The Impact of Industry 4.0 on Supply Chain Resilience Management

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Abstract. Supply chain resilience management is a growing topic in the last decade, considering the negative consequences caused by severe global disruptive events such as COVID-19, Ukraine War, natural disasters, and political instability. At the same time, Industry 4.0 (I4.0) and its enabling technologies are being applied in more key processes within the supply chain. This research performs a short systematic literature review and analyzes which I4.0 technologies are applied in supply chain management and how they relate to the resilience capabilities, principles, and elements. Big Data Analytics, Cloud Computing, Internet of Things, Blockchain, Cyber-Physical Systems, Artificial Intelligent and Additive Manufacturing technologies were analyzed. A direct relationship was established in the implementation of I4.0 technologies and supply chain resilience management, as a set of disruptive technologies for the establishment of strategic objectives in the supply chain.

Keywords: Industry 4.0 · I4.0 · Supply chain resilience management · SCREM · Supply chain management

1 Introduction

The current level of competitiveness in the globalized market and the rapid changes of customer requirements have led supply chains to adapt their competitive strategy and integrate processes with greater level of interoperability and collaboration between their members [1]. Although these interrelated processes have generated multiple benefits in supply chain management [2], a higher level of dependency between processes increases the level of vulnerability of the nodes [3, 4] and the negative consequences of a disruption and its ripple effect on supply chain operations [5].

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Supply chain resilience management (SCREM) is considered a strategic supply chain capability to prevent the occurrence and minimize the consequences of disruptive events, especially in activities that enable the continuity of their processes, recovery and adaptation to the market after the disruptive event [6, 7]. Disruptive events on a global scale, such as the COVID-19 pandemic, Ukraine war, natural disasters and political instability, require supply chains to implement resilient and innovative strategies to minimize the effects and negative consequences on their competitive strategy and market growth [8, 9].

SCREM is considered a strategic capability that modifies the scope of the chain and its performance in the marked [4, 9]. Understanding the principles related to resilience management becomes a priority to establish the best strategies applied in supply chains, especially when the study of resilience in supply chains has increased notably in recent years in response to disruptive events with severe negative consequences worldwide [3, 10].

Industry 4.0 (I4.0) and its enabling technologies implemented in recent industrial processes such as new production models [10], supplier management [9], last mile logistics, reverse logistics, and customer experience [11] can act as resilience enhancers and minimize the risks of disruptions in supply chain operations [12]. I4.0 integration can help achieve superior supply chain performance in disruption scenarios, establishing that the ability to digitize and analyze data can identify disruptive events in real-time [13]. Thus, it becomes a priority to analyze the impact of these enabling technologies in Industry 4.0 and their influence on resilience management.

This research, based on a systematic literature review, analyzes the importance and integration of Industry 4.0 as a competitive strategy in supply chain resilience management. The structure of the paper is as follows: Sect. 2 analyzes the literature as a preamble to the topic. Section 3 shows the methodology to be used. Section 4 details the results found, considering a temporal, bibliographic, and relational analysis between I4.0 and SCREM. Finally, conclusions, limitations, and future lines of research are presented.

2 Background

2.1 Supply Chain Resilience Management (SCREM)

Resilience comes from other areas of analysis such as psychology and ecology [14] and has been adapted to business management systems, and later, to supply chain management systems [10]. SCREM scope has varied over time [3]. Initially, it was considered as the management of risk and vulnerability in isolated and individual companies, but then its treatment was extended to management in supply chains in a preventive scope of disruptions [15]. Several studies show the evolution of the term resilience in supply chains [14–19].

The literature has identified five capabilities that supply chains must develop to manage resilience [14, 20]: (1) prevention: the ability to identify and anticipate the occurrence of disruptive events; (2) resistance: the ability to maintain operations while a disruptive event occurs without losing control of the situation; (3) response: the ability to act in an agile and efficient manner to minimize the consequences of the domino effect; (4) recovery and continuity: the ability to return to the initial or better conditions after the disruption has occurred; and (5) learning and continuous improvement: the ability to analyze the causes and effects of the disruptive event and establish actions to avoid a new occurrence. These capabilities are related to the four principles and elements of resilience: supply chain reengineering, collaboration, agility, and SCREM culture [3, 16].

In general, SCREM literature in the last decade is wide and varied according to the point of view analyzed. For this study, the definition, capabilities, principles, and elements proposed by [3] will be considered for the conceptual analysis and discussion.

2.2 Industry 4.0 and Supply Chain Management

I4.0 represents the beginning of a digital era in industries. I4.0 is designed to build economic and social systems that increase flexibility and responsiveness to market changes and maximize operations [21]. The term I4.0 has its origin in a German government initiative [22], with the aim of safeguarding manufacturing business development and its competitiveness in the market. Subsequently, terms related to I4.0 such as industrial internet, cyber-Physical Systems, internet of things (IoT), smart factory and smart systems were used [23, 24].

There are recent literature reviews that analyze the integration of I4.0 in the supply chain: [25] analyze the impact of I4.0 and identify possible drivers and barriers in supply chain management; [26] analyze 21 dimensions for managing a supply chain 4.0; [27] analyze 13 enabling of I4.0 for the sustainability of a supply chain and possible applied strategies. They consider that the development of I4.0 is facilitated by individual digital technologies, which together create systems that generate interconnected solutions in practice [28].

In general terms, the purpose of I4.0 is the integration of information and communication technologies in industrial processes, i.e., an intelligent interconnection of products and processes within the value chain to increase efficiency [29]. These major changes occurring in the industry are considered a fourth industrial revolution seeking a digital or intelligent manufacturing that allows the integration of networks, mobility, flexible industrial processes, interoperability of processes, integration with customers and suppliers and innovation in business strategy [30].

3 Method

To avoid ambiguity and to determine the scope of a literature review, it is relevant to define the research questions. To this purpose, the Systematic Literature Review (SLR) methodology was adopted [31]. The objective of this research answers the following questions: RQ1: *What are the main I4.0 enabling technologies applied for supply chain resilience management?* RQ2: *How does I4.0 affect resilience capabilities in supply chains?*

The answers to these questions will allow the development of relational analysis. For this purpose, a general search was conducted in the Scopus database using the following search string: (“supply chain”) AND (“performance” OR “management”) AND (“resilie*” OR “risk” OR “disruption”) AND (“industry 4.0” OR “smart industry”

OR "digital industry"). The keywords used respond to the topics and research questions RQ1 and RQ2.

The search initially generated 181 articles (Title-Abs-Key) considering a period from 2018 to January 2023. Inclusion criteria were limited to papers in peer-reviewed journals, articles, and literature reviews in the English language, and their focus coincides with the analysis of this research. Books, book chapters, and lectures were excluded, unless they are of great importance for the topic of analysis, resulting in 82 articles. After the process of the initial reading of the abstract and complete reading of the scope of the articles, 19 articles were established as the basis for the analysis. This research develops a bibliographic methodology supported using software for the relational analysis of its variables. Table 1 shows the search criteria applied in the research.

Table 1. Search criteria applied in research

Research questions	Search string	Database	Initial search	Inclusion criteria	Full content alignment
RQ1: *What are the main I4.0 enabling technologies applied for supply chain resilience management?* RQ2: *How does I4.0 affect resilience capabilities in supply chains?*	*("supply chain") AND ("performance" OR "management") AND ("resilie*" OR "risk" OR "disruption") AND ("industry 4.0" OR "smart industry" OR "digital industry")*	*Scopus*	***181 articles*** *(Tile, abs, Key)*	*- Peer-reviewed journals.* *- English language* *- 2018 to January 2023* *- Book, book chapters and lectures (excluded).*	***19 articles***
				82 articles	

4 Results

4.1 Temporal Analysis

The results of [3] show that the study of supply chain resilience management has been expanding since 2014, generating an important and constant upturn since 2016. The study of technologies implemented in I4.0 for supply chain resilience management has its peak in 2017, maintaining an increasing growth since that year. The subject matter is very relevant and, since 2020, literature reviews have been published, from different fields of analysis on I4.0 and SCREM [12, 32–34], being 21.05% of the analyzed articles. The main scientific journals where they have been published are the International Journal of Logistics Management (10.53%), International Journal of Production Research (10.53%), and Production Planning and Control (10.53%), coinciding with the main areas of analysis: Business, Management, and Accounting (28.9%), Engineering (22.2%), Computer Science (15.6%) and Decision Sciences (15.6%).

There are two factors that have allowed the development of this topic: first, serious disruptive events with negative global consequences such as the COVID-19 pandemic, Ukraine war, Brexit, trade war between the United States and China, natural disasters, political instability and other serious global crises, implying that research has focused on improving processes and the immediate return to normal operations with the adaptation of new market requirements [35]; and second, the maturity of I4.0 technologies as potential solutions to specific problems for supply chains [34].

4.2 Bibliometric Analysis

The bibliometric analysis allows to identify relevant articles, evaluate the contribution of authors, and find patterns and relationships of publications [36]. The VOSviewer software based on the VOS (visualization of similarities) methodology was used. To reinforce the relational analysis of the variables in the research, a map was developed based on the concurrences of the keywords of the Scopus publications in the final search (n = 19), with the dual objective of obtaining a general overview of the main areas of research related to I4.0 and SCREM, as well as categorizing the research topics according to their importance for the scientific community (Fig. 1).

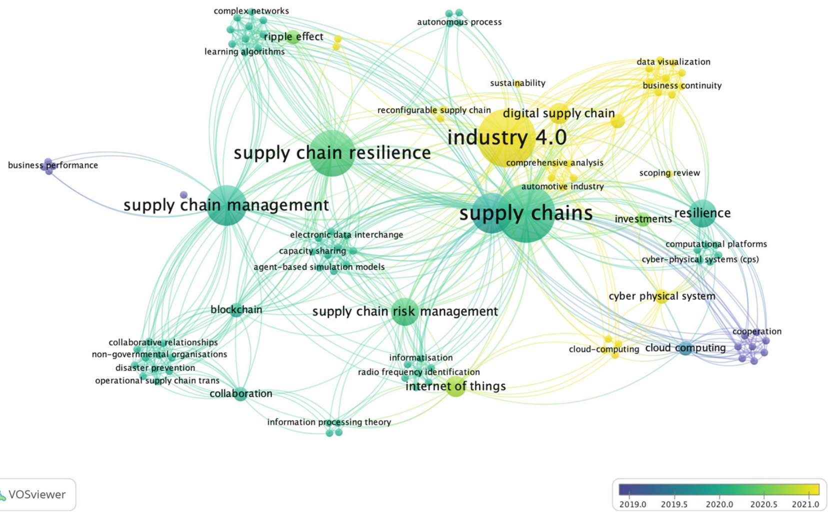

Fig. 1. Correlational analysis of keywords from the academic literature (n = 19, January 2023). Software VOSviewer: Normalization: association strength method. Layout: attraction 2 – repulsion 0. Visualization: occurrences.

Figure 1 shows how the term I4.0 has a higher level of concurrence and is directly related to supply chain management and risk management in recent years. The clusters allow for analyzing the main research approaches related to the thematic: elements of resilience in supply chains, methodologies, and mathematical techniques for performance management in supply chains, and the main enabling technologies of Industry 4.0 that are being implemented and that are related to resilience management such as blockchain, cloud computing, additive manufacturing, internet of thing, big data analytics, artificial intelligence, and cyber-physical system. The graph also shows the current relationship of the COVID-19 pandemic with the main affected industrial processes and their direct interaction with the supply chain management considering its sustainability and resilience. In other words, there is a direct influence between I4.0 and the increase or decrease of resilience in supply chains.

4.3 I4.0 Enabling Technologies and SCREM

Although there is no single definition for I4.0 nor are its enabling technologies consolidated into a single application framework [37], Table 2 shows the enabling technologies discussed in the base articles of this research. These enabling technologies coincide with studies [12, 34, 38], with Big Data Analytics (BDA) being the most widely used, followed by Cloud Computing (CC), Internet of Things (IoT), Blockchain (BC), and to a lesser extent Cyber-Physical Systems (CPS), Artificial Intelligent (AI) and Additive manufacturing (AM).

Table 2. I4.0 enabling technologies

Article	Year	Research type	*I4.0 enabling technologies*						
			CC	CPS	AI	AM	IoT	BC	BDA
[43]	2018	Empirical	X						
[44]	2019	Conceptual							X
[45]	2019	Conceptual							X
[39]	2020	Empirical					X		
[40]	2020	Conceptual					X		
[46]	2020	Conceptual						X	
[32]	2020	Conceptual		X					
[47]	2020	Empirical							X
[33]	2020	Empirical							X
[48]	2020	Conceptual						X	
[42]	2020	Conceptual		X					
[49]	2021	Conceptual							X
[41]	2021	Conceptual				X			
[50]	2021	Conceptual	X	X			X	X	X
[12]	2021	Conceptual	X	X	X	X	X	X	X
[38]	2022	Conceptual	X	X	X	X	X	X	X
[51]	2022	Conceptual	X		X				
[34]	2022	Conceptual	X	6	X	X	X	X	X
[52]	2022	Conceptual					X	X	

(*continued*)

Table 2. (*continued*)

Article	Year	Research type	*I4.0 enabling technologies*						
			CC	CPS	AI	AM	IoT	BC	BDA
Total			6	5	4	4	7	7	9
%			31,58	31,58	21,05	21,05	36,48	36,48	47,37

CC: Cloud computing; CPS: Cyber Physical Systems; AI: Artificial Intelligent; AM: additive manufacturing; IoT: Internet of Thing; BC: Blockchain; BDA: Big Data Analytics

The analysis of these technologies is developed individually in the early years, but current works develop a joint analysis of these technologies by analyzing the existing literature. The papers analyzing CPS, AM, and IoT focus their study mainly on the manufacturing and production systems of organizations [42, 43, 47, 49], and the focus on the other technologies is broader to all supply chain operations. Most studies develop a conceptual analysis.

To understand the relationships between I4.0 and SCREM, the linkage of enabling technologies with the capabilities, elements and principles of supply chain resilience management proposed by was analyzed [3]. Table 3 shows the relationships found in this research. A more comprehensive analysis of the relationship between the capabilities, elements, and principles of resilience in supply chains can be found in [3, 14–18].

The main relationships found are centered on the principles of collaboration and agility, considering the collection and processing of data and subsequent responses to disruptive events.

Cloud Computing is a permanent digital technological resource that allows the collecting, storing, processing, and sharing of data from multiple users among them. This technology can cover three different areas: intra-structure, operating systems, and applications [11]. It relates mainly to shared information, flexibility, visibility, and velocity elements. CC enables the supply chain to increase its ability to share relevant, efficient, and timely information on all processes and member status to make decisions together [43]. This raises the level of interoperability and thus the ability to mutually manage objectives [2]. CC is related to other technologies such as BDA and IoT [12, 38], allowing the collection of data on possible risks or disruptive events, analyzing, and interpreting them quickly to modify supply, production, transportation, or demand operations [43]. CC allows to support and respond to disruptive events [34]. This technology requires high-speed Internet access and very strict security protocols for information control and data protection.

It is precisely where Blockchain (BC) technology enables this purpose, offering a secure mechanism for the exchange of information between members of the supply chain. It generates information encryption and storage in a distributed manner to avoid a single point of failure or adulteration when a disruptive event occurs [28, 46]. BC is mainly related to the elements of trust, visibility, and velocity. Within the supply chain, it allows verifying the accuracy of information and tracking asset locations and statuses [49]. This allows the development of value processes, improving open communication, coordination, and trust, and increasing relationships between digitally connected chain members securely and reliably [48].

Table 3. Relationship I4.0 enabling technologies and SCREM capabilities, principles, and elements

Article	*SCREM Principles and elements*														*SCREM Capabilities*				
	SC Reengineering				*Collaboration*			*Agility*			*SCRM Culture*								
	F	**RE**	**RO**	**CP**	**SI**	**T**	**SA**	**VI**	**VE**	**MA**	**L**	**IN**	**DEA**	**KN**	**P**	**R**	**RS**	**RC**	**LCI**
[43]	X				X		X	X	X				X			X	X	X	
[44]							X		X	X			X	X		X	X		
[45]							X		X	X			X	X		X	X		
[39]	X	X	X	X				X	X	X		X	X	X	X	X	X	X	
[40]	X	X	X	X				X	X	X		X	X	X	X	X	X	X	X
[46]					X	X	X	X	X			X	X			X	X		
[32]	X	X	X	X				X	X	X	X	X	X	X	X	X	X	X	
[47]				X	X	X	X		X	X		X	X	X	X	X	X		
[33]	X			X	X		X		X	X			X	X	X	X	X		
[48]					X	X	X	X	X			X	X		X	X	X		
[42]	X	X	X					X	X		X	X	X	X		X	X	X	
[49]				X	X	X	X		X	X		X	X	X	X	X	X	X	
[41]	X		X	X					X			X	X				X	X	
[50]	X			X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
[12]	X	X		X	X	X		X	X		X	X	X	X	X	X	X	X	X
[38]	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
[51]	X				X		X	X	X			X	X			X	X		
[34]	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
[52]	X						X	X		X	X	X				X	X		
TOTAL	1	7	6	11	11	8	13	13	18	10	7	15	18	13	11	18	19	11	5
%	68,42	36,84	31,58	57,89	57,89	42,11	68,42	68,42	94,74	52,63	36,48	78,95	94,74	68,42	57,89	89,47	100,0	57,89	26,32

F: Flexibility; RE: Redundancy; RO: Robustness; CP: Contingency planning; SI: Shared Information; T: Trust; SA: Strategic alignment; VI: Visibility; VE: Velocity; MA; Market adaptation; L: Leadership; IN: Innovation; DEA: Disruptive environment awareness; KM: Knowledge management; P: Prevention; R: Resistance; RS: Response; RC: Recovery and continuity; LCI: Learning and continuous improvement.

Internet of Things (IoT) is a physical network with digital technology that allows autonomous interaction [39], considering all nodes of the supply chain. This technology allows the interconnection through the internet of intelligent devices that share information in real-time, maximizing and automating data capture and improving the traceability of processes [40]. Various monitoring devices such as RFID, GPS, cameras, sensors, barcodes, and lasers are used to facilitate data collection. The data generated from IoT serve as input for the application of other technologies such as BDA and CPS [38]. IoT is mainly related to the visibility, velocity, and flexibility elements of resilience, applied as a response to a disruptive event.

Cyber-Physical Systems (CPS) precisely integrate the physical infrastructure into digital systems enabling the exchange of information. CPS uses computers that monitor physical processes and makes necessary changes according to the characteristics of the environment in real-time [42]. It links with automation, monitoring, and control processes of operations comprehensively. In risk management, it is primordial to know the state of the supply chain in real-time to develop strategies to avoid disruption or minimize its consequences [52]. Sharing information is not only enough, but this information must also be true and timely [53], being guaranteed by the information reading, automation, and robotics systems implemented in the supply chain [32]. This technology represents a great opportunity to increase the economic profitability of the services, due to the ease of capturing information in real-time and the flexible management of assets in the face of a disruptive event, either with shipment tracking, route optimization, last-mile delivery, warehouse capacity, planned maintenance and adaptation of logistics processes according to market variation [54].

In many cases, the information obtained from the processes is of great volume, making it necessary to process this information. Big-Data Analysis (BDA) and data mining technology allow the processing of this information at high speed, establishing patterns, histories and trends that increase the efficiency of decision making [44, 55]. BDA presents a very close link with Artificial Intelligent (AI), considering the latter as part of BDA [33] or as an independent technology [49]. Data interpretation solutions should focus on autonomous learning for decision making, this being the differentiating contribution of AI applied in BDA [56].

BDA enables the combination of tools, techniques, and processes to integrate disruptive events from different sources and allows joint decision-making [45]. This allows the enhancement of another principle of resilience management: agility. This principle makes it possible to develop a rapid response of the supply chain to a disruptive event through the distribution of its resources, which are critical at that moment. BDA allows the development of risk event prediction, rapid and flexible response planning, and real-time performance monitoring [33, 47]. The results of efficient information processing become key to supporting disruption, response and adjust to new market requirements [3]. BDA supports the development and execution of contingency plans, combining simulation techniques to test alternative scenarios in a digital supply chain [49].

Artificial Intelligent (AI) comprises techniques that enable continuous learning from data and experiences. IoT, CPS and BDA feed learning information, AI analyzes these large volumes of data in real time, finds recorded patterns, identifies potential risks, and threats that may affect the supply chain, and makes decisions based on this information [34]. This allows for a proactive response to potential adverse events [38]. Among the main benefits of AI in supply chains are risk detection and prediction, optimization of supply chain planning, simulation, real-time monitoring and tracking, and collaboration and communication [49]. AI is an emerging technology analyzed conceptually.

Additive manufacturing (AM) is an enabling technology recently analyzed within I4.0 [38]. Its principle is based on the successive aggregation of materials layer by layer, being 3D printers its main tool [12], allowing the production of modules or components regardless of their place in the supply chain. It is related to flexibility in the chain operations, mainly in the transformation process [41].

Technologies linked to I4.0 also influence the resilient principle of supply chain reengineering. IoT, CPS, and AM allow organizations to make operational changes and increase the flexibility needed to adapt production to changes in demand fluctuations or other disruptive events. One of the techniques associated with increased resilience is redundancy at critical points to ensure continuity of operations, increasing the benefits of effective information processing and real knowledge of all requirements in the supply chain. In addition, the technologies analyzed allow having an overview of all the interoperability of the processes and generating prevention and contingency plans in the face of possible disruptive events [57]. The velocity of response was the element that is maximized with all the I4.0 technologies.

The transversal principle of SCRM culture in supply chains is directly related to the technologies linked to I4.0. Its elements of leadership, knowledge management, awareness of the disruptive environment, and mainly innovation allow members of the supply chain to recognize the existence of possible disruptions and execute actions to minimize them. These actions linked to disruptive technology for the modification of processes can increase effectiveness, generate learning among its members and improve the value chain [58]. This principle makes it possible to enhance the other elements of supply chain resilience management [59], although the study of the human factor is not very well developed. These I4.0 technologies related to strategies to increase resilience allow optimizing the value chain and market positioning, thus becoming a key strategy in supply chain management [3].

5 Conclusions

SCREM is a growing topic in recent years, especially due to the disruptive events with serious negative consequences that have occurred worldwide. Resilience, although coming from other disciplines, has been considered an essential part of the organizations' management systems and then of the supply chains, allowing to increase the chain's capacity to prevent the occurrence and minimize the consequences of disruptive events. With the inclusion of new technologies, related to I4.0, operational processes must be modified to adapt to the market. I4.0 seeks to contribute to cost reduction, improve traceability and information security, sharing real and in-the-moment data to improve joint decision-making.

The literature base analysis shows that the main enabling technologies in I4.0 applied to manage resilience in supply chains (RQ1) are Big Data Analytics (BDA), Cloud Computing (CC), Internet of Things (IoT), Blockchain (BC), Cyber-Physical Systems (CPS), Artificial Intelligent (AI) and Additive manufacturing (AM). BDA is the most studied technology within the area. AI and AM are the emerging technology.

This research established a direct relationship between the implementation of enabling technologies to I4.0 and supply chain resilience management, mainly in the principles of collaboration and agility. The main elements it modifies are the velocity of response, visibility, flexibility, shared information, trust, and disruptive environment awareness. The analyzed documentation shows I4.0 implementation mainly in the stages of resistance and response to the disruptive event, lesser proportion in the stages of prevention and continuity, and little treatment in the capacity for learning and continuous improvement.

I4.0 enhances the resilient elements in the supply chains, generating an increase in favorable response to disruptive events or minimizing their occurrence. As a factor that positively influences resilience in organizations, it becomes a fundamental pillar to increase the performance of the chain and thus generate greater competitiveness and market value. This makes it possible to establish the importance of I4.0 as a disruptive technology for the establishment of the strategic objectives of the supply chain.

This research has limitations associated with the terms of the initial search. The relational analysis is executed based on resilience principles and I4.0 technologies from other studies, being the research conceptual. It is necessary to empirically validate relationships under scenarios, and the consequences on supply chains of the COVID-19 pandemic, Ukraine war, and political disruption prove to be a great assessment scenario as a proposal for future research. In addition, it is necessary to analyze the influence of I4.0 on other co-management systems such as sustainability, and from the human factor.

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