* OR safe* OR social* OR sustain* OR waste*)
Web of Science (Core Collection)	TS = ("warehouse management system*") AND TS = (carbon OR CO_2 OR control* OR clean* OR degrad* OR eco OR emission OR energ* OR environment* OR ethic* OR green OR health* OR "life cycle" OR renewabl* OR repair* OR reus* OR recover* OR recycl* OR reduc* OR revers* OR regenerat* OR remanufactur* OR report* OR resourc* OR responsib* OR pollut* OR prevent* OR minimis* OR minimiz* OR safe* OR social* OR sustain* OR waste*)

Appendix C

Table A3. Full Details of Found 12 Articles on the Research Topic.

Index Number	Authors	Title	Year	Journal Title	Publisher	Volume	Issue	Art. No.	Page Start	Page End
I	Andelkovic A.; Radosavljevic M.	Improving Order-picking Process Through Implementation of Warehouse Management System	2018	Strategic Management	University of Novi Sad, Faculty of Economics, Subotica	23	1	-	3	10
II	Goomas D.T.; Yeow P.H.P.	IT-assisted equipment safety checks system to improve compliance: A case study at a distribution center	2013	Safety Science	Elsevier	60	Dec. 2013	-	77	86
III	Halawa F.; Dauod H.; Lee I.G.; Li Y.; Yoon S.W.; Chung S.H.	Introduction of a real time location system to enhance the warehouse safety and operational efficiency	2020	International Journal of Production Economics	Elsevier	224	-	107541	1	21
IV	Mostafa N.; Hamdy W.; Alawady H.	Impacts of internet of things on supply chains: A framework for warehousing	2019	Social Sciences	MDPI AG	8	3	84	1	10
V	Murauer N.; Pflanz N.	A full shift field study to evaluate user-and process-oriented aspects of smart glasses in automotive order picking processes	2018	Interaction Design and Architectures	Interaction Design & Architectures	-	38	-	64	82

Table A3. *Cont.*

VI	Passalacqua M.; Léger P.-M.; Nacke L.E.;Fredette M.; Labonté-Lemoyne É.; Lin X.; Caprioli T.; Sénécal S.	Playing in the backstore: interface gamification increases warehousing workforce engagement	2020	Industrial Management and Data Systems	Emerald Group Publishing Ltd.	120	7	-	1309	1330
VII	Periša M.; Kuljanić T.M.; Cvitić I.; Kolarovszki P.	Conceptual model for informing user with innovative smart wearable device in industry 4.0	2019	Wireless Networks	Springer New York LLC		-	-	1	12
VIII	Torabizadeh M.; Yusof N.M.; Ma'aram A.; Shaharoun A.M.	Identifying sustainable warehouse management system indicators and proposing new weighting method	2020	Journal of Cleaner Production	Elsevier	248	-	119190	1	11
IX	Trab S.; Bajic E.; Zouinkhi A.; Thomas A.; Abdelkrim M.N.; Chekir H.; Ltaief R.H.	A communicating object's approach for smart logistics and safety issues in warehouses	2017	Concurrent Engineering Research and Applications	SAGE Publications Ltd	25	1	-	53	67
X	Trab S.; Zouinkhi A.; Bajic E.; Abdelkrim M.N.; Chekir H.	IoT-based risk monitoring system for safety management in warehouses	2018	International Journal of Information and Communication Technology	Inderscience Publishers	13	4	-	424	438

Table A3. *Cont.*

XI	Hamdy, W.; Al-Awamry, A.; Mostafa, N.	Warehousing 4.0: A proposed system of using node-red for applying internet of things in warehousing	2022	Sustainable Futures	Elsevier	-	4	100069	
XII	Likhouzova, T., Demianova, Y.	Robot path optimization in warehouse management system	2022	Evolutionary Intelligence	-	-	-	-	
Index number	**DOI**	**Authors' keywords**	**ISSN**	**Journal impact factor (Clarivate 2019)**	**Cited by Scopus**	**Cited by WoS**	**Cited by Google Scholar**		**Country/Territory**
I	10.5937/StraMan-1801003A	Warehouse, process, warehouse management system, order-picking	1821-3448	-	-	10	35		Serbia
II	10.1016/j.ssci.2013.07.002	Compliance behavior, Computer technology, Equipment safety checks, Occupational Safety and Health Act (OSHA), Warehouse management system	-	4.105	5	3	8		United States, Malaysia
III	10.1016/j.ijpe.2019.107541	Data analytics, Industry 4.0, Real-time location system, Ultra-wide band, Warehouse management system	-	5.134	38	32	55		United States
IV	10.3390/socsci8030084	Industry 4.0, Internet of Things, Supply chain, Warehouse management system	2076-0760	-	58	42	111		Egypt

Table A3. *Cont.*

V	-	Augmented Reality, smart glasses, order picking processes, logistics, full shift usage	-	-	9	6	11	Germany
VI	10.1108/IMDS-08-2019-0458	Controlled experiment, Employee engagement, Gamification, NeuroIS, Warehouse management system (WMS)	-	3.329	22	16	36	United States, Canada
VII	10.1007/s11276-019-02057-9	Assistive technology, Internet of things, Smart environment, Wireless sensor network	-	2.659	16	9	20	Croatia, Slovakia
VIII	10.1016/j.jclepro.2019.119190	Multi-criteria analysis, Structural equation modeling (SEM), Sustainability key performance indicators (KPIs), Sustainable warehousing (SW), Weighting	-	7.246	27	21	52	Malaysia, Saudi Arabia
IX	10.1177/1063-293X16672508	communicating object, interaction mechanisms, Internet of Things, modeling, safety, smart logistics, warehouse management system	1063-293X	-	31	25	50	France, Tunisia

Table A3. *Cont.*

X	10.1504/IJI-CT.2018.095032	Intelligent product, Internet of things, IoT, Risk monitoring system, Safety management, Warehouse management system, WMS	-	-	9	-	13	France, Tunisia
XI	10.1016/j.sftr.2022.100069	Industry 4.0, Internet of things, Warehouse management system, Supply chain, Node-RED, MongoDB	-	-	3	2	7	Egypt
XII	10.1007/s12065-021-00614-w	EVIN, Neural network, Ant colony optimization, Warehouse management system, Control system, Robotic device	18645909	-	1	1	3	Ukraine

References

1. Liu, Z.; Ciais, P.; Deng, Z.; Lei, R.; Davis, S.J.; Feng, S.; Zheng, B.; Cui, D.; Dou, X.; Zhu, B.; et al. Near-real-time monitoring of global CO_2 emissions reveals the effects of the COVID-19 pandemic. *Nat. Commun.* **2020**, *11*, 5172. [CrossRef]
2. Kortelainen, H.; Happonen, A.; Hanski, J. From Asset Provider to Knowledge Company—Transformation in the Digital Era. Asset Intelligence through Integration and Interoperability and Contemporary Vibration Engineering Technologies. In *Lecture Notes in Mechanical Engineering*; Mathew, J., Lim, C., Ma, L., Sands, D., Cholette, M., Borghesani, P., Eds.; Springer: Cham, Switzerland, 2019; pp. 333–341. [CrossRef]
3. Fan, R.; Zhang, X.; Bizimana, A.; Zhou, T.; Liu, J.S.; Meng, X.Z. Achieving China's carbon neutrality: Predicting driving factors of CO_2 emission by artificial neural network. *J. Clean. Prod.* **2022**, *362*, 132331. [CrossRef]
4. Wei, Y.-M.; Chen, K.; Kang, J.-N.; Chen, W.; Wang, X.-Y.; Zhang, X. Policy and Management of Carbon Peaking and Carbon Neutrality: A Literature Review. *Engineering* **2022**, *14*, 52–63. [CrossRef]
5. Oubrahim, I.; Sefiani, N.; Happonen, A. Supply Chain Performance Evaluation Models: A Literature Review. *Acta Logist.* **2022**, *9*, 207–221. [CrossRef]
6. Alcaraz, J.L.G.; Reza, J.R.D.; Soto, K.C.A.; Escobedo, G.H.; Happonen, A.; Puig I Vidal, R.; Macías, E.J. Effect of Green Supply Chain Management Practices on Environmental Performance: Case of Mexican Manufacturing Companies. *Mathematics* **2022**, *10*, 1877. [CrossRef]
7. Ramaa, A.; Subramanya, K.N.; Rangaswamy, T.M. Impact of Warehouse Management System in a Supply Chain. *Int. J. Comput. Appl.* **2012**, *54*, 14–20. [CrossRef]
8. EPA. Emerging Trends in Supply Chain Emissions Engagement. 2018. Available online: https://www.epa.gov/sites/production/files/2018-06/documents/emerging_trends_in_supply_chain_emissions_engagement.pdf (accessed on 30 May 2023).
9. Bataille, C.; Waisman, H.; Briand, Y.; Svensson, J.; Vogt-Schilb, A.; Jaramillo, M.; Delgado, R.; Arguello, R.; Clarke, L.; Wild, T.; et al. Net-zero deep decarbonization pathways in Latin America: Challenges and opportunities. *Energy Strat. Rev.* **2020**, *30*, 100510. [CrossRef]
10. Kordestani, A.; Peighambari, K.; Foster, T. Emerging trends in sustainability research: A look back as we begin to look forward. *Int. J. Environ. Sustain. Dev.* **2015**, *14*, 154. [CrossRef]
11. Brenner, B.; Hartl, B. The perceived relationship between digitalization and ecological, economic, and social sustainability. *J. Clean. Prod.* **2021**, *315*, 128128. [CrossRef]
12. Giganti, P.; Falcone, P.M. Strategic Niche Management for Sustainability: A Systematic Literature Review. *Sustainability* **2022**, *14*, 1680. [CrossRef]
13. Ali, I.; Phan, H.M. Industry 4.0 technologies and sustainable warehousing: A systematic literature review and future research agenda. *Int. J. Logist. Manag.* **2022**, *33*, 644–662. [CrossRef]
14. Aravindaraj, K.; Chinna, P.R. A systematic literature review of integration of industry 4.0 and warehouse management to achieve Sustainable Development Goals (SDGs). *Clean. Logist. Supply Chain* **2022**, *5*, 100072. [CrossRef]
15. Freis, J.; Vohlidka, P.; Günthner, W.A. Low-Carbon Warehousing: Examining Impacts of Building and Intra-Logistics Design Options on Energy Demand and the CO_2 Emissions of Logistics Centers. *Sustainability* **2016**, *8*, 448. [CrossRef]
16. Doherty, S.; Hoyle, S. Supply Chain Decarbonization: Role of Transport and Logistics in Reducing Supply Chain Carbon Emissions, World Economic Forum Report. 2009. Available online: http://www3.weforum.org/docs/WEF_LT_SupplyChainDecarbonization_Report_2009.pdf (accessed on 30 May 2023).
17. Rüdiger, D.; Schön, A.; Dobers, K. Managing Greenhouse Gas Emissions from Warehousing and Transshipment with Environmental Performance Indicators. *Transp. Res. Procedia* **2016**, *14*, 886–895. [CrossRef]
18. Bank, R.; Murphy, R. Warehousing sustainability standards development. In *IFIPAICT*; Springer: Berlin/Heidelberg, Germany, 2013; Volume 414, pp. 294–301. [CrossRef]
19. Perotti, S.; Prataviera, L.B.; Melacini, M. Assessing the environmental impact of logistics sites through CO_2eq footprint computation. *Bus. Strat. Environ.* **2022**, *31*, 1679–1694. [CrossRef]
20. Ries, J.M.; Grosse, E.H.; Fichtinger, J. Environmental impact of warehousing: A scenario analysis for the United States. *Int. J. Prod. Res.* **2017**, *55*, 6485–6499. [CrossRef]
21. Burinskiene, A.; Lorenc, A.; Lerher, T. A Simulation Study for the Sustainability and Reduction of Waste in Warehouse Logistics. *Int. J. Simul. Model.* **2018**, *17*, 485–497. [CrossRef]
22. Kusrini, E.; Ahmad, A.; Murniati, W. Design Key Performance Indicator for Sustainable Warehouse: A Case Study in a Leather Manufacturer. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *598*, 012042. [CrossRef]
23. Minashkina, D.; Happonen, A. Decarbonizing warehousing activities through digitalization and automatization with WMS integration for sustainability supporting operations. *E3S Web Conf.* **2020**, *158*, 03002. [CrossRef]
24. VDI-Fachbereich Technische Logisti, 2015. VDI-Standard: VDI 3601. Available online: https://www.vdi.eu/nc/guidelines/vdi_3601-warehouse_management_systeme/ (accessed on 30 May 2023).
25. Minashkina, D.; Happonen, A. Systematic literature review and research gap issues on third party logistics operators selecting WMS for efficient operations for customers. *Int. J. Supply Chain Inventory Manag.* **2020**, *3*, 142. [CrossRef]
26. Faber, N.; de Koster, M.; Smidts, A. Organizing warehouse management. *Int. J. Oper. Prod. Manag.* **2013**, *33*, 1230–1256. [CrossRef]

27. Torabizadeh, M.; Yusof, N.M.; Ma'aram, A.; Shaharoun, A.M. Identifying sustainable warehouse management system indicators and proposing new weighting method. *J. Clean. Prod.* **2019**, *248*, 119190. [CrossRef]
28. Kraus, S.; Breier, M.; Dasí-Rodríguez, S. The art of crafting a systematic literature review in entrepreneurship research. *Int. Entrep. Manag. J.* **2020**, *16*, 1023–1042. [CrossRef]
29. Kitchenham, B. *Procedures for Performing Systematic Reviews*; Keele University: Keele, UK, 2004; Volume 33, pp. 1–26.
30. Ganeshkumar, P.; Gopalakrishnan, S. Systematic reviews and meta-analysis: Understanding the best evidence in primary healthcare. *J. Fam. Med. Prim. Care* **2013**, *2*, 9–14. [CrossRef] [PubMed]
31. Glasziou, P.; Vandenbroucke, J.; Chalmers, I. Assessing the quality of research. *BMJ* **2004**, *328*, 39–41. [CrossRef]
32. Siddaway, A. *What Is a Systematic Literature Review and How Do I Do One*; University of Stirling: Stirling, UK, 2014; Volume 1, pp. 1–13.
33. Tranfield, D.; Denyer, D.; Smart, P. Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. *Br. J. Manag.* **2003**, *14*, 207–222. [CrossRef]
34. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n71. [CrossRef] [PubMed]
35. Durach, C.F.; Kembro, J.; Wieland, A. A New Paradigm for Systematic Literature Reviews in Supply Chain Management. *J. Supply Chain Manag.* **2017**, *53*, 67–85. [CrossRef]
36. de Oliveira, O.J.; da Silva, F.F.; Juliani, F.; Barbosa, L.C.F.M.; Nunhes, T.V. Bibliometric method for mapping the state-of-the-art and identifying research gaps and trends in literature: An essential instrument to support the development of scientific projects. In *Scientometrics Recent Advances*; IntechOpen: London, UK, 2019. [CrossRef]
37. United Nations General Assembly. *Report of the World Commission on Environment and Development: Our Common Future*; United Nations General Assembly, Development and International Co-operation: Oslo, Norway, 1987.
38. Malinowska, M.; Rzeczycki, A.; Sowa, M. Roadmap to sustainable warehouse. In *SHS Web of Conferences*; EDP Sciences: Les Ulis, France, 2018; p. 01028. [CrossRef]
39. Bartolini, M.; Bottani, E.; Grosse, E.H. Green warehousing: Systematic literature review and bibliometric analysis. *J. Clean. Prod.* **2019**, *226*, 242–258. [CrossRef]
40. Gusenbauer, M.; Haddaway, N.R. Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources. *Res. Synth. Methods* **2020**, *11*, 181–217. [CrossRef] [PubMed]
41. Li, J.; Burnham, J.F.; Lemley, T.; Britton, R.M. Citation analysis: Comparison of Web of Science, Scopus, SciFinder, and Google Scholar. *J. Electron. Resour. Med. Libr.* **2010**, *7*, 196–217. [CrossRef]
42. Čablová, L.; Pates, R.; Miovský, M.; Noel, J. How to write a systematic review article and meta-analysis. In *Addiction Science: A Guide for the Perplexed*; Ubiquity Press: London, UK, 2017; pp. 173–189. [CrossRef]
43. Glavič, P.; Lukman, R. Review of sustainability terms and their definitions. *J. Clean. Prod.* **2007**, *15*, 1875–1885. [CrossRef]
44. Anđelković, A.; Radosavljević, M. Improving order-picking process through implementation of warehouse management system. *Strat. Manag.* **2018**, *23*, 3–10. [CrossRef]
45. Goomas, D.T.; Yeow, P.H. IT-assisted equipment safety checks system to improve compliance: A case study at a distribution center. *Saf. Sci.* **2013**, *60*, 77–86. [CrossRef]
46. Halawa, F.; Dauod, H.; Lee, I.G.; Li, Y.; Yoon, S.W.; Chung, S.H. Introduction of a real time location system to enhance the warehouse safety and operational efficiency. *Int. J. Prod. Econ.* **2020**, *224*, 107541. [CrossRef]
47. Mostafa, N.; Hamdy, W.; Alawady, H. Impacts of Internet of Things on Supply Chains: A Framework for Warehousing. *Soc. Sci.* **2019**, *8*, 84. [CrossRef]
48. Murauer, N.; Pflanz, N. A full shift field study to evaluate user- and process-oriented aspects of smart glasses in automotive order picking processes. *Interact. Des. Arch.* **2018**, *38*, 64–82. [CrossRef]
49. Passalacqua, M.; Léger, P.-M.; Nacke, L.E.; Fredette, M.; Labonté-Lemoyne, É.; Lin, X.; Caprioli, T.; Sénécal, S. Playing in the backstore: Interface gamification increases warehousing workforce engagement. *Ind. Manag. Data Syst.* **2020**, *120*, 1309–1330. [CrossRef]
50. Periša, M.; Kuljanić, T.M.; Cvitić, I.; Kolarovszki, P. Conceptual model for informing user with innovative smart wearable device in industry 4.0. *Wirel. Netw.* **2021**, *27*, 1615–1626. [CrossRef]
51. Trab, S.; Bajic, E.; Zouinkhi, A.; Thomas, A.; Abdelkrim, M.N.; Chekir, H.; Ltaief, R.H. A communicating object's approach for smart logistics and safety issues in warehouses. *Concurr. Eng.* **2016**, *25*, 53–67. [CrossRef]
52. Trab, S.; Zouinkhi, A.; Bajic, E.; Abdelkrim, M.N.; Chekir, H. IoT-based risk monitoring system for safety management in warehouses. *Int. J. Inf. Commun. Technol.* **2018**, *13*, 424–438. [CrossRef]
53. Hamdy, W.; Al-Awamry, A.; Mostafa, N. Warehousing 4.0: A proposed system of using node-red for applying internet of things in warehousing. *Sustain. Futur.* **2022**, *4*, 100069. [CrossRef]
54. Likhouzova, T.; Demianova, Y. Robot path optimization in warehouse management system. *Evol. Intell.* **2022**, *15*, 2589–2595. [CrossRef]
55. Seuring, S.; Müller, M. From a literature review to a conceptual framework for sustainable supply chain management. *J. Clean. Prod.* **2008**, *16*, 1699–1710. [CrossRef]

56. Staudt, F.H.; Alpan, G.; Di Mascolo, M.; Rodriguez, C.M.T. Warehouse performance measurement: A literature review. *Int. J. Prod. Res.* **2015**, *53*, 5524–5544. [CrossRef]
57. Glock, C.; Lange, A.; Grosse, E.H.; Das, A. Celebrating the 10th volume of IJISM: A bibliographic review and outlook. *Int. J. Integr. Supply Manag.* **2017**, *11*, 332. [CrossRef]
58. Spacer Marketing Team. Largest Warehouses in the World. 2021. Available online: https://www.spacer.com.au/blog/largest-warehouses-in-the-world (accessed on 30 May 2023).
59. Babaii, E.; Taase, Y. Author-assigned keywords in research articles: Where do they come from. *Iran. J. Appl. Linguist.* **2013**, *16*, 1–19.
60. Galeazzo, A.; Furlan, A.; Vinelli, A. The role of employees' participation and managers' authority on continuous improvement and performance. *Int. J. Oper. Prod. Manag.* **2021**, *41*, 34–64. [CrossRef]
61. Richards, G. *Warehouse Management: A Complete Guide to Improving Efficiency and Minimizing Costs in the Modern Warehouse*, 3rd ed.; Kogan Page Publishers: London, UK, 2017; p. 528. Available online: https://www.koganpage.com/product/warehouse-management-9780749479770 (accessed on 30 May 2023).
62. Andiyappillai, N. Digital Transformation in Warehouse Management Systems (WMS) Implementations. *Int. J. Comput. Appl.* **2020**, *177*, 34–37. [CrossRef]
63. Mrabti, N.; Hamani, N.; Delahoche, L. A sustainable collaborative approach to the distribution network design problem with CO_2 emissions allocation. *Int. J. Shipp. Transp. Logist.* **2022**, *14*, 114–140. [CrossRef]
64. Dewa, P.K.; Pujawan, I.N.; Vanany, I. Human errors in warehouse operations: An improvement model. *Int. J. Logist. Syst. Manag.* **2017**, *27*, 298. [CrossRef]
65. Das, A.; Pagell, M.; Behm, M.; Veltri, A. Toward a theory of the linkages between safety and quality. *J. Oper. Manag.* **2008**, *26*, 521–535. [CrossRef]
66. Popović, V.; Kilibarda, M.; Andrejić, M.; Jereb, B.; Dragan, D. A New Sustainable Warehouse Management Approach for Workforce and Activities Scheduling. *Sustainability* **2021**, *13*, 2021. [CrossRef]
67. Aloui, A.; Hamani, N.; Derrouiche, R.; Delahoche, L. Systematic literature review on collaborative sustainable transportation: Overview, analysis and perspectives. *Transp. Res. Interdiscip. Perspect.* **2021**, *9*, 100291. [CrossRef]
68. Ülgen, V.S.; Björklund, M.; Simm, N.; Forslund, H. Inter-Organizational Supply Chain Interaction for Sustainability: A Systematic Literature Review. *Sustainability* **2019**, *11*, 5488. [CrossRef]
69. Corsini, L.; Moultrie, J. What Is Design for Social Sustainability? A Systematic Literature Review for Designers of Product-Service Systems. *Sustainability* **2021**, *13*, 5963. [CrossRef]
70. Chiang, C.-T.; Kou, T.-C.; Koo, T.-L. A Systematic Literature Review of the IT-Based Supply Chain Management System: Towards a Sustainable Supply Chain Management Model. *Sustainability* **2021**, *13*, 2547. [CrossRef]
71. Marchuk, V.; Harmash, O.; Ovdiienko, O. World trends in warehousing logistics. *Intellect. Logist. Supply Chain. Manag.* **2020**, *2*, 32–50. [CrossRef]
72. Kumar, S.; Narkhede, B.E.; Jain, K. Revisiting the warehouse research through an evolutionary lens: A review from 1990 to 2019. *Int. J. Prod. Res.* **2021**, *59*, 3470–3492. [CrossRef]
73. Saracevic, S.; Schlegelmilch, B.B. The Impact of Social Norms on Pro-Environmental Behavior: A Systematic Literature Review of The Role of Culture and Self-Construal. *Sustainability* **2021**, *13*, 5156. [CrossRef]
74. Bachar, R.K.; Bhuniya, S.; Ghosh, S.K.; Sarkar, B. Controllable Energy Consumption in a Sustainable Smart Manufacturing Model Considering Superior Service, Flexible Demand, and Partial Outsourcing. *Mathematics* **2022**, *10*, 4517. [CrossRef]
75. Brown, P.; Ly, T.; Pham, H.; Sivabalan, P. Automation and management control in dynamic environments: Managing organisational flexibility and energy efficiency in service sectors. *Br. Account. Rev.* **2020**, *52*, 100840. [CrossRef]
76. Lewczuk, K.; Kłodawski, M.; Gepner, P. Energy Consumption in a Distributional Warehouse: A Practical Case Study for Different Warehouse Technologies. *Energies* **2021**, *14*, 2709. [CrossRef]
77. Klumpp, M.; Loske, D. Sustainability and Resilience Revisited: Impact of Information Technology Disruptions on Empirical Retail Logistics Efficiency. *Sustainability* **2021**, *13*, 5650. [CrossRef]
78. Gutelius, B.; Theodore, N. *The Future of Warehouse Work: Technological Change in the US Logistics Industry*; UC Berkeley Labor Center: Berkeley, CA, USA, 2019.
79. Fu, W.; Su, H.-C. Take actions or outsource? An empirical examination of strategic environmental options on greenhouse gas emissions. *Int. J. Oper. Prod. Manag.* **2020**, *40*, 753–776. [CrossRef]
80. Deus, R.M.; Savietto, J.P.; Battistelle, R.A.; Ometto, A.R. Trends in publications on the circular economy. *Rev. Espac.* **2017**, *38*. Available online: http://hdl.handle.net/11449/179432 (accessed on 30 May 2023).
81. Merli, R.; Preziosi, M.; Acampora, A. How do scholars approach the circular economy? A systematic literature review. *J. Clean. Prod.* **2018**, *178*, 703–722. [CrossRef]
82. Benton, W.; Maloni, M. The influence of power driven buyer/seller relationships on supply chain satisfaction. *J. Oper. Manag.* **2005**, *23*, 1–22. [CrossRef]
83. SDG Compass. The SDG Compass Provides Guidance for Companies on How They Can Align Their Strategies as Well as Measure and Manage Their Contribution to the Realization of the SDGs. 2017. Available online: http://sdgcompass.org (accessed on 30 May 2023).

84. UN News. World of Business Must Play Part in Achieving SDGs, Ban Says. 2016. Available online: https://www.un.org/sustainabledevelopment/blog/2016/01/world-of-business-must-play-part-in-achieving-sdgs-ban-says/ (accessed on 30 May 2023).
85. Zimon, D.; Tyan, J.; Sroufe, R. Drivers of sustainable supply chain management: Practices to alignment with un sustainable development goals. *Int. J. Qual. Res.* **2020**, *14*, 219–236. [CrossRef]
86. Liu, X.; Qian, C.; Wang, S. When do 3PLs initiate low-carbon supply chain integration? *Int. J. Oper. Prod. Manag.* **2020**, *40*, 1367–1395. [CrossRef]
87. Tan, K.; Ahmed, M.D.; Sundaram, D. Sustainable enterprise modelling and simulation in a warehousing context. *Bus. Process. Manag. J.* **2010**, *16*, 871–886. [CrossRef]
88. Mihova, L. The impact of sustainable development on warehousing. In Proceedings of the International Scientific Conference—EMAN 2020—Economics and Management: How to Cope With Disrupted Times, Virtual, Slovenia, 3 September 2020; pp. 135–141.
89. Minashkina, D.; Happonen, A. A development of the warehouse management system selection framework as academic-industrial collaboration work with sustainability considerations. *Int. Eng. Res. Conf.* **2020**, *2233*, 050012. [CrossRef]
90. Minashkina, D.; Happonen, A. A Systematic Literature Mapping of Current Academic Research Connecting Sustainability into the Warehouse Management Systems Context. *Curr. Approaches Sci. Technol. Res.* **2021**, *5*, 52–80. [CrossRef]
91. United Nations. The 17 Goals. 2015. Available online: https://sdgs.un.org/goals (accessed on 2 February 2023).
92. Abdelsalam, A.; Happonen, A.; Karha, K.; Kapitonov, A.; Porras, J. Toward Autonomous Vehicles and Machinery in Mill Yards of the Forest Industry: Technologies and Proposals for Autonomous Vehicle Operations. *IEEE Access* **2022**, *10*, 88234–88250. [CrossRef]
93. Kortelainen, H.; Happonen, A.; Kinnunen, S.-K. Fleet Service Generation—Challenges in Corporate Asset Management. In Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015), Tampere, Finland, 28–30 September 2015; Lecture Notes in Mechanical Engineering. Springer: Cham, Switzerland, 2016; pp. 373–380. [CrossRef]
94. Kinnunen, S.K.; Happonen, A.; Arola, S.M.; Kärri, T. Traditional and extended fleets in literature and practice: Definition and untapped potential. *Int. J. Strat. Eng. Asset Manag.* **2019**, *3*, 239. [CrossRef]
95. Ahi, P.; Searcy, C. Assessing sustainability in the supply chain: A triple bottom line approach. *Appl. Math. Model.* **2015**, *39*, 2882–2896. [CrossRef]
96. Ma, J. A Sustainable Modular Product Design Approach with Key Components and Uncertain End-of-life Options Consideration. Ph.D. Thesis, The Pennsylvania State University, State College, PA, USA, 2016.
97. Minashkina, D.; Happonen, A. A systematic literature mapping of current academic research linking warehouse management systems to the third-party logistics context. *Acta Logistica.* **2023**, *10*, 209–228. [CrossRef]
98. Nunes, M.F.; Park, C.L.; Paiva, E.L. Can we have it all? Sustainability trade-offs and cross-insurance mechanisms in supply chains. *Int. J. Oper. Prod. Manag.* **2020**, *40*, 1339–1366. [CrossRef]
99. Matos, S.V.; Schleper, M.C.; Gold, S.; Hall, J.K. The hidden side of sustainable operations and supply chain management: Unanticipated outcomes, trade-offs and tensions. *Int. J. Oper. Prod. Manag.* **2020**, *40*, 1749–1770. [CrossRef]

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ISBN 978-3-0365-9710-2