Resilient supply chains: quantitative methods and modeling approaches

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Abstract

In today's volatile global landscape, ensuring resilience in supply chains is paramount for businesses to withstand disruptions and maintain operational continuity. This paper presents a comprehensive investigation about supply chain resilience, focusing on indicators, quantitative methods, and modeling approaches. Furthermore, research gaps and future directions are identified, emphasizing the need for long-term resilience, integration of emerging technologies, collaboration among supply chain actors, and alignment with sustainability principles. This review provides a comprehensive foundation for advancing research and practice in SCR, underscoring the importance of holistic and proactive approaches to address challenges and risks in supply chains.

1. Introduction

The supply chain (SC) comprises a network of organizations engaged in various processes and activities, through up-stream and down-stream links, ultimately delivering value in the creation of products and services to the end consumer. Integration within the SC hinges on key elements that are contextual and unique to each process and link [1].

Companies need to innovate and cultivate collaborative practices to improve the interdependence this causes. However, these efforts can increase susceptibility to operational disruptions and jeopardize their long-term viability [2]. SC are particularly vulnerable to disruptions, not only because of their direct impact, but also because of the cascading risks they propagate [3]. Given these dynamics, proactive risk management in supply chains has become critical to ensure long-term stability, adaptability, and competitiveness. SCs must be designed to endure disruptions (low vulnerability) and recover quickly from them at minimal cost (high recoverability). [4]. This situation has led to a growing interest in the study of resilience in supply chains.

Resilience is understood as the capacity to recover, and evolve in response to disruptions, strengthening its ability to maintain a continuous flow of operations in the presence of disruptive events [5]. Resilience focuses on building recovery, robustness, and flexibility [6].

It is essential to develop quantitative indicators and methods to assess the current level of resilience within the SC and its relationship with other key performance indicators. In addition, it is necessary to develop modeling approaches that allow a better understanding of the overall resilience of the system and how it can be improved [7].

While literature reviews on supply chain resilience (SCR) are not scarce, those available are fundamentally conceptually and empirically oriented. There is a paucity of studies focusing on quantifying resilience attributes within SCs [6]. The literature provides insights into resilience frameworks and strategies, there remains a distinct absence in comprehensive quantitative modelling approaches and quantitative methods tailored specifically for enhancing resilience across SC.

The aim of this paper is to conduct a comprehensive review of the SCR literature, to identify gaps in existing research, formulate

relevant research questions, and outline novel contributions.
This will be achieved by analyzing the main quantitative methods to assess resilience and their interaction, as well as to examine different modeling approaches proposed in the literature for designing supply chains resilient.
The document is structured as follows: in section 1 a contextualization of the problem of resilience in the supply chain, justifying the importance of approaching resilience from analytical and mathematical perspectives. Section 2 describes the methods used to examine the existing literature. A set of research questions were defined to assess the state of the art. In section 3 Analysis of Findings derived from the literature review, including analysis of the current landscape and assessment of quantitative advances. Identification of gaps and limitations in existing research. Interpretation of the results in the context of the research objectives and possible future directions for research.

2. Methods

In this section, we will employ a systematic methodology for the comprehensive examination of literature proposed by Denyer and Tranfield [8]. This adopts an iterative approach encompassing the definition of study scope, research question, identification of pertinent keywords and research strings, literature selection and evaluation, analysis, and synthesis of the literature through bibliographic techniques.

2.1. Research context analysis and question formulation

The initial phase is pivotal in accurately and clearly delineating the scope of the research study, achieved through the formulation of pertinent research questions. Among the questions that will guide the review are: How has the concept of resilience been defined within the context of supply chains? What quantitative metrics are frequently employed to measure resilience in supply chains? What are the predominant operations research methods utilized in modeling SCR? What are the remaining challenges in research on resilience within supply chains, and what future directions should be pursued?

2.2. Sourcing of relevant literature and analysis and synthesis of results through bibliographic techniques

The search equation used is TITLE-ABS-KEY (("resilien*" OR "risk*") AND ("indicators" OR "quantitative methods" OR" model approaches") AND ("supply chain*" OR "supply network*"))
An initial search is carried out in the databases Web of science, Scopus, ScienceDirect and Google Scholar, for a total of 135 articles.
For a comprehensive analysis of scientific literature, the Tree of Science (ToS) tool was utilized. Based on graph theory metrics, this tool visualizes works in a field of knowledge as a tree, where the roots are classic articles, the trunk represents articles that allow the area to grow, and the leaves are recently published articles.
The classic articles, represented by the roots in the knowledge tree, have laid the foundation in risk management in logistics and SC activities. In these initial works, fundamental concepts on risk identification and evaluation are addressed, as well as strategies to mitigate them. Topics such as inventory management, supplier management and transportation route optimization are explored, focusing on improving operational efficiency and reducing vulnerability to potential disruptions. [9-13].
In the papers represented by the tree trunk, there is an evolution towards a more holistic approach to risk management. The keywords are framework, model, information, customer satisfaction, recognizing the interconnection of different aspects in the supply chain. Quantitative approaches to defining and modeling SCR, as well as empirical analysis of SC risks and their impact on business performance, are also explored. These works represent an intermediate stage in the evolution of the field, combining traditional approaches with new methodologies [14-18].
On the other hand, the most recent articles, represented by the leaves of the tree, show a change in focus towards emerging topics such as sustainability and industry 4.0. These works explore how SC risk management relates to environmental, social, and economic sustainability. [19-21]. It discusses how digitalization, technology, artificial intelligence, and the Internet of Things, are transforming risk management in the industry. [22-24]. There is growing interest in the application of these concepts in specific sectors, such as health, food and automotive, with the aim of improving the efficiency, resilience, and sustainability of supply chains.
The examination of keyword co-occurrence in the articles was conducted using the VOSviewer software, employing the technique of visualization of similarities clusterization for bibliometric mapping. Throughout the analysis, a minimum threshold of five keyword occurrences was established, following the default value within the software. The outcome revealed a total of 41

keywords and provided a detailed temporal description, corroborating that in recent years, research related to resilience in the SC has begun to be investigated (Figure 1).
Management of resilience in the SC has evolved considerably over time. Initially, it focused on reactive strategies and recovery measures after disruptive events. However, this perspective has broadened its focus to include proactive elements such as adaptation and anticipation. In more recent developments, the conceptual framework has expanded further, encompassing not only prevention and impact minimization strategies, but also a greater emphasis on continuous learning and continuous improvement. This evolution reflects a dynamic response to changing SC challenges, promoting a comprehensive and forward-looking approach to resilience management.

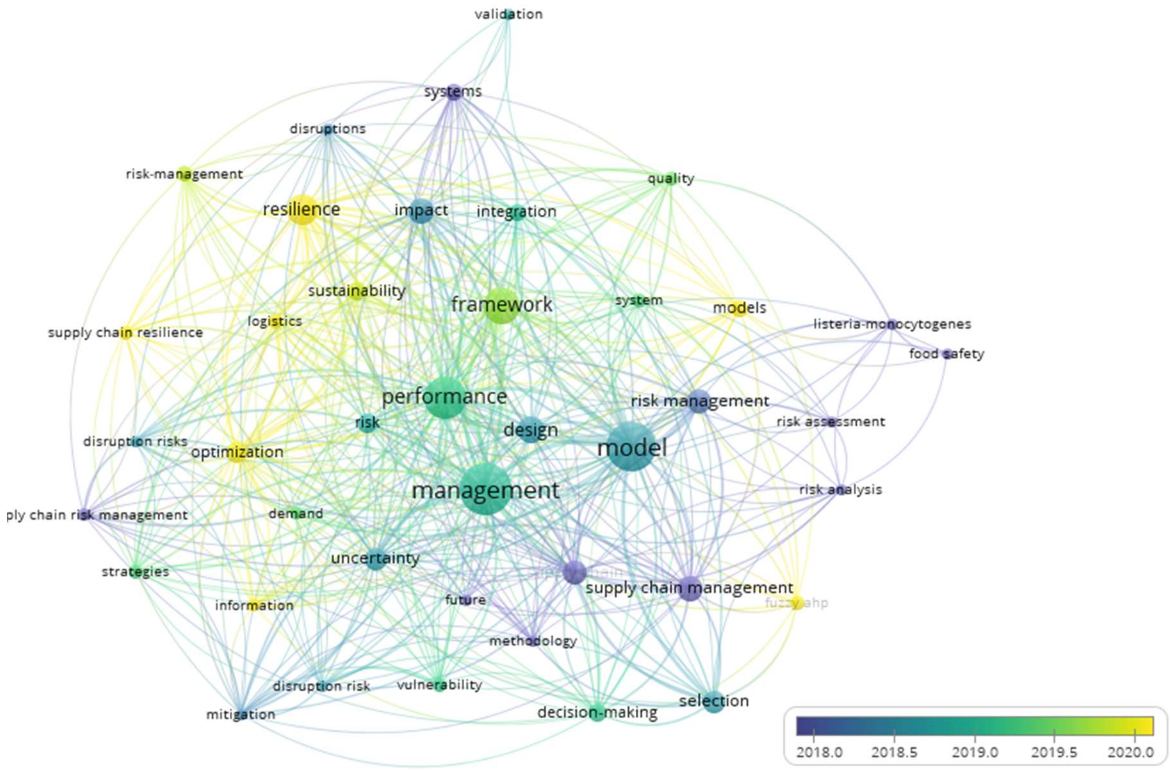

Figure 1: Co-occurrences analysis - VOSviewer software

3. Results and Discussion

Pressure on margins has led to a lot of organizations going for low-cost solutions. This may have resulted in leaner but much more fragile supply chains. Resilient SC, though not being the cheapest, are able to face contingencies in the business milieu.
Sheffi [25] suggests that resilience plays a crucial role in business competence by promoting an organizational culture, systems and processes that facilitate rapid and effective detection and response to disruptive crises.
Several authors have in common that the ability to recover from a disturbance is closely related to response capabilities through flexibility and redundancy. While robustness, some claim that it is a special case of resilience since it implies the return of the system to the original state after a disturbance occurs [26].
Sheffi [27] more precisely details the different phases of a SC crisis and its impact on performance as a function of time (Figure 2).

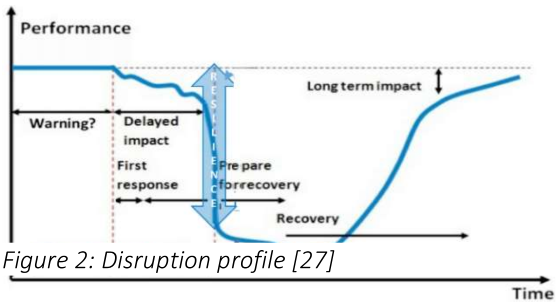

Figure 2: Disruption profile [27]

3.1. Quantitative methods of SCR

The review of the literature shows the lack of complete clarity in the internal and external

variables that can affect the resilience of the supply chain. Consistent with this are models that do not comprehensively present a set of quantitative metrics with the goal of addressing SC resilience, but instead present models that contain what we can now infer as resilience concerns.
As an illustration of this diversity of approaches, we will present representative indicators found in the literature that seek to measure resilience from different perspectives.
Cecere and Mayer [28] suggest that the resilience factor in a company is determined by the proximity between two key financial metrics: operating margin and inventory turns. Companies whose values on these metrics are closer to each other are assumed to demonstrate greater resilience compared to those whose values are further apart. In practical terms, this means that companies that manage to maintain a strong operating margin while maintaining high inventory turns have a greater ability to adapt and recover from shocks or changes in the business environment. Therefore, if the distance between these two metrics is smaller, the company is considered to have greater resilience.
To develop the values, a representation of the dispersion between the operating margin and inventory turnover was made. Where *ij* is calculated with the Euclidean distance between pairs of points *i* and *j*, and m is the total number of pairs. In equation 1, *R* measures the firm's resilience factor, defined as the average distance of all possible pairs of points at the intersection.

$$R = \frac{1}{m}\sum_i \sum_{j>i} d_{ij} \quad (1)$$

Torabi et al. [29] proposed a resilience metric based on absorptive capacity (through inventory prepositioning), adaptive capacity (through the existence of backup suppliers), and restorative capacity (through recovery of disrupted suppliers). Let's assume that the amount of lost capacity recovered by inventory prepositioning, backup supplier, and restoration of disrupted supplier is denoted by *A, B*, and *C*, respectively, and that LT_A LT_B and LT_C denote the time of receiving items associated with the *A, B*, and *C* resilience strategy. The loss of resilience can be mathematically calculated by equation 2. A lower value of *RE* results in higher supply resilience.

$$RE = A \times LT_A + B \times LT_B + C \times LT_C \quad (2)$$

Ojha et al. [30] developed a metric to quantify the resilience as a measure of service loss in the aftermath of disruption. Let's assume that SL_{kw} and SL_{k0} represent the service level of node *k* in week *w*, and service level of node *k* when there is no disruption. Suppose there are n nodes (suppliers) in the supply network, and the resilience index of node *n* denoted by RI_k is measured by equation 3.:

$$RI_k = 1 - \frac{\sum_{w=w_0}^{w_n}\left(1 - \frac{SL_{kw}}{SL_{k0}}\right)}{(w_n - w_0)} \quad (3)$$

Garrido Acevedo et al. [31] proposes an index with the objective of quantifying the level of resilience behavior B_R of a company *j* of SC. To do this, he considers different variables and suggests that these should be weighted based on the experts' criteria. As shown in equation 4.

$$(B_R)_j = \sum\left(w_{Ri} \times (P_R)_j\right) \quad (4)$$

P_{R1}= sourcing strategies to allow switching suppliers
P_{R2}= flexible sourcing
P_{R3}= strategic stock
P_{R4}= lead time reduction
P_{R5}= creating total SC visibility
P_{R6}= flexible transportation

In this case, the calculation of the value of resilience does not depend on economic indicators but on operational strategies that are evaluated from 1 to 5 on a Liker scale.
Wang [32] the resilience of a logistic network can be defined as the weighted sum of all demand nodes. The weight of a node can be defined as the percentage of its demand to the total demand. For a demand node *i,* its weight w_i is defined as:

$$w_i = \frac{d_i}{\sum_{l=1}^{n1} d_i} \quad (5)$$

Let the resilience index of the logistic network is calculated by following formula:

$$R = \sum_{i=1}^{n1} w_i r_i \quad (6)$$

where is the node resilience calculated depending on the network structure.

$$r_i = \frac{\sum_{j=1}^{q} p_j \left[1 - \prod_{l=1}^{h}\left(1 - q_{(j,i)}^{l}\right)\right] min\left\{d_i, s_j \sum_{l=1}^{h} c_{(j,i)}^{l}\right\}}{d_i} \quad (7)$$

$n=n_1+n_2$ total number of 2 kinds of nodes.
$m=|E|$ number of edges in the set *E.*
di, i = 1, 2,…,n1 demand of node *i ϵ D.*
sj, j = 1, 2,…,n2 available supply of node *j ϵ S*
pj, j = 1, 2,…,n2 supply reliability of node *j ϵ S.*
ck, k = 1, 2,…,m flow capacity of edge *k ϵ E.*
qk, k = 1, 2,…,m reliability of edge *k ϵ E.*

Carvalho et al. [33] classify the economic performance indicators associated with resilience and agility into six categories: (1) cost, (2) economic value added (EVA), (3) net operating profit, (4) return on assets, (5) cash cycle and (6) expense efficiency.
Zavala et al. [34] state that a low resilience capacity affects both operations, finances and sales, deteriorating levels of service quality, inventory performance and gross margin, and that together they lead to a high capital consumption that can lead to financial chaos, destroying the return on investment (ROI), so a series of both financial and non-financial metrics must be implemented that constantly monitor the evolution of investments, with special focus on spending in operations and inventory buffers.

3.2. Modeling approaches of SCR

Authors pursue various approaches in constructing quantitative models, with much consideration given to their objectives regarding the scope, depth, and application of the model.
Table 1 shows a summary of the main modeling approaches.

Table 1: Modeling approaches of Supply Chain Resilience

Modeling approaches		**References**
Graph theory	Complex network analysis methods, such as graph theory, are used to identify critical nodes and evaluate network connectivity and robustness. These models incorporate centrality and flow measures to determine the propagation of the disturbance, considering the structure of network, redundancy of nodes and alternative routes that exist in case of interruption.	[35]
Bayesian network	BNs capture dependencies between suppliers and manufacturers, especially in scenarios where supplier failure affects manufacturing. They excel at analyzing the domino effect of disruptions in complex supply networks and analyzing forward and backward propagation, updating the probabilities of unobserved variables based on observations of disruptions.	[15], [30]
Game theory	These consider the strategic interaction between CS actors and how this influences resilience. It can model conflict and cooperation situations and analyze how the strategic decisions of each actor affect the overall performance of the SC. Nash equilibrium models can identify optimal strategies to maximize the joint benefit of all participants while minimizing risks and vulnerabilities.	[36], [37]
Markov chain modeling	It allows analyzing how the transition probabilities between different chain states evolve in response to disturbances over time. By considering various sources of uncertainty and disruptive events, such as delivery delays or raw material shortages, this approach provides information to identify vulnerabilities and design strategies to mitigate risks.	[38]
Structural equations	It allows resilience to be modeled and evaluated by considering the causal relationships between key variables.	[39]
Multi-criteria decision-making	MCDM methods, such as TOPSIS, AHP, ANP, ELECTRE, VIKOR allow identifying key resilience criteria, selecting appropriate strategies, assessing risks and vulnerabilities, and optimizing resilience by considering multiple objectives and constraints.	[12], [40], [41]
Optimization models	These models focus on allocating resources efficiently and effectively. For example, they can optimize the location of facilities, establish optimal inventory levels, and design alternative transportation routes to ensure continuity of operations and reduce vulnerability.	[42]
Bi-objective stochastic programming	Addresses problems that have two conflicting objectives and where there are uncertainties in the decision variables due to random factors.	[43]
Simulation models	It captures the complex dynamics of the SC and create disruption scenarios and assess the impact on operational performance.	[44], [45]
Risk analysis models	Risk analysis techniques, such as failure and effects analysis (FMEA), fault tree analysis (FTA), and scenario-based risk analysis (SRA), to identify adverse events and their potential consequences.	[46]
Hybrid approaches using digital technologies	These methods integrate real-time data, predictive analytics, and simulation tools to improve SC responsiveness and adaptability to disruptions. For example, combining optimization models with cloud based SCM systems allows for more agile and flexible planning, while the use of IoT sensors and big data analytics enables continuous monitoring and early detection of problems. A digital twin represents the physical SC with real data in real time. Simulation on the digital twin can show the propagation of the outage, quantify its impact and test recovery and adaptation policies according to the situation.	[47], [48]

3.3. Resilient practices in the SC context

Among the main practices that we can find related to improving resilience in the SC are [4], [5], [7], [9], [18]:

Resilient practices developed upstream:

- Diversify suppliers and sources of supply to reduce dependence on a single source.
- Establish solid communication and collaboration relationships with suppliers and other business partners.
- Establish robust supplier performance metrics and monitoring mechanisms to assess supplier reliability, quality, and responsiveness.
- Implement interconnected technologies and automated systems that improve visibility, efficiency, and rapid response to interruptions.
- Maintain adequate and strategically located inventories. Having a clear view of upstream inventories and supply conditions.

Resilient practices implemented optionally:

- Design processes that can quickly adapt to changes in demand, or external conditions.
- Desing production systems to accommodate multiple products and real-time changes.
- Have a versatile workforce and reserve capacity.
- Produce minimum batch sizes.
- Minimize setups times and product changeovers.
- Reduce development cycle time.
- Have a strategic provision of additional capacity and/or inventory in possible “hot spots”.
- Adopt a culture of continuous improvement to identify and address inefficiencies in internal processes. This involves regular monitoring, evaluation, and optimization of workflows and procedures.
- Develop contingency plans and response protocols for various scenarios, such as natural disasters, geopolitical events, or supplier failures, to ensure rapid and effective response during crises.
- Establish clear and efficient communication channels within the organization to disseminate critical information, updates and instructions during emergencies or disruptions.
- Invest in advanced technologies and digital tools to automate processes, improve operational efficiency, and improve responsiveness to changing conditions or disruptions.
- Implement systems and technologies for real-time monitoring and visibility across the SC to detect early warning signs of potential disruptions and enable timely interventions.

Resilient practices developed downstream:

- Ensure compliance with relevant regulations, standards, and industry best practices to minimize legal and regulatory risks that could disrupt SC operations.
- Create visibility to have a clear view of production and purchasing schedules.
- Maintain a flexible transit fleet.
- Silently transfer product.
- Have demand-based management.
- Increase the speed in the levels of product customization and introduction of new products to the market.

3.4. Research gaps and future directions

The COVID-19 pandemic has exposed vulnerabilities in global supply chains, highlighting the need for resilience in economic, industrial, and health systems. To mitigate systemic collapse, strategies include designing resilient systems, quantifying resilience, managing system complexity, adding redundancies, and developing real-time decision support tools. Adopting a resilience mindset is crucial, as unforeseen shocks can lead to rapid system degradation and collapse. The pandemic disrupted supply chains worldwide, exacerbating economic challenges and revealing weaknesses in demand, supply, transport, logistics, regulation, and information dissemination.

Based on the literature review conducted, it can be concluded that the scientific field of SCR is experiencing significant progress. However, further research is still required and should focus on several key directions, as discussed below.

Most studies focus on short-term resilience. Additional research is needed on how to improve long-term resilience, considering the adaptability and transformational capacity of the SC in the face of structural changes and long-term trends.

Although some incipient studies have been conducted, research is needed to investigate how emerging technologies, such as artificial intelligence, the Internet of Things and cloud computing, can be leveraged to improve resilience in the SC by improving visibility, automated decision making and real-time risk management.

It is crucial to investigate how to improve collaboration and coordination between different SC actors to strengthen resilience, including developing information sharing mechanisms, building support networks, and promoting trust and transparency between partners.

There is a need to integrate holistic approaches that address resilience from a multidimensional perspective, considering not only operational aspects, but also social, environmental, and economic factors.

The interplay between resilience and sustainability within SCM presents a complex paradox with both

conflicting and symbiotic elements. On one hand, strategies aimed at enhancing resilience, such as implementing flexible SC designs and redundant operations, can lead to increased resource consumption and higher inventory levels. This contradicts the fundamental principle of sustainability, which advocates for the efficient use of available resources.
International tools and compulsory standards are crucial in resilient supply chains. The ISO 28000 standard provides a framework for supply chain security management, while the ISO 31000 standard addresses risk management across various organizational areas. ISO 31000, applicable to a wide range of risks including financial, operational, and environmental, facilitates informed decision-making and continuous improvement.

4. Conclusion

This article highlights the critical importance of resilience in an increasingly complex and dynamic business environment. Throughout the research, various techniques, and approaches to assess and improve resilience in supply chains are explored, ranging from indicators, optimization models to simulation and decision analysis. The need to consider multiple criteria and integrated approaches to address emerging challenges and disruptions in supply chains is highlighted. In addition, research gaps and areas for future development are identified, such as the integration of emerging digital technologies, long-term assessment of resilience, and interorganizational collaboration. As well as the importance of considering the empathy and conflict relationships that exist between achieving a resilient supply chain and a sustainable supply chain. Ultimately, this article provides a solid foundation for future research and practice in the field of supply chain resilience, highlighting the importance of taking a holistic and proactive approach to addressing challenges and risks in an increasingly volatile business environment.

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