sustainability

MDPI

Review

The Impact of Industry 4.0 Technologies on Key Performance Indicators for a Resilient Supply Chain 4.0

Catherine Marinagi [1,*], Panagiotis Reklitis [2], Panagiotis Trivellas [2] and Damianos Sakas [3]

[1] Department of Agribusiness and Supply Chain Management, School of Applied Economics and Social Sciences, Agricultural University of Athens, Iera Odos 75, GR11855 Athens, Greece
[2] Organizational Innovation and Management Systems Laboratory (ORIMAS), Department of Agribusiness and Supply Chain Management, School of Applied Economics and Social Sciences, Agricultural University of Athens, Iera Odos 75, GR11855 Athens, Greece; preklitis@aua.gr (P.R.); ptrivel@aua.gr (P.T.)
[3] Business Information and Communication Technologies in Value Chains Laboratory (BICTEVAC), Department of Agribusiness and Supply Chain Management, School of Applied Economics and Social Sciences, Agricultural University of Athens, Iera Odos 75, GR11855 Athens, Greece; d.sakas@aua.gr
* Correspondence: marinagi@aua.gr; Tel.: +30-2262022569

Abstract: The term "Resilient Supply Chain 4.0" incorporates two research areas: Industry 4.0 and Supply Chain Resilience (SCRes). Industry 4.0 technologies include innovations such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), Augmented Reality (AR), Cloud Computing (CC), the Internet of Services (IoS), Big Data Analytics (BDA), Artificial Intelligence (AI), Digital Twins (DT), Blockchain (BC), Industrial Robotics (IR), and Additive Manufacturing (AM). Industry 4.0 technologies do not have a direct impact on SCRes, but on resilience elements such as flexibility, redundancy, visibility, agility, collaboration, robustness, and information sharing. This paper aims to investigate which of the Industry 4.0 technologies can help improve the Key Performance Indicators (KPIs) that are used for creating a Resilient Supply Chain 4.0. A non-systematic literature review has been conducted for the identification of (a) the most important constituent elements of SCRes, (b) the Industry 4.0 technologies that improve the SCRes elements, and (c) the KPIs that enhance SCRes. A systematic literature review has been conducted to identify which of the Industry 4.0 technologies have an impact on the KPIs that enhance SCRes. The findings of this work demonstrate that Industry 4.0 technologies can help improve the KPIs for a Resilient Supply Chain 4.0.

Keywords: Resilient Supply Chain 4.0; supply chain resilience; Industry 4.0; key performance indicators; KPIs

Citation: Marinagi, C.; Reklitis, P.; Trivellas, P.; Sakas, D. The Impact of Industry 4.0 Technologies on Key Performance Indicators for a Resilient Supply Chain 4.0. *Sustainability* **2023**, *15*, 5185. https://doi.org/10.3390/su15065185

Academic Editor: Paulo Peças

Received: 10 January 2023
Revised: 8 March 2023
Accepted: 10 March 2023
Published: 15 March 2023

1. Introduction

Major disruptions with a frequent occurrence expose supply chains (SCs) to changes, increasing their vulnerability. The categories of risks that supply chains are facing are [1,2]: (a) external or environmental risks (e.g., pandemics, geopolitical conflicts, natural disasters, intentional attacks, and cyberattacks), which are unexpected and unavoidable and organizations can only be prepared to mitigate the disruptions, and (b) internal risks, which include production risks (e.g., equipment malfunctions), management risks (e.g., lack of skilled staff, coordination problems, productivity problems), information risks (e.g., loss of data, information system failure), and supply and demand risks (e.g., customer change orders, delays in delivery). Resilience capabilities in SCs enable adaptation to the disruptions and restoration of normal supply network operations [3,4].

Industry 4.0 expresses the fourth industrial revolution that characterizes the 21st century. The term "Industry 4.0" was introduced in Germany in 2011 by a Working Group of academics and industry professionals with the aim of studying the impact of innovative Digital Technology systems on manufacturing [5]. Examples of core Industry 4.0 technologies are the Internet of Things (IoT), Cyber-Physical Systems (CPS), Big Data

Analytics (BDA), Artificial Intelligence (AI) and Additive Manufacturing (AM). Many other digital technologies are considered as key enabling technologies for Industry 4.0 [6–39].

Many studies have explored the impression of Industry 4.0 on SC management and logistics [40–60]. Consequently, the term "Supply Chain 4.0" has been used to emphasize the applicability and impacts of Industry 4.0 technologies in the context of SC [45,47,59]. More specifically, when different functions of SC are digitalized using Industry 4.0 technologies, they are assumed to be transformed into 4.0 [47], namely, Logistics 4.0 [6,8], Procurement 4.0 [7], Warehousing 4.0 [8], and Manufacturing 4.0 [54]. Alternatively, researchers use the term "Smart Supply Chain" [11,18] and the terms smart logistics [10,12], smart procurement [43], smart warehousing [9,43], smart manufacturing [10,16,18,19], and smart factory [10,12,16]. The word "smart" is used to express the acquisition of connectivity, intelligence, and automation through the utilization of Industry 4.0 technologies. There are also many studies that have explored the potentials of a particular Industry 4.0 technology in SC management and logistics [61–79].

We introduce the term "Resilient Supply Chain 4.0" to express the interoperability of Industry 4.0 with a supply chain aiming to create resilience. Recent developments in Industry 4.0 technologies and the exploitation of their applications for supply chain resilience (SCRes) have attracted researchers' attention [80–116]. For example, Spieske and Birkel in 2021 [96] conducted a systematic review of Industry 4.0 technologies' potential to support SCRes and created a framework focusing on applications that could help mitigate risks caused by a pandemic. Some researchers explore the impact of the adoption of several digital tools of Industry 4.0 on SCRes [80–97], while others study the impact of a single digital tool on SCRes [98–116]. However, Industry 4.0 technologies do not have a direct impact on SCRes but on resilience elements such as flexibility, redundancy, visibility, agility, collaboration, robustness, security, and information sharing [96].

Key Performance Indicators (KPIs) are metrics that the organizations should calculate on a regular base to monitor and evaluate processes. KPIs are among the organizational strategy elements that are heavily impacted by Industry 4.0 [21]. Many researchers report that monitoring KPIs can help build resilient supply chains [117–119].

The aim of this research is to investigate which Industry 4.0 technologies can have an impact on the KPIs that are used for creating a resilient supply chain. In order to achieve this objective, first the constituent elements of SCRes need to be determined, and which of the Industry 4.0 technologies can improve each of the selected elements needs to be examined. The appropriate KPIs that enhance SCRes then need to be identified, and, finally, the specific Industry 4.0 technologies that influence the selected KPIs can be determined. The research methodology is the literature review.

The remainder of this paper is structured as follows. In Section 2, the research methodology of this study is presented. In Section 3, the resilience of SCs is discussed. Definitions of the term "Supply Chain Resilience" (SCRes) are given and the elements that enhance SCRes are explored. Section 4 deals with the Resilient Supply Chain 4.0. The most influential Industry 4.0 technologies are discussed, and then the impact of specific Industry 4.0 technologies on the SCRes is determined. In Section 5, the KPIs for SCRes are discussed, and the impact of Industry 4.0 technologies on the selected KPIs is determined. Section 6 concludes this paper, and Section 7 gives the limitations of this study and future research recommendations.

2. Research Methodology

The main objective of our study is to investigate how the KPIs for enhancing SCRes are affected by the most important Industry 4.0 technologies.

Specifically, this study examines the following research questions:

RQ1: Which of the Industry 4.0 technologies have an impact on each constituent element of SCRes?

RQ2: Which of the Industry 4.0 technologies have an impact on each KPI used for making an SC resilient?

To answer RQ1, first we need to investigate which are the most important SCRes constituent elements, and then how each of the selected Industry 4.0 technologies influence each of these SCRes elements. Additionally, to answer RQ2, first we need to search for publications that identify KPIs for SCRes, focusing on the relation between SCRes constituent elements and KPIs. We then need to exploit the results of RQ1 to determine how each of the selected Industry 4.0 technologies affect the selected KPIs.

In the following, we describe in detail the steps of the literature review that was conducted in this study. The gradual implementation of the overall research methodology is graphically illustrated in Figure 1.

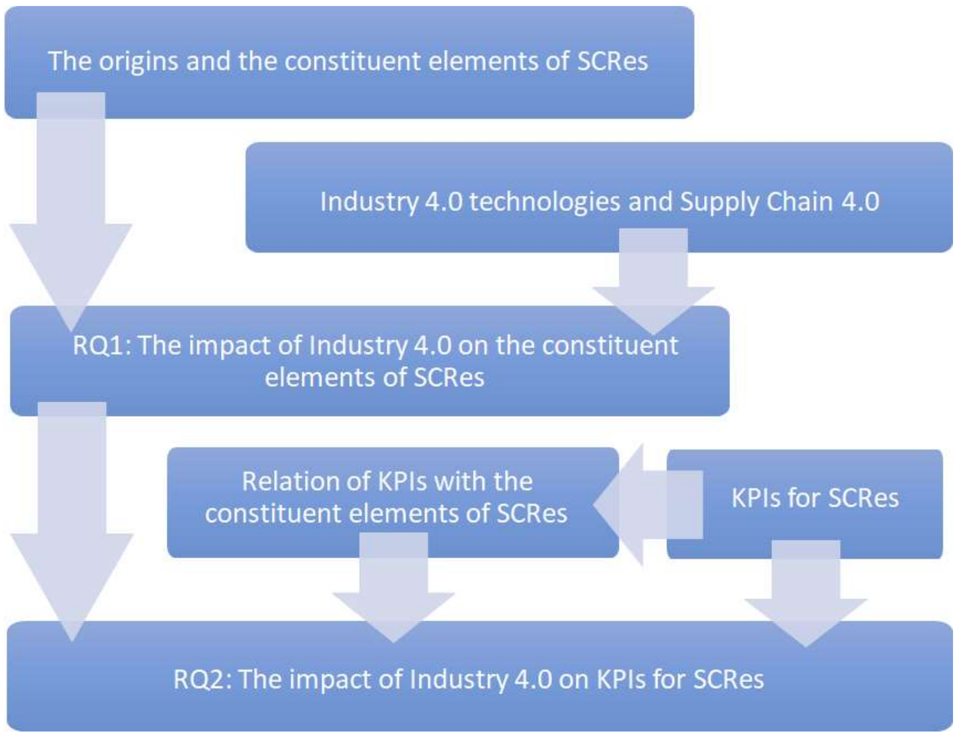

Figure 1. The steps of Research methodology.

We started non-systematically searching Google Scholar and Scopus databases to find some recently published papers that discuss the origins of SCRes [2,3,120], and we focused on publications that identify the constituent elements of SCRes [2,3,120–144]. During this investigation, we selected some definitions of SCRes [3,125–127,134,142]. Section 3 presents the results of this step of our investigation.

Regarding RQ1, we first non-systematically searched Google Scholar and Scopus databases for publications in Industry 4.0 technologies [6–39]. Among them, there are articles that present the state of the art and review Industry 4.0 technologies and applications [5,13–22]. Furthermore, we searched for publications that present studies on specific Industry 4.0 technologies [23–39]. We then continued searching for publications that explore the notion of Supply Chain 4.0 or smart supply chain [40–60] and the role of specific Industry 4.0 technologies in the supply chain [61–79]. Consequently, we non-systematically investigated Google Scholar and Scopus databases to find publications that explore the impact of Industry 4.0 technologies on SCRes [80–116]. Among them, there are studies that investigate the impact of a single Industry 4.0 technology on SCRes [98–116], while other studies explore the impact of the adoption of Industry 4.0 technologies on SCRes without focusing on a particular technology [80–97]. Since Industry 4.0 technologies do not have a direct impact on SCRes but on resilience elements such as flexibility, redundancy, visibility, agility, collaboration, robustness, and information sharing, we focused our research on determining how each of the Industry 4.0 technologies influence each of the most important constituent elements of SCRes. Section 4 presents the literature review and the results of the investigation related to RQ1.

Regarding RQ2, we searched systematically for publications that identify the impact of Industry 4.0 technologies on KPIs used for creating a resilient SC. The keywords were not determined from the beginning but emerged during the research process of the previous steps and particularly after answering RQ1. More specifically, we searched Scopus database using the following search rule:

TITLE-ABS-KEY ((“supply chain” OR “supply chain 4.0” OR “smart supply chain” OR “digital supply chain”) AND (resilien* OR risk) AND (“industry 4.0” OR “digital industry” OR *4.0 OR smart* OR IoT OR “Internet of Things” OR IoS OR “Internet of Services” OR “Cyber-Physical*” OR “Cyber Physical*” OR CPS OR “Artificial Intelligence” OR “Big Data” OR “Augmented Reality” OR “3D print*” OR “Additive Manufactur*” OR “Digital Twin*” OR blockchain* OR “cloud computing” OR robot*) AND ((performance AND (indicator* OR metric* OR measure*)) OR kpi*)).

This search gave back 133 results, where 86 are articles (duplicates were eliminated) and only 18 are relevant to our study [92,117,145–160]. Among them, 12 publications [145,147,148,151,152,154–160], even though they provide useful knowledge to our study, do not directly contribute to RQ2. For example, Essakly et al. [152] propose KPIs for the assessment of Industry 4.0 solutions in SC, but these KPIs are not related to SCRes.

Most relevant to RQ2 are only 5 out of 13 publications [92,117,146,149,150]. Dev et al. [92] propose the monitoring of KPIs to help create SCRes in a smart factory framework consisting of Industry 4.0 technologies. KPIs that are related with AM technology are considered in reverse logistics chain scenarios. The study conducted by Catellani and Bottani [149] identified KPIs for Lean, Agile, Resilient, and Green SC, and evaluated them. The role of Industry 4.0 technologies in SC performance was investigated in parallel but was not connected to each of the evaluated KPIs. Dumitrascu et al. [150] used AI techniques to predict which KPI should be linked to an identified problem within the organization. Monitoring KPIs, the trend line can be observed, and potential risks can be eliminated, increasing the SCRes. Ansari and Kohl [146] provided an approach based on AI for the analysis of KPIs for SCRes and manufacturing resilience. A recent study conducted by Patidar et al. [117] identified KPIs of a resilient SC and evaluated them under the perspective of Industry 4.0 technologies and sustainability. We have adopted the list of KPIs proposed in [117] and we have attempted further research aiming to determine which of the Industry 4.0 technologies affect these KPIs. Table 1 includes the aforementioned publications that identify KPIs for building a Resilient Supply Chain 4.0, and their main research objectives. The differentiation of our study is also mentioned.

Therefore, this study is built upon the work of Patidar et al. [117] to extend current results on how the KPIs for SCRes are influenced by the most important Industry 4.0 technologies. To achieve this objective, we first searched which of the Industry 4.0 technologies have a direct impact on the identified KPIs. We then explored the relation between the SCRes elements and the KPIs, and combined the results of RQ1 to give the Industry 4.0 technologies that improve each of the SCRes elements and indirectly improve the KPIs. Section 5 presents the results of the investigation related with the RQ2.

Table 1. Selected studies in KPIs for a Resilient Supply Chain 4.0.

Study	Research Objectives
Ansari and Kohl, 2022 [146]	Propose an approach based on AI for the analysis of KPIs for SCRes and manufacturing resilience
Dev et al., 2021 [92]	Evaluate KPIs for SCRes in a smart factory framework consisting of Industry 4.0 technologies. KPIs related with AM technology are identified
Dumitrascu et al., 2020 [150]	Utilize AI techniques to predict which KPI should be linked to an identified problem within the organization. Monitoring KPIs, the potential risks can be eliminated, increasing the SCRes
Catellani and Bottani, 2022 [149]	Identify and evaluate KPIs for Lean, Agile, Resilient, Green SC. The role of Industry 4.0 in SC performance is not connected with each of the KPIs
Patidar et al., 2022 [117]	Identify KPIs for SCRes and evaluate KPIs under Industry 4.0 and sustainability perspectives
Our study	Investigate the impact of discrete Industry 4.0 technologies on the KPIs for SCRes

3. Supply Chain Resilience

3.1. Definitions of Supply Chain Resilience

The concept of organization resilience [121,131,132] was determined earlier than that of SCRes. Mallak in 1998 [132] stated: "to be resilient (an individual or an organization) need to learn how to quickly design and implement positive adaptive behaviors matched to the immediate situation, while enduring minimal stress". According to Mallak [132], positive adaptive behavior perceives change as an opportunity, adapting responses to the needs of the situation.

Ali et al. [120] noticed that the foundation of the SCRes literature is mainly based on the findings reported in [3,125,135]. In 2003, Rice and Caniato [3] introduced the term "resilient supply network", stating: "A supply network is resilient when it can respond to unexpected disruptions and restore normal supply network operations". The term Supply Chain Resilience (SCRes) is mostly preferred in the literature.

Several other definitions of SCRes have been stated by researchers. We have selected six definitions of the term SCRes from 2003 to 2022, as shown in Table 2. Christopher and Peck, in 2004 [125], gave a brief but comprehensive definition, defining SCRes as the ability of a system to return to its original state or move to a new, more desirable state after being disturbed. In 2009, Ponomarov and Holocomb [134] gave a more descriptive definition, adding the ability of the supply chain to be prepared for unexpected events, except for the ability to respond to disruptions and recover from them. In 2012, Ponis and Koronis [142] extended previous definitions, stating that when a resilient SC network anticipates unexpected disruption, it gains a competitive advantage. Hohenstein et al., in 2015 [127], also added that a resilient SC returns to its original situation or grows by moving to a new, more desirable state, with the objective of increasing customer service, market share, and financial performance. Another interesting definition was given by Datta, in 2017 [126], with SCRes as a dynamic process of directing activities that protect the organization from disruptions, and in case a disruption occurs, trigger a very rapid response that maintains or regains a dynamically stable state, thereby enabling the adaptation of operations to the new requirements before the competitors.

Table 2. Definitions of Supply Chain Resilience.

Author(s)	Definition of Supply Chain Resilience
Rice and Caniato, 2003 [3]	"A supply network is resilient when it can respond to unexpected disruptions and restore normal supply network operations".
Christopher and Peck, 2004 [125]	"The ability of a system to return to its original state or move to a new, more desirable state after being disturbed".
Ponomarov and Holocomb, 2009 [134]	"The adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function".
Ponis and Koronis, 2012 [142]	"The ability to proactively plan and design the Supply Chain network for anticipating unexpected disruptive (negative) events, respond adaptively to disruptions while maintaining control over structure and function and transcending to a post-event robust state of operations, if possible, more favorable than the one prior to the event, thus gaining competitive advantage".
Hohenstein et al., 2015 [127]	"Supply chain's ability to be prepared for unexpected risk events, responding and recovering quickly to potential disruptions to return to its original situation or grow by moving to a new, more desirable state in order to increase customer service, market share and financial performance".
Datta, 2017 [126]	"Supply chain resilience is a dynamic process of steering the actions so that the organisation always stays out of danger zone, and if the disruptive/uncertain event occurs, resilience implies initiating a very rapid and efficient response to minimise the consequences and maintaining or regaining a dynamically stable state, which allows it to adapt operations to the requirements of the changed environment before the competitors and succeed in the long run".

3.2. Capabilities and Elements of Supply Chain Resilience

In the literature, we can find different lists of elements that enhance SCRes. Researchers agree that Industry 4.0 technologies influence SCRes indirectly, affecting specific elements [96]. For this reason, it is crucial to identify these elements first, and then determine which of them are improved by specific Industry 4.0 technologies. The elements are also referred as indicators [160,161], enablers [133,136], enhancers [137], capabilities [138], or antecedents [96]. Many researchers have contributed, adding more elements, grouping elements into levels, or prioritizing the most important elements.

Ponis and Koronis in 2012 [142] propose that the most important elements of SCRes are agility, flexibility, velocity, visibility, availability, redundancy, mobilization of resources, collaboration, and SC structure knowledge. The authors proposed a grouping of these elements in four structural elements, namely, agility, redundancy, collaboration, and knowledge of SC structure. They also clarified that agility includes flexibility and velocity, redundancy is differentiated from flexibility and agility, and collaboration includes information sharing, collaborative work, joint decision making, and visibility. According to Scholten and Schilder [143], collaboration in the form of information sharing can increase SCRes via increased visibility, velocity, and flexibility.

Ali et al. in 2017 [120] analyzed 103 articles from 2003 to 2015 and concluded that the definition of SCRes is three dimensional. The first dimension is related to the time of reaction: before, during, or after disruption. The second dimension concerns the strategies that are applied—namely, proactive, concurrent, and reactive. The proactive strategy concerns the pre-disruption phase, the concurrent strategy concerns the phase during the disruption, and the reactive strategy concerns the post-disruption phase. The third dimension is related with the capabilities that are necessary for a resilient supply chain. The capabilities include one proactive capability, i.e., the ability to anticipate risk; two concurrent capabilities, i.e., the ability to adapt and the ability to respond; and two reactive capabilities, i.e., the ability to recover and the ability to learn. The authors [120] also identified 27 elements that build SCRes capabilities. Out of these 27 elements, 13 essential elements are selected to support the five resilient capabilities. The ability to anticipate is supported by situation awareness, robustness, increasing visibility, and knowledge management (pre-disruption). The ability to adapt is supported by increasing flexibility and building redundancy. The ability to respond is supported by collaboration and agility. The ability to recover is supported by contingency planning and market position. Finally, the ability to learn is supported by knowledge management (post-disruption) and building social capital.

In 2009, Ponomarov and Holocomb [134] studied the concept of SCRes as a multidimensional phenomenon. Social, psychological, and economic dimensions were explored. Three phases of SCRes were determined: readiness, response, and recovery. Three psychological principles were determined: control, coherence, and connectedness. Control is the guidance and adjustment of strategic and tactical actions throughout the supply network. Coherence is the deeper understanding of a disruption or a threat. Connectedness is the tendency of people to gather when a crisis occurs. A set of elements are then grouped into these phases and categories. For example, flexibility, agility, and risk-sharing are grouped into the response phase and coherence principle.

Numerous other studies propose lists of elements for SCRes and the grouping of these elements. For example, we could mention the studies that are reported by Christopher and Peck in 2004 [125], Blackhurst et al. in 2005 [137], Wieland and Wallenburg in 2012 [140] and 2013 [141], Pettit et al. in 2013 [138], Tukamuhabwa et al. in 2015 [2], Kochan and Nowicki in 2018 [130], Pereira et al. in 2014 [133], Datta in 2019 [126], Singh, et al. in 2019 [161], and Spieske and Birkel in 2021 [96]. Table 3 shows the most essential elements of SCRes and their description according to the literature.

Table 3. The constituent elements of SCRes.

Element	Description	Sample References
SC configuration/ SC network design	The ability to quickly redesign the supply chain	Christopher and Peck, 2004 [125]; Blackhurst et al., 2005 [137]; Pereira et al., 2014 [133]; Scholten et al., 2014 [144]; Soni et al., 2014 [136]; Tukamuhabwa et al., 2015 [2]; Ali et al., 2017 [120]; Singh et al., 2019 [161]; Spieske and Birkel, 2021 [96]
Redundancy	The maintenance of extra capacity in case of supply deficiencies	Christopher and Peck, 2004 [125]; Ponis and Koronis, 2012 [142]; Pettit et al., 2013 [138]; Pereira et al., 2014 [133]; Tukamuhabwa et al., 2015 [2]; Ali et al., 2017 [120]; Kochan and Nowicki, 2018 [130]; Singh et al., 2019 [161]; Hsu et al., 2021 [1]
Flexibility	The capacity of the supply chain to adjust to changes occurring at resource and shop floor level, at plant level, at firm level, and at network level	Christopher and Peck, 2004 [125]; Rice and Caniato, 2003 [3]; Blackhurst et al., 2005 [137]; Sheffi and Rice, 2005 [135]; Ponomarov and Holcomb, 2009 [134]; Ponis and Koronis, 2012 [142]; Pettit et al., 2013 [138]; Pereira et al., 2014 [133]; Soni et al., 2014 [136]; Scholten & Schilder, 2015 [143]; Tukamuhabwa et al., 2015 [2]; Ali et al., 2017 [120]; Kochan and Nowicki, 2018 [130]; Hsu et al., 2021 [1]
Visibility	The ability to see the supply chain from one end to another and find the place of a disruptive event	Christopher and Peck, 2004 [125]; Ponis and Koronis, 2012 [142]; Pettit et al., 2013 [138]; Pereira et al., 2014 [133]; Soni et al., 2014 [136]; Scholten & Schilder, 2015 [143]; Tukamuhabwa et al., 2015 [2]; Ali et al., 2017 [120]; Kochan and Nowicki, 2018 [130]; Singh et al., 2019 [161]; Spieske and Birkel, 2021 [96]; Hsu et al., 2021 [1]
Collaboration	The ability to plan and execute supply chain operations jointly with other firms. Mutual trust and willingness to share information are needed	Ponis and Koronis, 2012 [142]; Pettit et al., 2013 [138]; Pereira et al., 2014 [133]; Scholten et al., 2014 [144]; Soni et al., 2014 [136]; Scholten & Schilder, 2015 [143]; Tukamuhabwa et al., 2015 [2]; Kochan and Nowicki, 2018 [130]; Ali et al., 2017 [120]; Datta, 2019 [126]; Spieske and Birkel, 2021 [96]; Hsu et al., 2021 [1]

Table 3. *Cont.*

Element	Description	Sample References
Agility	The ability to react rapidly to an unpredictable change in supply and/or demand. Responsiveness	Christopher and Peck, 2004 [125]; Ponis and Koronis, 2012 [142]; Wieland and Wallenburg, 2012 [140]; Pereira et al., 2014 [133]; Scholten et al., 2014 [144]; Soni et al., 2014 [136]; Scholten & Schilder, 2015 [143]; Tukamuhabwa et al., 2015 [2]; Ali et al., 2017 [120]; Kochan and Nowicki, 2018 [130]; Singh et al., 2019 [161]; Datta, 2019 [126]; Spieske and Birkel, 2021 [96]; Hsu et al., 2021 [1]
Situation Awareness	The ability to understand SC vulnerabilities and plan for disruption events	Ali et al., 2017 [120]; Singh et al., 2019 [161]; Datta, 2019 [126]; Spieske and Birkel, 2021 [96]; Hsu et al., 2021 [1]
Information Sharing	The ability to share information of organization assets or events pre/during/post-disruption	Pereira et al., 2014 [133]; Soni et al., 2014 [136]; Ali et al., 2017 [120]; Singh et al., 2019 [161]; Hsu et al., 2021 [1]
SC Risk Management (SCRM) Culture	Risk understanding, supply chain structure understanding, SCRM learning	Christopher and Peck, 2004 [125]; Pereira et al., 2014 [133]; Tukamuhabwa et al., 2015 [2]; Ali et al., 2017 [120]; Singh et al., 2019 [161]; Spieske and Birkel, 2021 [96]
Security	Essential part of SCRes. Can be physical security, information security or freight security	Christopher and Peck, 2004 [125]; Rice and Caniato, 2003 [3]; Pettit et al., 2013 [138]; Scholten et al., 2014 [144]; Tukamuhabwa et al., 2015 [2]; Ali et al., 2017 [120]; Kochan and Nowicki, 2018 [130]; Singh et al., 2019 [161]; Hsu et al., 2021 [1]
Robustness	The ability of the supply chain to resist change and anticipate change proactively	Christopher and Peck, 2004 [125]; Sheffi and Rice, 2005 [135]; Wieland and Wallenburg, 2012 [140] and 2013 [141]; Soni et al., 2014 [136]; Scholten & Schilder, 2015 [143]; Ali et al., 2017 [120]; Singh et al., 2019 [161]
Risk Management	A set of actions that increase the ability to anticipate risk, respond, and/or recover from the impacts of disruption	Scholten et al., 2014 [144]; Soni et al., 2014 [136]; Scholten and Schilder, 2015 [143]; Ali et al., 2017 [120]; Singh et al., 2019 [161]; Datta, 2019 [126]
Knowledge Management	Pre-disruption: The ability to acquire knowledge from past experiences to be prepared for a future disruption Post-disruption: The ability to learn how to develop better solutions after a disruption occurs	Christopher and Peck, 2004 [125]; Rice and Caniato, 2003 [3]; Ponomarov and Holcomb, 2009 [134]; Ponis and Koronis, 2012 [142]; Pettit et al., 2013 [138]; Pereira et al., 2014 [133]; Scholten et al., 2014 [144]; Soni et al., 2014 [136]; Tukamuhabwa et al., 2015 [2]; Ali et al., 2017 [120]
Velocity	The speed of performing flexible adaptations and recover from a disruption	Ponis and Koronis, 2012 [142]; Tukamuhabwa et al., 2015 [2]; Ali et al., 2017 [120]; Kochan and Nowicki, 2018 [130]; Singh et al., 2019 [161]; Spieske and Birkel, 2021 [96]; Hsu et al., 2021 [1]

4. Resilient Supply Chain 4.0

Legner et al. [22] clarified the difference between the terms digitization and digitalization. Digitization is the process associated with converting analogue signals into a digital form, while digitalization refers to "the sociotechnical phenomena and processes of adopting of these (digital) technologies in broader individual, organizational and societal perspectives". Queiroz et al. [53] argue that digitalization is a superset of digitization. In the context of SC management, digitation refers to the adoption of capabilities concerning digital technologies, while in digitalization these adopted capabilities impact all stakeholders of the SC and can enable the improvement of an organization's competitiveness.

The digital technologies that are considered as enablers for Industry 4.0 include innovations such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), Augmented Reality (AR), Cloud Computing (CC), the Internet of Services (IoS), Big Data Analytics (BDA), Artificial Intelligence (AI), Digital Twins (DT), Industrial Robotics (IR), Blockchain

(BC), Additive Manufacturing (AM). Govindan et al. [47] classify Industry 4.0 innovations into technologies (e.g., CPS, AR, AI, BDA, DT, IR, AM) and concepts (e.g., IoT, IoS, CC).

In the following, we will investigate the impact of these selected Industry 4.0 technologies on SCRes based on previous literature. The reader can find a long list of Industry 4.0 technologies in Mittal et al. in 2019 [19], in Amoozad Mahdiraji et al. in 2022 [157], and in published reviews on Industry 4.0 technologies, such as the reviews reported by Lu in 2017 [16], Hofmann and Rüsch in 2017 [48], Xu et al. in 2018 [15], Oztemel and Gursev in 2018 [17], and Kosacka-Olejnik and Pitakaso in 2019 [13].

"Supply Chain 4.0" or "Smart Supply Chain" is a term that declares the transformation of a traditional SC when Industry 4.0 technologies are adopted [11,45,59,80]. There are numerous studies that analyze the impression of Industry 4.0 on SC management and logistics [40–60]. The study presented in [56] by Sharma et al., shows that Industry 4.0 technologies can support the implementation of sustainable SC management initiatives in multi-tier manufacturing SCs. The results of the study conducted by Tjahjono et al. [59] showed that the areas which are most affected by the introduction of Industry 4.0 technologies in SC are order fulfillment and transport logistics. Garay-Rondero et al. [46] proposed a conceptual framework of digital SC, which incorporates the role of Industry 4.0. Moreover, there are many studies that focus on the impact of a single Industry 4.0 technology on SC management and logistics [61–79].

Interesting applications of Industry 4.0 technologies are reported in different SCs, such as fashion SC [1], manufacturing SC [36] (including automotive industry) [81,150], and airline industry [81], agri-food SC [57], fresh food SC [73], food retail SC [148], humanitarian SC [49], pharmaceutical SC [93], and vaccine SC [1].

A "Resilient Supply Chain 4.0" results when Industry 4.0 technologies are applied to a SC aiming to enhance its resilience. The literature related to "Resilient Supply Chain" is mainly focused on the determination of the constituent elements of SCRes, their interrelation, and their grouping. The literature related to "Resilient Supply Chain 4.0" investigates the impact of Industry 4.0 technologies on SCRes or on the constituent elements of SCRes.

A recent study conducted in 2022 by Tortorella et al. [80] identified the contribution of Industry 4.0 technologies into SCs with the objective of improving SCRes. Several studies give evidence that Industry 4.0 technologies positively impacts SCRes [84,95,119], while Sharma et al. [56] found that resilient practices are positively associated with Industry 4.0 technologies. Dilyard et al. [82] examined the use of Industry 4.0 technologies to enhance SCRes in the case of the COVID-19 pandemic.

Ivanov, Dolgui, and Sokolov [91] have studied how Industry 4.0 affect the SC disruption risk management and the ripple effect to design a resilient supply chain. The ripple effect occurs when a disruption cannot be prevented at a local level but is propagated downstream impacting SC performance. Valilai and Sodachi [60] consider that resiliency is embedded in sustainability assessment. They propose a sustainability assessment model that connects the sustainability assessment frameworks with Industry 4.0 related analytical platforms, with the help of the resiliency concept.

Table 4 includes the selected Industry 4.0 technologies, which are found to influence SCRes according to the literature review. In the following, we will discuss each of these technologies and report how they influence each of the selected SCRes elements that are included in Table 3. The results of this investigation are then included in Table 5.

Table 4. Industry 4.0 technologies that enhance SCRes.

Industry 4.0 Technology	Sample References
IoT	Ashton, 2009 [23]; Gnimpieba et al., 2015 [62]; Maslarić et al., 2016 [12]; Witkowski, 2017 [77]; Douaioui et al., 2018 [10]; Zhang, 2018 [63]; Al-Talib et al., 2020 [98]; Dev et al., 2021 [92]; Zouari et al., 2021 [84]; Fatorachian and Kazemi, 2021 [97]; Spieske and Birkel, 2021 [96]; Shrivastava et al., 2021 [27]; Hofmann and Rüsch, 2017 [48]; Govindan et al., 2022 [47]; Tortorella et al., 2022 [80]
CPS	Kyoung-Dae et al., 2012 [25]; Vogel-Heuser et al., 2016 [20]; Almada-Lobo, 2016 [5]; Douaioui et al., 2018 [10]; Zhang, 2018 [63]; Nica, 2019 [99]; Tran et al., 2019 [26]; Dev et al., 2021 [92]; Spieske and Birkel, 2021 [96]; Fatorachian and Kazemi, 2021 [97]; Hofmann and Rüsch, 2017 [48]; Govindan et al., 2022 [47]; Tortorella et al., 2022 [80]
AR	Fraga-Lamas et al., 2017 [28]; del Amo et al., 2018 [30]; Butt, 2020 [36]; Lavingia and Tanwar, 2020 [29]; Rejeb et al., 2021 [64]; Zouari et al., 2021 [84]; Govindan et al., 2022 [47]; Tortorella et al., 2022 [80]
CC	Arsovski et al., 2017 [121]; Ding, 2018 [93]; Spieske and Birkel, 2021 [96]; Fatorachian and Kazemi, 2021 [97]; Zouari et al., 2021 [84]; Hofmann and Rüsch, 2017 [48]; Govindan et al., 2022 [47]; Tortorella et al., 2022 [80]
IoS	Maslarić et al., 2016 [12]; Douaioui et al., 2018 [10]; Reis and Gonçalves, 2018 [31]; Dev et al., 2021 [92]; Hofmann and Rüsch, 2017 [48]; Govindan et al., 2022 [47]
BDA	Lee et al., 2013 [32]; Addo-Tenkorang and Helo 2016 [65]; Richey et al., 2016 [67]; Wang et al., 2016 [68]; Gunasekaran et al., 2016 [66]; Witkowski, 2017 [77]; Papadopoulos et al., 2017 [102]; Choi and Lambert, 2018 [101]; Nguyen et al., 2018 [69]; Ding, 2018 [93]; Brintrup et al., 2020 [100]; Ferraris et al., 2019 [104]; Zouari et al., 2021 [84]; Dubey et al., 2021 [103]; Spieske and Birkel, 2021 [96]; Fatorachian and Kazemi, 2021 [97]; Govindan et al., 2022 [47]; Tortorella et al., 2022 [80]
AI	Singh et al., 2022 [83]; Baryannis et al., 2018 [70]; Pan & Tang 2014 [71]; Ding, 2018 [93]; Belhadi et al., 2021 [107]; Spieske and Birkel, 2021 [96]; Govindan et al., 2022 [47]; Ansari and Kohl, 2022 [146]
DT	Uhlemann et al., 2017 [35]; Kalaboukas et al., 2021 [108]; Ivanov and Dolgui, 2020 [109]; Frazzon et al., 2021 [44]; Wang et al., 2022 [72]; Govindan et al., 2022 [47]; Tortorella et al., 2022 [80]
BC	Weber et al., 2016 [76]; Kshetri, 2018 [74]; Mendling et al., 2018 [75]; Perboli et al., 2018 [73]; Min, 2019 [111]; Yoon et al., 2019 [113]; Lohmer et al., 2020 [110]; Bayramova et al., 2021 [114]; Spieske and Birkel, 2021 [96]; Zouari et al., 2021 [84]; Shrivastava et al., 2021 [27]; Taghizadeh and Taghizadeh, 2021 [85]; Govindan et al., 2022 [47]; Tortorella et al., 2022 [80]; Sreenu et al., 2022 [1]; Akhavan and Philsoophian, 2022 [145]; Manupati et al., 2022 [158]
IR	Ghadge et al., 2018 [116]; Azadeh et al., 2019 [37]; Goel and Gupta, 2020 [38]; Dev et al., 2021 [92]; Zouari et al., 2021 [84]; Görçün, 2022 [78]; Govindan et al., 2022 [47]
AM	Fraga-Lamas, 2018 [28]; Ding, 2018 [93]; Savolainen, 2020 [39]; Dev et al., 2021 [92]; Spieske and Birkel, 2021 [96]; Zouari et al., 2021 [84]; Dev et al., 2021 [92]; Govindan et al., 2022 [47]; Tortorella et al., 2022 [80]; Ghadge et al., 2018 [116]; Ekren et al., 2023 [151]

4.1. Internet of Things (IoT)

The term IoT was introduced by Kevin Ashton in a presentation that he gave at Procter & Gamble in 1999. Ten years later, Ashton [23] comments that the economy, society, and survival of humanity are mainly based on things, not on ideas or information. IoT is considered one of the core components of Industry 4.0. Connected via the Internet, smart things communicate with each other at any time and at any place, and exchange data using radio frequency identification (RFID). In a SC management context, things can be palettes, containers, or packages that can be automatically directed through logistics systems. The transport of goods can be controlled using RFID tags with appropriate sensors, such as temperature sensors for frozen goods and vibration sensors for fragile goods [50]. RFID can improve freight security and visibility, since cargo transportation is tracked and monitored [3]. When IoT is applied to industry, it is called Industrial Internet of Things (IIoT) [5,19].

Examining the impact of IoT on the elements of SCRes, studies and reports have provided evidence for most of the elements. Firstly, IoT has an effect on flexibility, enabling quick SC reconfiguration, and rapid recovery from disruptions through the efficient utilization of information. [98]. IoT can improve the visibility of inventory positions and logistics flows [47,80,98]. Moreover, IoT improves agility by increasing the speed of information flow [47,98]. IoT enables information sharing across multiple tiers [47,51,80] and improves collaboration by increasing trust among partners due to the acceleration of information sharing [47,96,98]. Then, IoT influences the management of knowledge within organizations, since it enables the collection and exchange of internal and external data [24]. Finally, other SCRes elements that are reported to be enhanced by IoT are: situation awareness [96], SCRM culture [96], security [98], robustness [47], risk management [47], and velocity [96] (see Table 5).

4.2. Cyber-Physical Systems (CPSs)

CPSs are considered among the main drivers of Industry 4.0. CPSs are systems that integrate both cybernetic and physical components allowing manufacturing equipment to embed computing power [63]. The cybernetic network consists of linked intelligent controllers, and the physical network consists of interconnected components of the infrastructure [10]. CPSs achieve the integration using IoT, RFID and sensor networks [26]. CSPs transform the operation of many traditional industrial systems, improving the effectiveness and efficiency of the entire industry [16]. The impact of CPSs on the SC is related to the high level of connectivity, intelligence, and automation [63]. A specific category of CPSs applied in the domain of manufacturing/production are Cyber-Physical Production Systems (CPPSs) [20]. CPPSs are smart production systems with embedded sensors and actuators, being aware of their condition and taking decisions without human intervention [5].

AI can be applied to provide a CPS with intelligent behavior. In case of machine damage, the machine agent decides the recovery method, such as overcoming the damage, cooperating with other machines to assign the work to an appropriate machine, or rescheduling [26].

According to the literature, among the elements of SCRes that are supported by CPSs are: SC configuration [96], flexibility [47], visibility [96], collaboration [97], information sharing [47,97], SCRM culture [96], robustness [25,47], and velocity [96] (see Table 5).

4.3. Augmented Reality (AR)

AR uses electronic devices to view a real-world physical environment combined with virtual elements in real time [28]. AR gadgets and equipment include head up displays, helmet mounted displays, holographic displays, smart glasses, and handheld devices (cell phones and tablets) [29]. AR can be applied to service, manufacturing, sales and marketing, design, operations, quality affirmation, and staff training and support [28,29]. It must be clarified that Virtual Reality differs from AR. In Virtual Reality, a computer-assisted simulation tool uses multi-sensory channels to permit human-computer interactions and create a self-contained world that is disconnected from reality [36,64].

AR can be used for creating virtual models of the product during the development phase, allowing the detection of flaws without the physical prototypes [18]. This improves flexibility and the risk of damage is minimized [64]. Another example is the application of AR in staff training and support as real-time information, which can be provided either at the working environment or remotely [18,64]. Therefore, collaboration among partners is facilitated [84]. Concerning knowledge management, del Amo et al. [30] has shown that AR can be used to support three main knowledge management activities: knowledge transfer, knowledge capture, and knowledge discovery.

Concluding the impact of AR on the elements of SCRes, the literature review provides evidence that AR contributes to the enhancement of flexibility [64], collaboration [84], knowledge management [30], and velocity [47] (see Table 5).

4.4. Cloud Computing (CC)

CC services permit on-demand network access to computing resources, which are remotely provided by an internet service provider [18]. The combination of IoT with CC permits the implementation of wireless equipment connection and information sharing. In other words, different machines, devices, or items can be connected and exchange information in real time, resulting in enhanced decision making [18]. CC is also utilized for big data storage and process enabling BDA.

Arsovski et al. [121] proposed a model for assessment of organizational resilience potential in small and medium enterprises of the automotive SC, when cloud technology is used for logistics management, database management, and forecasting and planning demands.

In the literature, the impact of CC on the elements of SCRes is reported. In particular, CC can enhance flexibility [47], visibility [47,96,139], collaboration [96], agility [47], information sharing [47,51], risk management [47], and velocity [96] (see Table 5).

4.5. Internet of Services (IoS)

IoS enables companies to provide their services through the Web technologies to make services easily accessible [10]. Therefore, IoS permits the offering of internal and cross organizational services to all participants of the value chain, with the support of CC and BDA [12,31,47]. IoS consists of four different parts: services, business models, participants, and infrastructure [46,47]. Users can access services via various channels. According to Reis and Gonçalves [31], IoS, IoT, and CPS are the pillars of Industry 4.0 that can support the creation of a smart factory.

According to Govindan et al. [47], IoS can improve flexibility, visibility, robustness, and risk management (see Table 5).

4.6. Big Bata Analytics (BDA)

BDA provides analysis and categorization of massive volumes of data into useful information and knowledge, which can support the decision-making processes in organizations [104]. Since BDA enables access to real-time critical information, organizations can exploit this information to act proactively and reduce disruption risks [105,106]. Moreover, BDA can trace the origin of disruptions, monitor disruption propagation, improve risk management, and be used to best achieve SCRes [84]. Yamin [155] gave evidence that BDA has a moderating impact on SCRes and sustainable SC performance. Although BDA improves SCRes, recent studies reveal that BDA is relatively low when implemented by manufacturing companies [18,70].

According to the literature, the elements of SCRes that are improved though the adoption of BDA are numerous. In particular, BDA is reported to enhance SC configuration [96], redundancy [47], flexibility [47], visibility [70,80,84,91,96], collaboration [96], agility [47,84,105], situation awareness [84,96], information sharing [51,80,102], security [70,84], robustness [47], risk management [47,70,84], knowledge management [104], and velocity [96] (see Table 5).

4.7. Artificial Intelligence (AI)

Baryannis et al. [70] state that the key approaches in AI include: (a) mathematical programming approaches (stochastic programming, fuzzy programming, robust optimization, and hybrid approaches of various forms of mathematical programming); (b) network-based models (Petri Nets and Bayesian networks); (c) agent-based modeling and multi-agent systems; (d) automated reasoning; and (e) Machine Learning and BDA. It is worth mentioning that some researchers consider BDA to be a part of AI [70], while some consider AI and BDA as two separate branches of computer science that complement each other [33,91,96]. Other researchers have focused on the impact of Machine Learning [80,84], agent-based simulation [154], and Dynamic Bayesian Networks [146] on SCRes.

The findings of various studies indicate that AI techniques have a positive impact on SCRes [70,83,107]. According to a survey conducted in 279 firms by Belhadi et al. in 2021 [107], the information processing capabilities of AI can be exploited to develop SCRes for enhancing SC performance. In particular, the results indicate the mediating role of collaboration and adaptive capacity between AI and SCRes. Ali et al. [120] argue that increasing flexibility or building redundancy can improve the ability of companies to adapt to changes in case of disruption.

According to the literature, AI techniques enhance various elements of SCRes, such as redundancy (adaptive capability) [107], flexibility [47,146], visibility [47], collaboration [96,107], agility [84], situation awareness [96], information sharing [47], SCRM culture [96], security [84], robustness [47,146], knowledge management [34,106], and velocity [96] (see Table 5).

4.8. Digital Twins (DT)

Ivanov and Dolgui [109] identify a DT supply chain as "a computerized model that represents network states for any given moment in real time". The physical SC is mirrored in a virtual SC using advanced technology. DT constitutes an innovative solution for building a smart SC [72]. The main technologies that are utilized to create a DT from a physical SC are simulation and optimization combined with data analytics [109]. In addition, CPS, RFID, IoT, and BDA are among the key technologies of DT supply chain [109,147]. The DT model proposed by Ivanov and Dolgui [109] can be used in risk management. Kalaboukas et al. [108] propose the concept of Cognitive DT for SC management, which can predict trends and can also be flexible in dynamic environments.

According to the literature, among the elements of SCRes that are improved through the adoption of DT are: flexibility [47], visibility [47,96,108], collaboration [108], agility [108], situation awareness [96,108], information sharing [108], robustness [47], and risk management [47,109,147] (see Table 5).

4.9. Blockchain (BC)

BC technology can be considered as a distributed database where ledger data is stored and shared among participants from different organizations. Participants agree in advance the rules of data sharing [73]. All data shared are performed in an encrypted version. "Block" is used to name each new set of transactions added to the platform. Bitcoin and Ethereum are famous examples of public BC platforms with open access [114]. There are also private BCs and consortium BCs that combine public and private BCs, permitting access to pre-defined participants [73,114].

BC can directly connect all partners and systems in the SC and enhance SCRes by exploiting accurate and real-time data to make decisions [85]. Weber et al. [76] proposed the adoption of BC technology for increasing trust in collaborative business processes. Risk management in the SC is influenced by BC since secure information sharing is facilitated almost in real-time [110]. Manupati et al. [158] propose the application of BC technology to predict the time of the occurrence of a disruption in the SC network. Smart contracts can be used to monitor the response of merchandise assets to the uncertainty. A threshold limit is used to detect if the disruption is complete or partial and proceed to proper actions. Sreenu et al. [1] propose the integration of IoT sensors with BC to monitor temperature in vaccine SC. BC records any temperature violation as a transaction that cannot be changed. In such a case, the purchase order is rejected by the buyer.

Since BC security problems have become known recently, increasing security is a need [139]. Shrivastava et al. [27] have discussed the connection between AI and BC to provide defense against cyber threats. A recent literature review conducted by Bayramova et al. in 2021 [114] found that BC has the potential to enhance SCRes to cybercrime. The findings of a study reported by Lohmer et al. [110] revealed that BC improves SCRes, reducing the recovery time, the cost of disruption, and the number of affected partners. The researchers [110] found that if BC is poorly implemented, then short disruptions have a strong negative impact on SCRes. Similarly, Hervani et al. [159] argue that the firms' resilience performance relies on the implementation of BC internally and across their SCs.

According to the literature, among the elements of SCRes that are improved though the adoption of BC are: SC configuration [91,110], flexibility [91,110,145], visibility [73, 85,96,106,110,114,139], collaboration [76,96,110,114,145], agility [110], information sharing [73,110,111], SCRM culture [91], robustness [76], risk management [85,110,114], and velocity [91,96,110,145] (see Table 5).

4.10. Industrial Robotics (IR)

IR can take advantage of AI, BDA, and CC to become more intelligent, resulting in a complete transformation of the production and manufacturing phase [38]. In the Industry 4.0 context, IR have integrated sensors which collect data in real-time and upload data to the cloud computers. Data is stored, traced, and analyzed [93], and then utilized to enable sensing, comprehension, acting, and learning [38]. A special category of robots are collaborative robots or cobots, which help workers perform their tasks, using different modes of collaboration. Cobots can make workers more effective and efficient [36].

According to the literature, among the elements of SCRes that are enhanced using IR are: flexibility [38,47], collaboration [38], agility (responsiveness) [47], security [84], and robustness [47] (see Table 5).

4.11. Additive Manufacturing (AM)

AM (or 3D printing) is used for the construction of 3D products by adding layers of materials on top of each other. AM can be used to facilitate rapid and on-demand production [93]. AM is utilized by different sectors, such as aerospace, automotive, construction, medical, and consumer goods [36]. Companies can exploit AM to accelerate the production of several prototypes and complex parts, which can then be used in the production process.

AM provides flexibility in design and operation, since different components and products can be produced in the same production line, achieving the customization of products when this is demanded [18,91,116,151]. Moreover, AM can reduce the number of SC layers and suppliers [91].

According to the literature, AM enhance various elements of SCRes such as SC configuration [96,116], redundancy [18], flexibility [18,47,79,91,116,151], agility [47,84,92,151], robustness [47], and velocity [91,96,116,151] (see Table 5).

Table 5. Impact of Industry 4.0 technologies on elements of SCRes.

	SC Configuration	Redundancy	Flexibility	Visibility	Collaboration	Agility	Situation Awareness	Information Sharing	SCRM Culture	Security	Robustness	Risk Management	Knowledge Management	Velocity
IoT			√	√	√	√	√	√	√	√	√	√	√	√
CPS	√		√	√	√			√	√		√			√
AR			√		√								√	√
CC			√	√	√	√		√				√		√
IoS			√	√							√	√		
BDA	√	√	√	√	√	√	√	√		√	√	√	√	√
AI		√	√	√	√	√	√	√	√	√	√		√	√
DT			√	√	√	√	√	√			√	√		
BC	√		√	√	√	√		√	√		√	√		√
IR			√		√	√				√	√			
AM	√	√	√			√					√			√

4.12. Industry 5.0 Technologies

It is worth mentioning that even though organizations have not fully integrated Industry 4.0, the recent European Commission announcement of the fifth Industrial Revolution, or Industry 5.0 [162], has created an increased worldwide interest. Many key enabling technologies support the transition from Industry 4.0 to Industry 5.0, such as BDA, DT, BC, AI, and Cobots (collaborative robots) [163]. In Industry 4.0, these technologies are mainly utilized to fulfil the objective of the technological evolution of manufacturing and production systems. Industry 5.0 goes further, focusing on human-centricity, sustainability, and resilience [162–164]. In other words, Industry 5.0 respects worker needs, sustainability, and environmental harmony, plus the need to enhance resilience across value chains and supply chains [163].

New advanced technologies can support Industry 5.0, such as the Internet of Everything (IoE), Edge Computing (EC), eXtended Reality (XR), and 5G and Beyond [163]. IoE extends IoT, connecting not only physical objects but also persons, organizations, and systems. EC allows for data processing at or near the user where data is being generated. Examples of edge devices are self-driving vehicles, autonomous robots, and sensors. XR is a term which includes AR, Virtual Reality (VR), and Mixed Reality (MR). 5G and 6G networks are expected to support future high-quality services of Industry 5.0.

5. Key Performance Indicators for a Resilient Supply Chain 4.0

5.1. Determining KPIs for SCRes

Key Performance Indicators (KPIs) are criteria that enable the evaluation of the performance of processes of operations in any organization. Decision #makers continuously monitor KPIs, aiming to improve an organization's performance. KPIs can also be used for the identification of the origin of a problem.

In Section 2, we discussed the literature review approaches that have appeared by searching the Scopus database for publications investigating the impact of Industry 4.0 technologies on KPIs used for creating a resilient SC. Table 1 depicts the most relevant publications [92,117,146,149,150] of our investigation in the Scopus database. In the following part, we discuss some of the non-financial KPIs that are referred to these publications.

Dev et al. [92] show that the manufacturing on an AM machine improves SCRes in case of a disruption in the diffusion of green products, increasing the service level (or fill rate), increasing the recovery speed, and decreasing the stock level.

Patidar et al. [117] evaluated KPIs for SCRes analyzing expert views with fuzzy analytic hierarchy process. The results included four KPI categories of a resilient SC: time oriented, operational, structural, and organizational. Time-oriented KPIs include lead time, time to recovery, and order cycle time. These KPIs are widely used to measure the SCRes. Operational KPIs include capacity utilization, risk assessment frequency, supplier delivery efficiency, supplier rejection rate, SC cycle time, and demand and supply variations. Structural KPIs include the number of SC nodes and the proximity to suppliers and customers. Finally, organizational KPIs include service rate, equipment effectiveness, inventory velocity, stock level, and forecasting accuracy and errors.

Ansari and Kohl [146] propose an AI-enhanced approach that can improve KPIs for SCRes, such as Remaining Useful Lifetime, Mean-Time Between Failure, and Uptime, which have an impact on Overall Equipment Efficiency of production systems.

Catellani and Bottani [149] conducted a survey for evaluating the usage of 112 metrics to measure SC performance. Among the KPIs for SCRes that were asked to be evaluated are safety stock, inventory gap, recovery time, on-time delivery, and customer service level. The KPI that was used by any company that participated in the survey was the on-time delivery. The authors [149] evaluated the impact of Industry 4.0 technologies on SC performance, but they did not determine the relation of Industry 4.0 technologies with each of the selected KPIs.

Dumitrascu et al. [150] developed a SC management performance evaluation model that links specific problems with the most relevant KPIs. The authors used data mining to discover the relationships between SC management subsystems and specific KPIs. The results show the top five KPIs for every one of the nine subsystems of SC management. For example, safety stock is related to warehouse management, production lead time is related to production management, SC cycle time is related to demand management, while perfect order delivery rate is related to distribution management.

Moreover, we have investigated approaches that identify KPIs for enhancing SCRes, without the restriction of the Industry 4.0 perspective. The results mainly contribute to the enhancement of the comprehension of the KPIs that we have already mentioned.

Karl et al. [118] identify thirteen elements of SCRes and categorize them into three phases: before disruption, during disruption, and after disruption. They then analyze the relationship of SCRes elements with 10 non-financial KPIs of organizations. For example, the supplier rejection rate is a KPI that requires the collaboration of SC partners to improve its operational results. Karl et al. [118] propose two indicators related with the customer: consumer satisfaction and damage return rate. While customer satisfaction is revealed to be related to many SCRes elements, damage return rate is revealed to be connected only with collaboration in the during-disruption phase [118]. The authors [118] found that two SCRes elements, i.e., financial strength and visibility, have no link to any of the KPIs, and we have adopted these results. Moreover, an interesting result [118] is that the knowledge management element has the highest co-occurrence in literature with the identified KPIs.

Rajesh [160] considers five elements of SCRes: flexibility, responsiveness, quality, productivity, and accessibility. For each of these elements, Rajesh [160] proposes several measures. For example, an important responsiveness indicator is on-time delivery ratio. Productivity indicators, which are also related with customer satisfaction, include order compliance, fill rate, storage space utilization, and units moved per person-hour.

Singh et al. [161], propose a SCRes framework where they identify KPIs for each of the SCRes constituent elements. For example, collaboration, information sharing, and awareness are SCRes elements that can help achieve an accurate forecast demand. Velocity is another SCRes element that can improve the speed of recovery.

Johnson et al. [165] differentiate the robust SC from the resilient SC. A robust SC can return to near normal operation after a disruption of low to medium severity, while a resilient SC can return to normal operation even after a disruption with high severity. The authors [165] test the effectiveness of four risk mitigation strategies for SCRes in case of disruptions with various severity levels, using KPIs such as order fulfillment rates and profits. They found that flexibility and strategic capacity, i.e., the spare capacity at each facility, are the most successful strategies for moderate and severe disruptions. The proposed risk mitigation strategies for a robust SC are node redundancy and supply redundancy. Increasing the number of SC nodes results in decentralization being achieved, which means that if a node fails, total failure is avoided and robustness is maintained.

Rahman et al. [166] evaluate the most critical KPIs for SCRes and sustainability in the healthcare supply chain in the context of the COVID-19 pandemic. The results show that in the case of unusual disruptions, the KPIs, which are more crucial, are first the SC planning and forecasting performance, next the delivery and distribution performance, and finally the manufacturing and production performance as well as the procurement and sourcing performance.

Carvalho et al. [167] propose a framework for modeling the resilience of on-time delivery to capacity and material shortages. They argue that the reduction of recovery time is achieved by improving flexibility, collaboration, and responsiveness.

Lamballais et al. [168] model and analyze the performance of robotic mobile fulfilment systems. The proposed models estimate robot utilization, workstation utilization, and average order cycle time. The findings of this study [168] also show that the location of the workstations around the storage areas affects the maximum order throughput.

Kinra et al. [169] use KPIs of risk inclusion in the SC, focusing on supplier vulnerability. They propose a supplier risk exposure model, which can be used to quantify the ripple effect of a disruption occurring on the supplier side. KPIs, such as supplier reliability, time to survive, and fill rate are used to calculate the supplier risk exposure and the ripple effect exposure of the supply chain.

Li & Zobel [170] identify KPIs for SCRes in case of risk propagation. The authors [170] propose three dimensions of resilience: robustness, recovery time, and average functionality. Two types of robustness are considered, at initial impact and at full impact. Then they propose specific structural KPIs, such as the number of healthy nodes, which is the number of non-disrupted nodes, and the size of the Largest Connected Component (LCC), which is the size of the largest connected subnetwork after the occurrence of a disruption. The authors [170] also argue that increasing the number of SC nodes can lead to higher robustness, while the recovery time increases, too.

Stevenson and Spring [171] argue that information sharing can help, among others, avoiding lost sales, avoiding over-production, and reducing inventories. Therefore, information sharing can help reducing supply and demand variations.

Considering the results of our investigation as presented above, we have formulated a list of non-financial KPIs used for building SCRes. In Table 6, the selected KPIs are listed. For each KPI, a description is given, and, in some cases, related KPIs found in the literature review are referenced.

Table 6. KPIs for SCRes.

KPIs	Descriptions and References
Lead time	The time elapsed in between the placement of an order from a customer until the delivery to the customer [47,117,161] (Production lead time [150], Order lead time [118], Delivery lead time [92,118])
Time to recovery	The time needed for a facility to regain its usual level of functionality after a disruption [81,117,149,167,169,170] (Speed of recovery [92,120,161])
Order cycle time	The time between two placed orders [117,168]
Capacity utilization	The ratio of the actual output to the maximum output [117,118]
Risk assessment frequency	Indicates how frequently risks are being identified [117]
Supplier delivery efficiency	Indicates how efficiently a supplier delivers the supplies [117,118] (Supplier reliability: The ratio of the quantity received over the quantity ordered [169])
Supplier rejection rate	The quantity of supplies rejected by the suppliers over the total quantity received [117,118]
SC cycle time	The sum of the longest lead time for each stage Indicates the efficiency of the supply chain [117,150]
Demand and supply variations	The variability between demand and supply [117,171]
No of nodes in SC	Number of product stops during the production process [117,165,170]
Proximity to suppliers and customers	The proximity between company and suppliers and the proximity between company and customers [117]
Service rate	The level of service to the customers [47,117,118,149,160,165] (Order fill rate: The ratio of the quantity shipped to the customer over the total quantity ordered [160,165]) (Customer satisfaction [47,118])
On-time delivery	The ratio of the number of orders delivered on date over the total number of orders delivered [118,148,149,160,167,169]
Equipment effectiveness /efficiency	The effectiveness/efficiency of the equipment in a manufacturing plant [117] (The ratio of fully productive time to planned production time [146])
Inventory velocity	The time interval between supplying raw materials and selling finished products [117]
Stock level	The optimum stock level [47,92,117,118,149,150]
Forecasting accuracy	The deviation of the actual demand from the forecasting demand [47,117,161,166]

5.2. Determining the Impact of Industry 4.0 Technologies on KPIs for a Resilient Supply Chain 4.0

In Section 4, we investigated the influence of Industry 4.0 technologies on selected SCRes elements. The findings are included in Table 5.

In Section 5.1, we investigated the KPIs for SCRes and the results are included in Table 6. In this Section, we report how each of the Industry 4.0 technologies is related with each of the KPIs, considering the literature review. The results of our investigation are then synthesized and aggregated in Table 7. For each KPI in Table 7, the findings include:

(a) the Industry 4.0 technologies that have a direct impact on the KPI, and/or
(b) the Industry 4.0 technologies that have an indirect impact on the KPI through the improvement of the SCRes elements which are related with the KPI.

Since Table 7 contains many repetitions for the sake of references, we have gathered the findings in Table 8. There, the matches show which Industry 4.0 technology improves which KPI of SCRes.

In the following, a discussion of the literature review findings is made by technology. Tables 7 and 8 then aggregate these findings.

5.2.1. Internet of Things (IoT)

IoT can help reducing the time spent by workers in filling and shipping orders and can facilitate tracking products and services [98]. Moreover, IoT can provide accurate information when a disruption event is observed and enable immediate handling [119]. As a result, IoT provides the benefit of shorter lead times [47], shorter time to recovery [119], shorter order cycle time, and shorter SC cycle time by increasing time efficiency in production [47], better service rate [47], better equipment effectiveness by reducing downtime [47], increased inventory velocity by inventory picking process improvement [47], and better forecasting accuracy [47] (see Table 7).

Furthermore, IoT can contribute to the enhancement of SCRes elements such as flexibility, agility, collaboration, information sharing, situation awareness, SCRM culture, risk management, knowledge management, and velocity, which are improved by Industry 4.0 technologies (see Tables 5 and 7). Table 7 shows which of these SCRes elements are related with each of the following KPIs: lead time [117,118,161], time to recovery [161,167], capacity utilization [118], risk assessment frequency, supplier delivery efficiency [118], supplier rejection rate [118], demand and supply variations [171], no of nodes in SC [117,170], service rate [118], on-time delivery [118,167], stock level [117,118], and forecasting accuracy [117,161] (see Tables 7 and 8).

5.2.2. Cyber-Physical Systems (CPSs)

CPS can reduce waste and work in lean manufacturing, improve maintenance, and increase traceability and transparency in distribution [47]. Therefore, CPS can reduce lead time [47], reduce order cycle time and SC cycle time by increasing time efficiency in production [47], and improve equipment effectiveness by reducing downtime [47] (see Table 7).

Moreover, CPS can enhance SCRes elements such as SC configuration, flexibility, collaboration, information sharing, robustness, and velocity, which are improved by Industry 4.0 technologies (see Tables 5 and 7). Table 7 includes these SCRes elements which are related with each of the following KPIs: lead time [118,161], time to recovery [161,167], capacity utilization [118], supplier delivery efficiency [118], demand and supply variations [171], no of nodes in SC [117,170], service rate [118], on-time delivery [118,167], stock level [118], and forecasting accuracy [117,161] (see Tables 7 and 8).

5.2.3. Augmented Reality (AR)

AR contributes to flexibility in manufacturing assembling, which improves equipment effectiveness [47,64], reduces delivery lead times [64], increases inventory velocity by improving inventory picking process [47], improves service rate by improving customer satisfaction [47], and reduces stock level [47] (see Table 7).

Additionally, AR can enhance SCRes elements such as flexibility, collaboration, knowledge management, and velocity, which are improved by Industry 4.0 technologies (see Tables 5 and 7). Table 7 shows which of these SCRes elements are related to each of the following KPIs: lead time [118,161], time to recovery [161,167], capacity utilization [118], risk assessment frequency, supplier delivery efficiency [118], supplier rejection rate [118], service rate [118], on-time delivery [118,167], and stock level [118] (see Tables 7 and 8).

5.2.4. Cloud Computing (CC)

CC can reduce SC cycle time by increasing efficiency [47], improve service rate by improving customer satisfaction [47], reduce the stock level [47], improve equipment effectiveness by reducing downtime [47], increase inventory velocity by improving the inventory picking process [47], and improve forecasting accuracy [47] (see Table 7).

Furthermore, CC can enable the enhancement of SCRes elements such as flexibility, collaboration, agility, information sharing, risk management, and velocity, which are improved by Industry 4.0 technologies (see Tables 5 and 7). Table 7 shows which of these SCRes elements are linked with each of the following KPIs: lead time [118,161], time to recovery [161,167], capacity utilization [118], supplier delivery efficiency [118], supplier rejection rate [118], demand and supply variations [171], service rate [118], on-time delivery [118,167], stock level [118], and forecasting accuracy [117,161] (see Tables 7 and 8).

5.2.5. Internet of Services (IoS)

IoS can reduce SC cycle time by increasing efficiency [47], improve equipment effectiveness by reducing downtime [47], and improve forecasting accuracy [47] (see Table 7).

Moreover, IoS can enhance SCRes elements such as flexibility, robustness, and risk management, which are improved by Industry 4.0 technologies (see Tables 5 and 7). Table 7 shows which of these SCRes elements have a relation with each of the following KPIs: lead time [118], time to recovery [167], capacity utilization [118], supplier delivery efficiency [118], no of nodes in SC [117,170], and on-time delivery [118,167] (see Tables 7 and 8).

5.2.6. Big Bata Analytics (BDA)

A study conducted in 2022 by Iftikhar et al. [106] investigated the mediating effect of BDA between SC complexities and SCRes. Two types of SC complexities are considered: structural complexities (e.g., no of SC nodes, products, parts, suppliers, customers) and dynamic complexities (e.g., lead times from suppliers, supplier delivery efficiency). The results showed that BDA has a mediating effect for structural and dynamic complexities on SCRes. Moreover, dynamic SC complexity only influences SCRes via BDA. According to Zouari [84], BDA can facilitate the tracing of the origin of disruptions and monitor disruption propagation. For this reason, BDA contributes to the reduction of recovery time, since accurate information concerning the occurrence of a disruption is available in time [106,119]. BDA can also reduce SC cycle time by increasing efficiency [47], improve equipment effectiveness by reducing downtime [47], and increase inventory velocity by improving the inventory picking process [47] (see Table 7).

In addition, BDA can contribute to the improvement of SCRes elements such as SC configuration, redundancy, flexibility, collaboration, agility, information sharing, situation awareness, robustness, risk management, knowledge management, and velocity, which are improved by Industry 4.0 technologies (see Tables 5 and 7). Table 7 includes the SCRes elements that are related to each of the following KPIs: lead time [117,118,161], time to recovery [161,167], capacity utilization [117,118], risk assessment frequency, supplier delivery efficiency [118], supplier rejection rate [118], demand and supply variations [171], no of nodes in SC [117,170], service rate [118], on-time delivery [118,167], stock level [118], and forecasting accuracy [117,161] (see Tables 7 and 8).

5.2.7. Artificial Intelligence (AI)

AI methods can be used for the proactive response to changes [80,84,146]. Examples of the utilization of AI methods are the management of urban freight transportation using agent-based simulation [154], and route optimization [117]. AI thereby contributes to the increase in proximity to suppliers and customers through real-time route optimization [117,154] and can also provide accurate forecasting [117]. Machine Learning (a key approach of AI [70]) can improve time to recovery by providing accurate information about the occurrence of a disruption in time [119], increase capacity utilization [47], improve inventory velocity [47], improve service rate [47], improve equipment effectiveness by reducing downtime [47,146], and improve forecasting accuracy [47] (see Table 7).

Additionally, AI can enhance SCRes elements such as redundancy, flexibility, collaboration, agility, situation awareness, information sharing, security, robustness, knowledge management, robustness, risk management, and velocity, which are improved by Industry 4.0 technologies (see Tables 5 and 7). Table 7 depicts these SCRes elements, which are linked with each of the following KPIs: lead time [117,118,161], time to recovery [161,167], capacity utilization [117,118], risk assessment frequency, supplier delivery efficiency [118], supplier rejection rate [118], demand and supply variations [171], no of nodes in SC [117,170], service rate [118], on-time delivery [118,167], stock level [118], and forecasting accuracy [117,161] (see Tables 7 and 8).

5.2.8. Digital Twins (DT)

DT can help to minimize lead times [108], reduce SC cycle time by increasing efficiency [47], increase service rate by improving interaction with the customer [47,147], reduce equipment effectiveness by reducing downtimes [47], improve equipment effectiveness by reducing downtime [47], increase inventory velocity by improving inventory picking process [47], and improve forecasting accuracy [47,108] (see Table 7).

Moreover, DT can improve SCRes elements such as flexibility, collaboration, agility, situation awareness, information sharing, robustness, and risk management, which are improved by Industry 4.0 technologies (see Tables 5 and 7). As depicted in Table 7, these SCRes elements are related to each of the following KPIs: lead time [118,161], time to recovery [161,167], capacity utilization [118], risk assessment frequency, supplier delivery efficiency [118], supplier rejection rate [118], no of nodes in SC [117,170], service rate [118], on-time delivery [118,167], stock level [118], and forecasting accuracy [117,161] (see Tables 7 and 8).

5.2.9. Blockchain (BC)

BC can contribute to the increase in supplier delivery efficiency [85], the decrease in demand and supply variations by reducing lost demand [85], the reduction of stock level [85], and the increase of forecasting accuracy [85] (see Table 7). BC also contributes to the reduction of lead time [117,119], the significant shortening of recovery time [110,117,119], and the reduction of order cycle time and SC cycle time [117] (see Table 7).

Additionally, BC can help enhance SCRes elements such as SC configuration, flexibility, agility, collaboration, information sharing, SCRM culture, knowledge management and velocity, which are improved by Industry 4.0 technologies (see Tables 5 and 7). Table 7 lists the SCRes elements that are related to each of the following KPIs: lead time [118,161], time to recovery [161,167], capacity utilization [118], risk assessment frequency, supplier delivery efficiency [118], supplier rejection rate [118], demand and supply variations [171], service rate [118], on-time delivery [118,167], and stock level [118] (see Tables 7 and 8).

5.2.10. Industrial Robotics (IR)

IR can contribute to the reduction of order cycle time (the performance of a robotic fulfillment system is reported in [168]), the reduction SC cycle time [36,47], the increase in equipment effectiveness by downtime reduction [47], the increase in inventory velocity by inventory picking process improvement [47], and the minimization of stock level [47] (see Table 7).

Moreover, IR can improve SCRes elements such as flexibility, agility, collaboration, security, and robustness, which are improved by Industry 4.0 technologies (see Tables 5 and 7). Table 7 includes the SCRes elements that are related to each of the following KPIs: lead time [118,161], time to recovery [167], capacity utilization [118], supplier delivery efficiency [118], supplier rejection rate [118], no of nodes in SC [117,170], service rate [118], on-time delivery [118,167], and stock level [118] (see Tables 7 and 8).

5.2.11. Additive Manufacturing (AM)

AM can help to reduce lead time [47,91,116], decrease time to recovery [92], increase capacity utilization [47], reduce order cycle time [116], reduce SC cycle time by increasing resource efficiency [47], increase equipment effectiveness by reducing downtime [47], increase service rate [92], and reduce stock level since fewer items need to be held [91,92,116,151] (see Table 7).

In addition, AM can enhance SCRes elements such as SC configuration, redundancy, flexibility, agility, robustness, and velocity, which are improved by Industry 4.0 technologies (see Tables 5 and 7). Table 7 shows which of these SCRes elements are related to each of the following KPIs: lead time [117,118,161], time to recovery [92,167], capacity utilization [117,118], no of nodes in SC [117,170], service rate [118], on-time delivery [118,167], and stock level [118] (see Tables 7 and 8).

Table 7. Industry 4.0 technologies that influence KPIs.

KPIs	Industry 4.0 Technologies
Lead time	(IoT, AI, AM) [47], AR [64], BDA [106], DT [108], BC [117,119], AM [91,116]
	• SC Configuration [118] improved by CPS, BDA, BC, AM • Redundancy [117,118,161] improved by BDA, AI, AM • Flexibility [118] improved by IoT, CPS, AR, CC, IoS, BDA, AI, DT, BD, IR, AM • Collaboration [118] improved by IoT, CPS, AR, CC, BDA, AI, DT, BC, IR • Agility [118,161] improved by IoT, CC, BDA, AI, DT, BC, IR, AM • Risk management [118] improved by IoT, CC, IoS, BDA, DT, BC • Knowledge management [118] improved by IoT, AR, BDA, AI
Time to recovery	IoT [119], BDA [84,106,119], AI [119], BC [110,117,119], AM [92]
	• Flexibility [167] improved by IoT, CPS, AR, CC, IoS, BDA, AI, DT, BD, IR, AM • Agility (responsiveness) [167] improved by IoT, CC, BDA, AI, DT, BC, IR, AM • Collaboration [167] improved by IoT, CPS, AR, CC, BDA, AI, DT, BC, IR • Velocity [161] improved by IoT, CPS, AR, CC, BDA, AI, BC, AM
Order cycle time	(IoT, CPS) [47], BC [117], IR [168], AM [116]
Capacity utilization	(IoT, CC, BDA, AI, AM) [47]
	• Redundancy [117] improved by BDA, AI, AM • Flexibility [118] improved by IoT, CPS, AR, CC, IoS, BDA, AI, DT, BC, IR, AM • Agility [118] improved by IoT, CC, BDA, AI, DT, BC, IR, AM • Knowledge management [118] improved by IoT, AR, BDA, AI
Risk assessment frequency	• Situation awareness improved by IoT, BDA, AI, DT • SCRM culture improved by IoT, CPS, AI, BC • Knowledge management improved by IoT, AR, BDA, AI

Table 7. *Cont.*

KPIs	Industry 4.0 Technologies
Supplier delivery efficiency	BDA [106], BC [85] • Collaboration [118] improved by IoT, CPS, AR, CC, BDA, AI, DT, BC, IR • Security [118] improved by IoT, BDA, AI, IR • Risk management [118] improved by IoT, CC, IoS, BDA, DT, BC • Knowledge management [118] improved by IoT, AR, BDA, AI
Supplier rejection rate	• Collaboration [118] improved by IoT, CPS, AR, CC, BDA, AI, DT, BC, IR
SC cycle time	(IoT, CPS, CC, IoS, BDA, DT, IR, AM) [47], BC [117], IR [36,47]
Demand and supply variations	BC (by reducing lost demand) [85] • Information sharing [171] improved by IoT, CPS, CC, BDA, AI, DT, BC
No of nodes in SC	BDA [106] • Robustness [117,165,170] improved by IoT, CPS, IoS, BDA, AI, DT, BC, IR, AM
Proximity to suppliers and customers	AI [117,154]
Service rate	(IoT, AR, CC, BDA, AI, DT) [47], DT [147], AM [92] • SC configuration [118] improved by CPS, BDA, BC, AM • Redundancy [118] improved by BDA, AI, AM • Collaboration [118] improved by IoT, CPS, AR, CC, BDA, AI, DT, BC, IR • Agility (responsiveness) [118] improved by IoT, CC, BDA, AI, DT, BC, IR, AM • Information sharing [92,118] improved by IoT, CPS, CC, BDA, AI, DT, BC • Security [118] improved by IoT, BDA, AI, IR • Knowledge management [118] improved by IoT, AR, BDA, AI
On-time delivery	• Redundancy [167] improved by BDA, AI, AM • Flexibility [118,167] improved by IoT, CPS, AR, CC, IoS, BDA, AI, DT, BC, IR, AM • Collaboration [118,167] improved by IoT, CPS, AR, CC, BDA, AI, DT, BC, IR • Agility (responsiveness) [167] improved by IoT, CC, BDA, AI, DT, BC, IR, AM • Security [118] improved by IoT, BDA, AI, IR • Knowledge management [118] improved by IoT, AR, BDA, AI
Equipment effectiveness	(IoT, CPS, CC, IoS, BDA, AI, DT, IR, AM) (by reducing downtime) [47], AR [64], AI [146]
Inventory velocity	(IoT, AR, CC, BDA, AI, DT, AM, IR) (by improving inventory picking process) [47], AR [64]
Stock level	(IoT, AR, CC, BDA, AI, DT, IR, AM) [47], BC [85], AM [91,116,151] • Redundancy [117,118] improved by BDA, AI, AM • Risk management [118] improved by IoT, CC, IoS, DT, BC • Agility [118] improved by IoT, CC, BDA, AI, DT, BC, IR, AM • Information sharing [118] improved by IoT, CPS, CC, BDA, AI, DT, BC • Robustness [118] improved by IoT, CPS, IoS, BDA, AI, DT, BC, IR, AM
Forecasting accuracy	(IoT, CC, IoS, BDA, AI, DT) [47], BC [85], DT [108], AI [117] • Information sharing [117,161] improved by IoT, CPS, CC, BDA, AI, DT, BC • Situation awareness [161] improved by IoT, BDA, AI, DT • Collaboration [161] improved by IoT, CPS, AR, CC, BDA, AI, DT, BC, IR

Table 8. Industry 4.0 technologies and the affected KPIs for SCRes.

	Lead Time	Time to Recovery	Order Cycle Time	Capacity Utilization	Risk Assessment Frequency	Supplier Delivery Efficiency	Supplier Rejection Rate	SC Cycle Time	Demand and Supply Variations	No. of Nodes in SC	Proximity to Suppliers & Customers	Service Rate	On-Time Delivery	Equipment Effectiveness	Inventory Velocity	Stock Level	Forecasting Accuracy
IoT	√	√	√	√	√	√	√	√	√	√		√	√	√	√	√	√
CPS	√	√	√	√	√	√	√	√	√	√		√	√	√		√	√
AR	√	√		√	√	√	√					√	√		√	√	√
CC	√	√		√		√	√	√	√			√	√	√	√	√	√
IoS	√	√		√		√		√		√		√	√	√		√	√
BDA	√	√		√	√	√	√	√	√	√		√	√	√	√	√	√
AI	√	√		√	√	√	√		√	√	√	√	√	√	√	√	√
DT	√	√		√	√	√	√	√	√	√		√	√	√	√	√	√
BC	√	√	√	√	√	√	√	√	√	√		√	√			√	√
IR	√	√	√	√		√	√	√		√		√	√	√	√	√	√
AM	√	√	√	√				√		√		√	√	√	√	√	

6. Conclusions

This study aims to extend current research results on how the KPIs for making a resilient SC are influenced by the most important Industry 4.0 technologies. In order to fulfill this objective, we have examined two research questions. The first research question (RQ1) sought to find which of the Industry 4.0 technologies can improve SCRes. Since the impact of Industry 4.0 technologies on SCRes is not straightforward, we explored how each of the Industry 4.0 technologies influence the most important SCRes constituent elements, and we discussed the findings. The results are aggregated in Table 5. Therefore, we answered RQ1.

The second research question (RQ2) sought to investigate which of the Industry 4.0 technologies influence the KPIs for a resilient SC. We followed a systematic literature review method to answer RQ2. The search results in Scopus database were very limited, and so we extended our literature review. We studied the literature findings, and we decided to mainly adopt Patidar's et al. [117] list of non-financial KPIs for a resilient SC, enhanced with more literature references. These KPIs are depicted in Table 6. For each KPI appeared in Table 6, a two-fold research process was followed. Firstly, we investigated the link between the SCRes constituent elements and the adopted KPIs. In other words, for each KPI, the related SCRes constituent elements were determined according to the literature review. We synthesized these findings with the findings of RQ1 (depicted in Table 5), and we concluded which Industry 4.0 technologies influence each KPI. Secondly, based on the literature review, we determined which Industry 4.0 technologies have a direct impact on each KPI. For each Industry 4.0 technology, we presented the related KPIs and we depicted the detailed results in Table 7. For reasons of simplicity and comprehension, the findings shown in Table 7 were then aggregated in Table 8.

Our study is differentiated from other studies. Among the results of the systematic literature review, only Patidar et al. [117] is closer to our study. The authors [117] evaluated KPIs for SCRes and investigated the influence of Industry 4.0 technologies on these KPIs based on the literature review. However, we have extended this research investigating the impact of Industry 4.0 technologies on the constituent elements of SCRes (such as Govindan et al. [47]) and the relation of the KPIs for SCRes with the constituent elements of SCRes (such as Karl et al. [118]). Other studies are concentrated on the impact of a particular Industry 4.0 technology on KPIs for SCRes (e.g., AM [92]), while others evaluate the impact of Industry 4.0 technologies on SC performance without determining the relation of Industry 4.0 technologies with each of the KPIs (e.g., [149]).

The findings of this work could be exploited by academics and practitioners who are interested in the concept of a Resilient Supply Chain 4.0. The Industry 4.0 technologies that are revealed to improve the KPIs for creating SCRes could be considered for adoption by companies of various industries who intend to improve the resilience of their SC.

7. Limitations and Future Research

This study has some limitations. At first, the study relied on high quality articles published in journals that were mainly searched in Google Scholar and Scopus databases. As a result, there is a possibility that some relevant articles are not included. A second limitation is that we have based our research on results presented by other researchers. For the future, we plan to conduct an empirical investigation in order to identify the KPIs that help measure resilience in Supply Chain 4.0 and then evaluate these KPIs using a decision support method. The impact of Industry 4.0 technologies on the evaluated KPIs could be investigated using case studies and interviews with experts.

Figures and tables were used for the visualization of our work on the literature review and the results of this research. Advanced tools such as VOS Viewer [172] can be applied to construct and analyze bibliometric networks and provide a clear depiction of item connections.

An interesting future work would be the investigation of the influence of the Industry 4.0 maturity models on the KPIs for SCRes. Maturity models of Industry 4.0 are used for auditing any company, measuring its progress, and comprehending its strengths and weaknesses [173]. Taking into consideration that the introduction of Industry 4.0 in enterprises, especially in SMEs, should be implemented systematically, maturity models can be useful tools [174,175]. Different maturity models of Industry 4.0 are found in the literature [176].

For the future, the business society should take into account that the 4th and the 5th Industrial Revolutions co-exist, where Industry 4.0 is considered technology-driven and Industry 5.0 is considered value-driven [164]. Resilience is one of the core values of Industry 5.0, which is interconnected with human-centricity and sustainability [163,164]. The new emerging digital technologies such as individualized human-machine interaction, bio-inspired technologies, smart materials, and innovations in AI [164] will force industries to continually transform products and processes [17].

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

Funding: This research has been co-financed by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH–CREATE–INNOVATE (project code: T1EDK-02266).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research has been co-financed by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH–CREATE–INNOVATE (project code: T1EDK-02266).

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

References

1. Hsu, C.-H.; Chang, A.-Y.; Zhang, T.-Y.; Lin, W.-D.; Liu, W.-L. Deploying Resilience Enablers to Mitigate Risks in Sustainable Fashion Supply Chains. *Sustainability* **2021**, *13*, 2943. [CrossRef]
2. Tukamuhabwa, B.R.; Stevenson, M.; Busby, J.; Zorzini, M. Supply chain resilience: Definition, review and theoretical foundations for further study. *Int. J. Prod. Res.* **2015**, *53*, 5592–5623. [CrossRef]
3. Rice, B.J.; Caniato, F. Building a Secure and Resilient Supply Network. *Supply Chain Manag. Rev.* **2003**, *7*, 22–30.
4. MacCarthy, B.L.; Blome, C.; Olhager, J.; Srai, J.S.; Zhao, X. Supply chain evolution—Theory, concepts and science. *Int. J. Oper. Prod. Manag.* **2016**, *36*, 1696–1718. [CrossRef]
5. Almada-Lobo, F. The Industry 4.0 revolution and the future of Manufacturing Execution Systems (MES). *J. Innov. Manag.* **2016**, *3*, 16–21. [CrossRef]
6. Demir, S.; Paksoy, T.; Koçhan, Ç. Logistics 4.0: SCM in Industry 4.0 Era. In *Logistics 4.0. Digital Transformation of Supply Chain Management*, 1st ed.; Paksoy, T., Koçhan, Ç., Ali, S.S., Eds.; CRC Press: Boca Raton, FL, USA, 2021; Chapter 2; pp. 15–26. [CrossRef]
7. Bienhaus, F.; Haddud, A. Procurement 4.0: Factors influencing the digitisation of procurement and supply chains. *Bus. Process Manag. J.* **2018**, *24*, 965–984. [CrossRef]
8. Tutam, M. Warehousing 4.0 in Logistics 4.0. In *Logistics 4.0 and Future of Supply Chains*, 1st ed.; Iyigün, I., Görçün, Ö.F., Eds.; Springer: Singapore, 2022; Chapter 7; pp. 95–118. [CrossRef]
9. Geest, M.; Tekinerdogan, B.; Catal, C. Smart Warehouses: Rationale, Challenges and Solution Directions. *Appl. Sci.* **2021**, *12*, 219. [CrossRef]
10. Douaioui, K.; Fri, M.; Mabrouki, C.; Semma, E. The interaction between industry 4.0 and smart logistics: Concepts and perspectives. In Proceedings of the 2018 International Colloquium on Logistics and Supply Chain Management (LOGISTIQUA), Tangier, Morocco, 26–27 April 2018; pp. 128–132. [CrossRef]
11. Wu, L.; Yue, X.; Jin, A.; Yen, D.C. Smart supply chain management: A review and implications for future research. *Int. J. Logist. Manag.* **2016**, *27*, 395–417. [CrossRef]
12. Maslarić, M.; Nikolicic, S.; Mirčetić, D. Logistics Response to the Industry 4.0: The Physical Internet. *Open Eng.* **2016**, *6*, 511–517. [CrossRef]
13. Kosacka-Olejnik, M.; Pitakaso, R. Industry 4.0: State of the art and research implications. *Logforum* **2019**, *15*, 475–485. [CrossRef]
14. Rajput, S.; Singh, S.P. Industry 4.0—Challenges to implement circular economy. *Benchmarking Int. J.* **2021**, *28*, 1717–1739. [CrossRef]
15. Xu, L.D.; Xu, E.L.; Li, L. Industry 4.0: State of the art and future trends. *Int. J. Prod. Res.* **2018**, *56*, 2941–2962. [CrossRef]
16. Lu, Y. Industry 4.0: A survey on technologies, applications and open research issues. *J. Ind. Inf. Integr.* **2017**, *6*, 1–10. [CrossRef]
17. Oztemel, E.; Gursev, S. Literature review of industry 4.0 and related technologies. *J. Intell. Manuf.* **2018**, *31*, 127–182. [CrossRef]
18. Frank, A.; Dalenogare, L.; Néstor, A. Industry 4.0 technologies: Implementation patterns in manufacturing companies. *Int. J. Prod. Econ.* **2019**, *210*, 15–26. [CrossRef]
19. 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.* **2019**, *233*, 1342–1361. [CrossRef]
20. Vogel-Heuser, B.; Hess, D. Guest editorial: Industry 4.0—Prerequisites and visions. *IEEE Trans. Autom. Sci. Eng.* **2016**, *13*, 411–413. [CrossRef]
21. Sony, M.; Naik, S. Key ingredients for evaluating Industry 4.0 readiness for organizations: A literature review. *Benchmarking Int. J.* **2020**, *27*, 2213–2232. [CrossRef]
22. Legner, C.; Eymann, T.; Hess, T.; Matt, C.; Böhmann, T.; Drews, P.; Mädche, A.; Urbach, N.; Ahlemann, F. Digitalization: Opportunity and challenge for the business and information systems engineering community. *Bus. Inf. Syst. Eng.* **2017**, *59*, 301–308. [CrossRef]
23. Ashton, K. That 'Internet of Things' Thing. *RFID J.* **2009**, *22*, 97–114. Available online: http://www.rfidjournal.com/article/view/4986 (accessed on 28 September 2022).
24. Santoro, G.; Vrontis, D.; Thrassou, A.; Dezi, L. The Internet of Things: Building a knowledge management system for open innovation and knowledge management capacity. *Technol. Forecast. Soc. Chang.* **2018**, *136*, 347–354. [CrossRef]
25. Kyoung-Dae, K.; Kumar, P.R. Cyber–Physical Systems: A Perspective at the Centennial. *Proc. IEEE 100 Spec. Centen. Issue* **2012**, *100*, 1287–1308. [CrossRef]
26. Tran, N.-H.; Park, H.-S.; Nguyen, Q.-V.; Hoang, T.-D. Development of a Smart Cyber-Physical Manufacturing System in the Industry 4.0 Context. *Appl. Sci.* **2019**, *9*, 3325. [CrossRef]
27. Shrivastava, A.; Krishna, M.K.; Rinawa, M.L.; Soni, M.; Ramkumar, G.; Jaiswal, S. Inclusion of IoT, ML, and Blockchain Technologies in Next Generation Industry 4.0 Environment. *Mater. Today Proc.* 2021, *in press*. [CrossRef]

28. Fraga-Lamas, P.; Fernandez-Carames, T.M.; Blanco-Novoa, O.; Vilar-Montesinos, M.A. A Review on Industrial Augmented Reality Systems for the Industry 4.0 Shipyard. *IEEE Access* **2018**, *6*, 13358–13375. [CrossRef]
29. Lavingia, K.; Tanwar, S. Augmented Reality and Industry 4.0. In *A Roadmap to Industry 4.0: Smart Production, Sharp Business and Sustainable Development*; Nayyar, A., Kumar, A., Eds.; Advances in Science, Technology & Innovation; Springer: Cham, Switzerland, 2020; pp. 143–155. [CrossRef]
30. Del Amo, I.F.; Erkoyuncu, J.A.; Roy, R.; Palmarini, R.; Onoufriou, D. A systematic review of Augmented Reality content-related techniques for knowledge transfer in maintenance applications. *Comput. Ind.* **2018**, *103*, 47–71. [CrossRef]
31. Reis, J.Z.; Gonçalves, R.F. The Role of Internet of Services (IoS) on Industry 4.0 through the Service Oriented Architecture (SOA). In *Advances in Production Management Systems. Smart Manufacturing for Industry 4.0. IFIP Advances in Information and Communication Technology*; Moon, I., Lee, G., Park, J., Kiritsis, D., von Cieminski, G., Eds.; Springer: Cham, Switzerland, 2018; Volume 536, pp. 20–26. [CrossRef]
32. Lee, J.; Lapira, E.; Bagheri, B.; Kao, H. Recent advances and trends in predictive manufacturing systems in big data environment. *Manuf. Lett.* **2013**, *1*, 38–41. [CrossRef]
33. Demigha, S. The impact of Big Data on AI. In Proceedings of the International Conference on Computational Science and Computational Intelligence (CSCI), Las Vegas, NV, USA, 16–18 December 2020; pp. 1395–1400. [CrossRef]
34. Jarrahi, M.H.; Askay, D.; Eshraghi, A.; Smith, P. Artificial intelligence and knowledge management: A partnership between human and AI. *Bus. Horiz.* 2022, *in press*. [CrossRef]
35. Uhlemann, T.H.-J.; Lehmann, C.; Steinhilper, R. The Digital Twin: Realizing the Cyber-Physical Production System for Industry 4.0. *Procedia CIRP* **2017**, *61*, 335–340. [CrossRef]
36. Butt, J. A Strategic Roadmap for the Manufacturing Industry to Implement Industry 4.0. *Designs* **2020**, *4*, 11. [CrossRef]
37. Azadeh, K.; De Koster, R.; Roy, D. Robotized and Automated Warehouse Systems: Review and Recent Developments. *Transp. Sci.* **2019**, *53*, 917–945. [CrossRef]
38. Goel, R.; Gupta, P. Robotics and industry 4.0. In *A Roadmap to Industry 4.0: Smart Production, Sharp Business and Sustainable Development*; Nayyar, A., Kumar, A., Eds.; Advances in Science, Technology & Innovation; Springer: Cham, Switzerland, 2020; pp. 157–169. [CrossRef]
39. Savolainen, J.; Collan, M. How Additive Manufacturing Technology Changes Business Models?—Review of Literature. *Addit. Manuf.* **2020**, *32*, 101070. [CrossRef]
40. Büyüközkan, G.; Göçer, F. Digital Supply Chain: Literature review and a proposed framework for future research. *Comput. Ind.* **2018**, *97*, 157–177. [CrossRef]
41. Chauhan, C.; Singh, A. A review of Industry 4.0 in supply chain management studies. *J. Manuf. Technol. Manag.* **2020**, *31*, 863–886. [CrossRef]
42. Cisneros-Cabrera, S.; Pishchulov, G.; Sampaio, P.; Mehandjiev, N.; Liu, Z.; Kununka, S. An approach and decision support tool for forming Industry 4.0 supply chain collaborations. *Comput. Ind.* **2021**, *125*, 103391. [CrossRef]
43. Efthymiou, O.K.; Ponis, S.T. Industry 4.0 Technologies and Their Impact in Contemporary Logistics: A Systematic Literature Review. *Sustainability* **2021**, *13*, 11643. [CrossRef]
44. Frazzon, E.M.; Freitag, M.; Ivanov, D. Intelligent methods and systems for decision making support: Toward digital supply chain twins. *Int. J. Inf. Manag.* **2021**, *57*, 102281. [CrossRef]
45. Frederico, G.F.; Garza-Reyes, J.A.; Anosike, A.; Kumar, V. Supply Chain 4.0: Concepts, maturity and research agenda. *Supply Chain Manag.* **2020**, *25*, 262–282. [CrossRef]
46. Garay-Rondero, C.L.; Martinez-Flores, J.L.; Smith, N.R.; Morales, S.O.C.; Aldrette-Malacara, A. Digital supply chain model in industry 4.0. *J. Manuf. Technol. Manag.* **2019**, *31*, 887–933. [CrossRef]
47. Govindan, K.; Kannan, D.; Jørgensen, T.B.; Nielsen, T.S. Supply Chain 4.0 performance measurement: A systematic literature review, framework development, and empirical evidence. *Transp. Res. Part E Logist. Transp. Rev.* **2022**, *164*, 102725. [CrossRef]
48. Hofmann, E.; Rüsch, M. Industry 4.0 and the current status as well as future prospects on logistics. *Comput. Ind.* **2017**, *89*, 23–34. [CrossRef]
49. Kumar, P.; Singh, R.K. Application of Industry 4.0 technologies for effective coordination in humanitarian supply chains: A strategic approach. *Ann. Oper. Res.* **2021**, *319*, 379–411. [CrossRef]
50. Marinagi, C.; Belsis, P.; Skourlas, C. New directions for pervasive computing in logistics. *Procedia Soc. Behav. Sci.* **2013**, *73*, 495–502. [CrossRef]
51. Marinagi, C.; Skourlas, C.; Galiotou, E. Advanced Information Technology Solutions for Implementing Information Sharing across Supply Chains. In Proceedings of the 22th Panhellenic Conference on Informatics with International Participation (PCI 18), Athens, Greece, 29 November–1 December 2018; ACM International Proceeding Series; pp. 99–102. [CrossRef]
52. Núñez-Merino, M.; Maqueira-Marín, J.M.; Moyano-Fuentes, J.; Martínez-Jurado, P.J. Information and digital technologies of Industry 4.0 and Lean supply chain management: A systematic literature review. *Int. J. Prod. Res.* **2020**, *58*, 5034–5061. [CrossRef]
53. Queiroz, M.M.; Pereira, S.C.F.; Telles, R.; Machado, M.C. Industry 4.0 and digital supply chain capabilities. *Benchmarking Int. J.* **2019**, *28*, 1761–1782. [CrossRef]
54. Raut, R.D.; Gotmare, A.; Narkhede, B.E.; Govindarajan, U.H.; Bokade, S.U. Enabling Technologies for Industry 4.0 Manufacturing and Supply Chain: Concepts, Current Status, and Adoption Challenges. *IEEE Eng. Manag. Rev.* **2020**, *48*, 83–102. [CrossRef]

55. Reyes, J.; Mula, J.; Díaz-Madroñero, M. Development of a conceptual model for lean supply chain planning in industry 4.0: Multidimensional analysis for operations management. *Prod. Plan. Control* **2021**. [CrossRef]
56. Sharma, M.; Kamble, S.; Mani, V.; Sehrawat, R.; Belhadi, A.; Sharma, V. Industry 4.0 adoption for sustainability in multi-tier manufacturing supply chain in emerging economies. *J. Clean. Prod.* **2021**, *281*, 125013. [CrossRef]
57. Soosay, C.; Kannusamy, R. Scope for Industry 4.0 in Agri-food Supply Chain. In *The Road to a Digitalized Supply Chain Management. Smart and Digital Solutions for Supply Chain Management, Proceedings of the Hamburg International Conference of Logistics (HICL)*; Kersten, W., Blecker, T., Ringle, C., Eds.; Hamburg University of Technology (TUHH), Institute of Business Logistics and General Management: Hamburg, Germany, 2018; Volume 25, pp. 37–56. Available online: https://ideas.repec.org/h/zbw/hiclch/209342.html (accessed on 30 September 2022).
58. Sun, X.; Yu, H.; Solvang, W.D.; Wang, Y.; Wang, K. The application of Industry 4.0 technologies in sustainable logistics: A systematic literature review (2012–2020) to explore future research opportunities. *Environ. Sci. Pollut. Res.* **2022**, *29*, 9560–9591. [CrossRef]
59. Tjahjono, B.; Esplugues, C.; Ares, E.; Pelaez, G. What does Industry 4.0 mean to Supply Chain? *Procedia Manuf.* **2017**, *13*, 1175–1182. [CrossRef]
60. Valilai, O.F.; Sodachi, M. Inspiration of Industry 4.0 to Enable a Proactive Sustainability Assessment Model through the Supply Chain. *Procedia Manuf.* **2020**, *52*, 356–362. [CrossRef]
61. Ben-Daya, M.; Hassini, E.; Bahroun, Z. Internet of things and supply chain management: A literature review. *Int. J. Prod. Res.* **2019**, *57*, 4719–4742. [CrossRef]
62. Gnimpieba, Z.D.R.; Nait-Sidi-Moh, A.; Durand, D.; Fortin, J. Using Internet of Things technologies for a collaborative supply chain: Application to tracking of pallets and containers. *Procedia Comput. Sci.* **2015**, *56*, 550–557. [CrossRef]
63. Zhang, N. Smart logistics path for cyber-physical systems with internet of things. *IEEE Access* **2018**, *6*, 70808–70819. [CrossRef]
64. Rejeb, A.; Keogh, J.G.; Wamba, S.F.; Treiblmaier, H. The potentials of augmented reality in supply chain management: A state-of-the-art review. *Manag. Rev. Q.* **2021**, *71*, 819–856. [CrossRef]
65. Addo-Tenkorang, R.; Helo, P.T. Big data applications in operations/supply-chain management: A literature review. *Comput. Ind. Eng.* **2016**, *101*, 528–543. [CrossRef]
66. Gunasekaran, A.; Tiwari, M.K.; Dubey, R.; Wamba, S.F. Big data and predictive analytics applications in supply chain management. *Comput. Ind. Eng.* **2016**, *101*, 525–527. [CrossRef]
67. Richey, R.G.; Morgan, T.R.; Lindsey-Hall, K.; Adams, F.G. A global exploration of big data in the supply chain. *Int. J. Phys. Distrib. Logist. Manag.* **2016**, *46*, 710–739. [CrossRef]
68. Wang, G.; Gunasekaran, A.; Ngai, E.W.T.; Papadopoulos, T. Big data analytics in logistics and supply chain management: Certain investigations for research and applications. *Int. J. Prod. Econ.* **2016**, *176*, 98–110. [CrossRef]
69. Nguyen, T.; Zhou, L.; Spiegler, V.; Ieromonachou, P.; Lin, Y. Big data analytics in supply chain management: A state-of-the-art literature review. *Comput. Oper. Res.* **2018**, *98*, 254–264. [CrossRef]
70. Baryannis, G.; Validi, S.; Dani, S.; Antoniou, G. Supply chain risk management and artificial intelligence: State of the art and future research directions. *Int. J. Prod. Res.* **2019**, *57*, 2179–2202. [CrossRef]
71. Pan, Y.; Tang, Z. Intelligent Agent Technology in Supply Chains. In *Encyclopedia of Business Analytics and Optimization*; IGI Global: Hershey, PA, USA, 2014; pp. 1262–1274. [CrossRef]
72. Wang, L.; Deng, T.; Shen, Z.M.; Hu, H.; Qi, Y. Digital twin-driven smart supply chain. *Front. Eng. Manag.* **2022**, *9*, 56–70. [CrossRef]
73. Perboli, G.; Musso, S.; Rosano, M. Blockchain in Logistics and Supply Chain: A Lean Approach for Designing Real-World Use Cases. *IEEE Access* **2018**, *6*, 62018–62028. [CrossRef]
74. Kshetri, N. 1 Blockchain's roles in meeting key supply chain management objectives. *Int. J. Inf. Manag.* **2018**, *39*, 80–89. [CrossRef]
75. Mendling, J.; Weber, I.; Van Der Aalst, W.; Brocke, J.V.; Cabanillas, C.; Daniel, F.; Debois, S.; Di Ciccio, C.; Dumas, M.; Dustdar, S.; et al. Blockchains for business process management challenges and opportunities. *ACM Trans. Manag. Inf. Syst.* **2018**, *9*, 1–16. [CrossRef]
76. Weber, J.; Xu, X.; Riveret, R.; Governatori, G.; Ponomarev, A.; Mendling, J. Untrusted business process monitoring and execution using blockchain. In *Proceedings of the 14th International Conference on Business Process Manage, Rio de Janeiro, Brazil, 18–22 September 2016*; Lecture Notes in Computer Science Book Series; Springer: Berlin/Heidelberg, Germany, 2016; Volume 9850, pp. 329–347. [CrossRef]
77. Witkowski, K. Internet of Things, Big Data, Industry 4.0—Innovative Solutions in Logistics and Supply Chains. *Procedia Eng.* **2017**, *182*, 763–769. [CrossRef]
78. Görçün, Ö.F. Autonomous Robots and Utilization in Logistics process. In *Logistics 4.0 and Future of Supply Chains*, 1st ed.; Iyigün, I., Görçün, Ö.F., Eds.; Springer: Singapore, 2022; Chapter 6; pp. 83–94. [CrossRef]
79. Chiu, M.-C.; Lin, Y.-H. Simulation based method considering design for additive manufacturing and supply chain. An empirical study of lamp industry. *Ind. Manag. Data Syst.* **2016**, *116*, 322–348. [CrossRef]
80. Tortorella, G.; Fogliatto, F.S.; Gao, S.; Chan, T.-K. Contributions of Industry 4.0 to supply chain resilience. *Int. J. Logist. Manag.* **2022**, *33*, 547–566. [CrossRef]

81. 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]
82. Dilyard, J.; Zhao, S.; Jacqueline, J.Y. 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]
83. Singh, D.; Sharma, A.; Rana, S.R. Role of Industry 4.0 Practices in Supply Chain Resilience. *ECS Trans.* **2022**, *107*, 6607. [CrossRef]
84. Zouari, D.; Ruel, S.; Viale, L. Does digitalising the supply chain contribute to its resilience? *Int. J. Phys. Distrib. Logist. Manag.* **2021**, *51*, 149–180. [CrossRef]
85. Taghizadeh, E.; Taghizadeh, E. The Impact of Digital Technology and Industry 4.0 on Enhancing Supply Chain Resilience. In Proceedings of the 11th Annual International Conference on Industrial Engineering and Operations Management, Singapore, 9–11 March 2021; pp. 2021–2029.
86. Wang, M.; Asian, S.; Wood, L.C.; Wang, B. Logistics innovation capability and its impacts on the supply chain risks in the Industry 4.0 era. *Mod. Supply Chain. Res. Appl.* **2020**, *2*, 83–98. [CrossRef]
87. Amann, P.; James, J.I. Designing robustness and resilience in digital investigation laboratories. *Digit. Investig.* **2015**, *12*, S111–S120. [CrossRef]
88. Das, A.; Gottlieb, S.; Ivanov, D. Managing disruptions and the ripple effect in digital supply chains: Empirical case studies. In *Handbook of the Ripple Effects in the Supply Chain*; Ivanov, D., Dolgui, A., Sokolov, B., Eds.; International Series in Operations Research & Management Science; Springer: Cham, Switzerland, 2019; Volume 276, pp. 261–285. [CrossRef]
89. Ivanov, D. New Drivers for Supply Chain Structural Dynamics and Resilience: Sustainability, Industry 4.0, Self-Adaptation. In *Structural Dynamics and Resilience in Supply Chain Risk Management*; Price, C.C., Ed.; Part of International Series in Operations Research & Management Science; Springer: Cham, Switzerland, 2018; Volume 265, pp. 293–313. [CrossRef]
90. Ivanov, D.; Blackhurst, J.; Das, A. Supply chain resilience and its interplay with digital technologies: Making innovations work in emergency situations. *Int. J. Phys. Distrib. Logist. Manag.* **2021**, *51*, 97–103. [CrossRef]
91. Ivanov, D.; Dolgui, A.; Sokolov, B. The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *Int. J. Prod. Res.* **2019**, *57*, 829–846. [CrossRef]
92. Dev, N.K.; Shankar, R.; Zacharia, Z.G.; Swami, S. Supply chain resilience for managing the ripple effect in Industry 4.0 for green product diffusion. *Int. J. Phys. Distrib. Logist. Manag.* **2021**, *51*, 897–930. [CrossRef]
93. Ding, B. Pharma Industry 4.0: Literature review and research opportunities in sustainable pharmaceutical supply chains. *Process Saf. Environ. Prot.* **2018**, *119*, 115–130. [CrossRef]
94. Mubarik, M.S.; Naghavi, N.; Mubarik, M.; Kusi-Sarpong, S.; Khan, S.A.; Zaman, S.I.; Kazmi, S.H.A. Resilience and cleaner production in industry 4.0: Role of supply chain mapping and visibility. *J. Clean. Prod.* **2021**, *292*, 126058. [CrossRef]
95. Ralston, P.; Blackhurst, J. Industry 4.0 and resilience in the supply chain: A driver of capability enhancement or capability loss? *Int. J. Prod. Res.* **2020**, *58*, 5006–5019. [CrossRef]
96. Spieske, A.; Birkel, H. Improving supply chain resilience through industry 4.0: A systematic literature review under the impressions of the COVID-19 pandemic. *Comput. Ind. Eng.* **2021**, *158*, 107452. [CrossRef] [PubMed]
97. Fatorachian, H.; Kazemi, H. Impact of Industry 4.0 on supply chain performance. *Prod. Plan. Control* **2021**, *32*, 63–81. [CrossRef]
98. Al-Talib, M.; Melhem, W.Y.; Anosike, A.I.; Reyes, J.A.G.; Nadeem, S.P.; Kumar, A. Achieving resilience in the supply chain by applying IoT technology. *Procedia CIRP* **2020**, *91*, 752–757. [CrossRef]
99. Nica, E. Cyber-Physical Production Networks and Advanced Digitalization in Industry 4.0 Manufacturing Systems: Sustainable Supply Chain Management, Organizational Resilience, and Data-driven Innovation. *J. Self Gov. Manag. Econ.* **2019**, *7*, 27–33. [CrossRef]
100. Brintrup, A.; Pak, J.; Ratiney, D.; Pearce, T.; Wichmann, P.; Woodall, P.; McFarlane, D. Supply chain data analytics for predicting supplier disruptions: A case study in complex asset manufacturing. *Int. J. Prod. Res.* **2020**, *58*, 3330–3341. [CrossRef]
101. Choi, T.-M.; Lambert, J.H. Advances in risk analysis with big data. *Risk Anal.* **2017**, *37*, 1435–1442. [CrossRef]
102. Papadopoulos, T.; Gunasekaran, A.; Dubey, R.; Altay, N.; Childe, S.J.; Wamba, S.F. The role of Big Data in explaining disaster resilience in supply chains for sustainability. *J. Clean. Prod.* **2017**, *142*, 1108–1118. [CrossRef]
103. Dubey, R.; Gunasekaran, A.; Childe, S.J.; Wamba, S.F.; Roubaud, D.; Foropon, C. Empirical investigation of data analytics capability and organizational flexibility as complements to supply chain resilience. *Int. J. Prod. Res.* **2021**, *59*, 110–128. [CrossRef]
104. Ferraris, A.; Mazzoleni, A.; Devalle, A.; Couturier, J. Big data analytics capabilities and knowledge management: Impact on firm performance. *Manag. Decis.* **2019**, *57*, 1923–1936. [CrossRef]
105. Shamout, M.D. Supply Chain Data Analytics and Supply Chain Agility: A Fuzzy Sets (fsQCA) Approach. *Int. J. Organ. Anal.* **2020**, *28*, 1055–1067. [CrossRef]
106. Iftikhar, A.; Purvis, L.; Giannoccaro, I.; Wang, Y. The impact of supply chain complexities on supply chain resilience: The mediating effect of big data analytics. *Prod. Plan. Control* **2022**. [CrossRef]
107. Belhadi, A.; Mani, V.; Kamble, S.S.; Khan, S.A.R.; Verma, S. Artificial intelligence-driven innovation for enhancing supply chain resilience and performance under the effect of supply chain dynamism: An empirical investigation. *Ann. Oper. Res.* **2021**. [CrossRef] [PubMed]
108. 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]

109. 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* **2020**, *32*, 775–788. [CrossRef]
110. Lohmer, J.; Bugert, N.; Lasch, R. Analysis of resilience strategies and ripple effect in blockchain-coordinated supply chains: An agent-based simulation study. *Int. J. Prod. Econ.* **2020**, *228*, 107882. [CrossRef] [PubMed]
111. Min, H. Blockchain technology for enhancing supply chain resilience. *Bus. Horiz.* **2019**, *62*, 35–45. [CrossRef]
112. Nguyen, S.; Chen, P.S.-L.; Du, Y. Risk identification and modeling for blockchain-enabled container shipping. *Int. J. Phys. Distrib. Logist. Manag.* **2021**, *51*, 126–148. [CrossRef]
113. Yoon, J.; Talluri, S.; Yildiz, H.; Sheu, C. The value of Blockchain technology implementation in international trades under demand volatility risk. *Int. J. Prod. Res.* **2019**, *58*, 2163–2183. [CrossRef]
114. Bayramova, A.; Edwards, D.; Roberts, C. The Role of Blockchain Technology in Augmenting Supply Chain Resilience to Cybercrime. *Buildings* **2021**, *11*, 283. [CrossRef]
115. Sreenu, M.; Gupta, N.; Jatoth, C.; Saad, A.; Alharbi, A.; Nkenyereye, L. Blockchain based secure and reliable Cyber Physical ecosystem for vaccine supply chain. *Comput. Commun.* **2022**, *191*, 173–183. [CrossRef]
116. Ghadge, A.; Karantoni, G.; Chaudhuri, A.; Srinivasan, A. Impact of additive manufacturing on aircraft supply chain performance: A system dynamics approach. *J. Manuf. Technol. Manag.* **2018**, *29*, 846–865. [CrossRef]
117. Patidar, A.; Sharma, M.; Agrawal, R.; Sangwan, K.S. Supply chain resilience and its key performance indicators: An evaluation under Industry 4.0 and sustainability perspective. *Manag. Environ. Qual.* **2022**. [CrossRef]
118. Karl, A.; Micheluzzi, J.; Leite, L.R.; Pereira, C.R. Supply chain resilience and key performance indicators: A systematic literature review. *Production* **2018**, *28*, e20180020. [CrossRef]
119. Qader, G.; Junaid, M.; Abbas, Q.; Mubarik, M.S. Industry 4.0 enables supply chain resilience and supply chain performance. *Technol. Forecast. Soc. Chang.* **2022**, *185*, 122026. [CrossRef]
120. Ali, A.; Mahfouz, A.; Arisha, A. Analysing supply chain resilience: Integrating the constructs in a concept mapping framework via a systematic literature review. *Int. J. Supply Chain Manag.* **2017**, *22*, 16–39. [CrossRef]
121. Arsovski, S.; Arsovski, Z.; Stefanović, M.; Tadić, D.; Aleksić, A. Organizational resilience in a cloud-based enterprise in a SC: A challenge for innovative SMEs. *Int. J. Comput. Integr. Manuf.* **2017**, *30*, 409–419. [CrossRef]
122. Bakshi, N.; Kleindorfer, P. Co-opetition and investment for supply-chain resilience. *Prod. Oper. Manag.* **2009**, *18*, 583–603. [CrossRef]
123. Behzadi, G.; O'Sullivan, M.J.; Olsen, T.L.; Zhang, A. Agribusiness SC risk management: A review of quantitative decision models. *Omega* **2017**, *79*, 21–42. [CrossRef]
124. Brusset, X.; Teller, C. SC capabilities, risks, and resilience. *Int. J. Prod. Econ.* **2017**, *184*, 59–68. [CrossRef]
125. Christopher, M.; Peck, H. Building the Resilient Supply Chain. *Int. J. Logist. Manag.* **2004**, *15*, 1–14. [CrossRef]
126. Datta, P. Supply network resilience: A systematic literature review and future research. *Int. J. Logist. Manag.* **2017**, *28*, 1387–1424. [CrossRef]
127. Hohenstein, N.-O.; Feisel, E.; Hartmann, E. Research on the phenomenon of supply chain resilience: A systematic review and paths for further investigation. *Int. J. Phys. Distrib. Logist. Manag.* **2015**, *45*, 90–117. [CrossRef]
128. Ivanov, D. Supply Chain Resilience: Modeling, Management, and Control. In *Structural Dynamics and Resilience in Supply Chain Risk Management*; Price, C.C., Ed.; Part of International Series in Operations Research & Management Science; Springer: Cham, Switzerland, 2018; Volume 265, pp. 45–89. [CrossRef]
129. Ivanov, D.; Dolgui, A.; Sokolov, B.; Ivanova, M. Literature review on disruption recovery in the supply chain. *Int. J. Prod. Res.* **2017**, *55*, 6158–6174. [CrossRef]
130. Kochan, C.G.; Nowicki, D.R. Supply chain resilience: A systematic literature review and typological framework. *Int. J. Phys. Distrib. Logist. Manag.* **2018**, *48*, 842–865. [CrossRef]
131. Madani, F.; Parast, M.M. An integrated approach to organizational resilience: A quality perspective. *Int. J. Qual. Reliab. Manag.* **2021**, *40*, 192–225. [CrossRef]
132. Mallak, L. Putting Organisational Resilience to Work. *Ind. Manag.* **1998**, *40*, 8–13.
133. Pereira, R.C.; Christopher, M.; Silva, A.L. Achieving supply chain resilience: The role of procurement. *Int. J. Supply Chain Manag.* **2014**, *19*, 626–642. [CrossRef]
134. Ponomarov, S.Y.; Holcomb, M.C. Understanding the concept of supply chain resilience. *Int. J. Logist. Manag.* **2009**, *20*, 124–143. [CrossRef]
135. Sheffi, Y.; Rice, B.J. A Supply Chain View of the Resilient Enterprise. *MIT Sloan Manag. Rev.* **2005**, *47*, 41–48.
136. Soni, U.; Jain, V.; Kumar, S. Measuring supply chain resilience using a deterministic modeling approach. *Comput. Ind. Eng.* **2014**, *74*, 11–25. [CrossRef]
137. Blackhurst, J.; Dunn, K.S.; Craighead, C.W. An Empirically Derived Framework of Global Supply Resiliency. *J. Bus. Logist.* **2011**, *32*, 374–391. [CrossRef]
138. Pettit, T.J.; Croxton, K.L.; Fiksel, J. Ensuring Supply Chain Resilience: Development and Implementation of an Assessment Tool. *J. Bus. Logist.* **2013**, *34*, 46–76. [CrossRef]
139. Pettit, T.J.; Croxton, K.L.; Fiksel, J. The evolution of resilience in supply chain management: A retrospective on ensuring supply chain resilience. *J. Bus. Logist.* **2019**, *40*, 56–65. [CrossRef]

140. Wieland, A.; Wallenburg, M.C. Dealing with supply chain risks: Linking risk management practices and strategies to performance. *Int. J. Phys. Distrib. Logist. Manag.* **2012**, *42*, 887–905. [CrossRef]
141. Wieland, A.; Wallenburg, M.C. The influence of relational competencies on supply chain resilience: A relational view. *Int. J. Phys. Distrib. Logist. Manag.* **2013**, *43*, 300–320. [CrossRef]
142. Ponis, S.T.; Koronis, E. Supply Chain Resilience: Definition of Concept and its Formative Elements. *J. Appl. Bus. Res.* **2012**, *28*, 921–930. [CrossRef]
143. Scholten, K.; Schilder, S. The role of collaboration in supply chain resilience. *Supply Chain. Manag.* **2015**, *20*, 471–484. [CrossRef]
144. Scholten, K.; Scott, P.S.; Fynes, B. Mitigation processes-antecedents for building supply chain resilience. *Supply Chain Manag.* **2014**, *19*, 211–228. [CrossRef]
145. Akhavan, P.; Philsoophian, M. Improving of Supply Chain Collaboration and Performance by Using Block Chain Technology as a Mediating Role and Resilience as a Moderating Variable. *J. Knowl. Econ.* **2022**. [CrossRef]
146. Ansari, F.; Kohl, L. AI-Enhanced Maintenance for Building Resilience and Viability in Supply Chains. In *Supply Network Dynamics and Control*; Dolgui, A., Ivanov, D., Sokolov, B., Eds.; Springer Series in Supply Chain Management; Springer: Cham, Switzerland, 2022; Volume 20, pp. 163–185. [CrossRef]
147. Barykin, S.Y.; Bochkarev, A.A.; Kalinina, O.V.; Yadykin, V.K. Concept for a Supply Chain Digital Twin. *Int. J. Math. Eng. Manag. Sci.* **2020**, *5*, 1498–1515. [CrossRef]
148. 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] [PubMed]
149. Catellani, L.; Bottani, E. Supply Chain Performance Metrics in the Lean, Agile, Resilient, Green Perspectives: A survey and model. In Proceedings of the 24th International Conference on Harbor, Maritime and Multimodal Logistic Modeling & Simulation (HMS), Rome, Italy, 19–21 September 2022. [CrossRef]
150. Dumitrașcu, O.; Dumitrașcu, M.; Dobrotă, D. Performance Evaluation for a Sustainable Supply Chain Management System in the Automotive Industry Using Artificial Intelligence. *Processes* **2020**, *8*, 1384. [CrossRef]
151. Ekren, B.Y.; Stylos, N.; Zwiegelaar, J.; Turhanlar, E.E.; Kumar, V. Additive manufacturing integration in E-commerce supply chain network to improve resilience and competitiveness. *Simul. Model. Pract. Theory* **2023**, *122*, 102676. [CrossRef]
152. Essakly, A.; Wichmann, M.; Spengler, T. A reference framework for the holistic evaluation of Industry 4.0 solutions for small-and medium-sized enterprises. *IFAC PapersOnLine* **2019**, *52*, 427–432. [CrossRef]
153. Sesana, M.; Tavola, G. Resilient Manufacturing Systems enabled by AI support to AR equipped operator. In Proceedings of the 2021 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), Cardiff, UK, 21–23 June 2021; pp. 1–5. [CrossRef]
154. Sun, Y.; Zhang, C.; Liang, X. An Agent-Based Simulation for Coupling Carbon Trading Behaviors with Distributed Logistics System. In *Advances in Intelligent Systems and Interactive Applications, IISA 2019*; Xhafa, F., Patnaik, S., Tavana, M., Eds.; Advances in Intelligent Systems and Computing; Springer: Cham, Switzerland, 2020; Volume 1084, pp. 222–229. [CrossRef]
155. Yamin, M.A. Investigating the Drivers of Supply Chain Resilience in the Wake of the COVID-19 Pandemic: Empirical Evidence from an Emerging Economy. *Sustainability* **2021**, *13*, 11939. [CrossRef]
156. Aityassine, F.; Soumadi, M.; Aldiabat, B.; Al-Shorman, H.; Akour, I.; Alshurideh, M.; Al-Hawary, S. The effect of supply chain resilience on supply chain performance of chemical industrial companies. *Uncertain Supply Chain. Manag.* **2022**, *10*, 1271–1278. [CrossRef]
157. Mahdiraji, H.A.; Yaftiyan, F.; Abbasi-Kamardi, A.; Garza-Reyes, J.A. Investigating potential interventions on disruptive impacts of Industry 4.0 technologies in circular supply chains: Evidence from SMEs of an emerging economy. *Comput. Ind. Eng.* **2022**, *174*, 108753. [CrossRef]
158. Manupati, V.K.; Schoenherr, T.; Ramkumar, M.; Panigrahi, S.; Sharma, Y.; Mishra, P. Recovery strategies for a disrupted supply chain network: Leveraging blockchain technology in pre- and post-disruption scenarios. *Int. J. Prod. Econ.* **2022**, *245*, 108389. [CrossRef]
159. Hervani, A.A.; Nandi, S.; Helms, M.M.; Sarkis, J. A performance measurement framework for socially sustainable and resilient supply chains using environmental goods valuation methods. *Sustain. Prod. Consum.* **2022**, *30*, 31–52. [CrossRef]
160. Rajesh, R. Forecasting supply chain resilience performance using grey prediction. *Electron. Commer. Res. Appl.* **2016**, *20*, 42–58. [CrossRef]
161. Singh, C.S.; Soni, G.; Badhotiya, G.K. Performance indicators for supply chain resilience: Review and conceptual framework. *J. Ind. Eng. Int.* **2019**, *15* (Suppl. 1), 105–117. [CrossRef]
162. European Commission; Directorate-General for Research and Innovation; Breque, M.; De Nul, L.; Petridis, A. *Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry*; Publications Office: Luxembourg, 2021. Available online: https://data.europa.eu/doi/10.2777/308407 (accessed on 7 February 2023).
163. Mourtzis, D.; Angelopoulos, J.; Panopoulos, N. A Literature Review of the Challenges and Opportunities of the Transition from Industry 4.0 to Society 5.0. *Energies* **2022**, *15*, 6276. [CrossRef]
164. Xu, X.; Lu, Y.; Vogel-Heuser, B.; Wang, L. Industry 4.0 and Industry 5.0—Inception, conception and perception. *J. Manuf. Syst.* **2021**, *61*, 530–535. [CrossRef]
165. Johnson, A.R.; Johnson, M.E.; Nagarur, N. Supply chain design under disruptions considering risk mitigation strategies for robustness and resiliency. *Int. J. Logist. Syst. Manag.* **2021**, *38*, 1–29. [CrossRef]

166. Rahman, T.; Moktadir, M.A.; Paul, S.K. Key performance indicators for a sustainable recovery strategy in healthcare supply chains: COVID-19 pandemic perspective. *J. Asia Bus. Stud.* **2022**, *16*, 472–494. [CrossRef]
167. Carvalho, H.; Naghshineh, B.; Govindan, K.; Cruz-Machado, V. The resilience of on-time delivery to capacity and material shortages: An empirical investigation in the automotive supply chain. *Comput. Ind. Eng.* **2022**, *171*, 108375. [CrossRef]
168. Lamballais, T.; Roy, D.; De Koster, R. Estimating Performance in a Robotic Mobile Fulfillment System. *Eur. J. Oper. Res.* **2016**, *256*, 976–990. [CrossRef]
169. Kinra, A.; Ivanov, D.; Das, A.; Dolgui, A. Ripple effect quantification by supplier risk exposure assessment. *Int. J. Prod. Res.* **2020**, *58*, 5559–5578. [CrossRef]
170. Li, Y.; Zobel, C.W. Exploring supply chain network resilience in the presence of the ripple effect. *Int. J. Prod. Econ.* **2020**, *228*, 107693. [CrossRef]
171. Stevenson, M.; Spring, M. Flexibility from a supply chain perspective: Definition and review. *Int. J. Oper. Prod. Manag.* **2007**, *27*, 685–713. [CrossRef]
172. Van Eck, N.J.; Waltman, L. *Manual for VOSviewer Version 1.6.15*; Universiteit Leinden: Leiden, The Netherlands, 2020. Available online: https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.15.pdf (accessed on 7 February 2023).
173. Amaral, A.; Jorge, D.; Peças, P. Small Medium Enterprises and Industry 4.0: Current Models' Ineptitude and the Proposal of a Methodology to Successfully Implement Industry 4.0 in Small Medium Enterprises. *Procedia Manuf.* **2019**, *41*, 1103–1110. [CrossRef]
174. Amaral, A.; Peças, P.A. Framework for Assessing Manufacturing SMEs Industry 4.0. Maturity. *Appl. Sci.* **2021**, *11*, 6127. [CrossRef]
175. Mittala, S.; Khana, M.A.; Romerob, D.; Wuest, T. A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). *J. Manuf. Syst.* **2018**, *49*, 194–214. [CrossRef]
176. Santos, R.C.; Martinho, J.L. An Industry 4.0 maturity model proposal. *J. Manuf. Technol. Manag.* **2019**, *31*, 1023–1043. [CrossRef]