International Journal of Economics, Business and Management Research

Vol. 9, No.10; 2025

ISSN: 2456-7760

The Impact of Covid-19 on Supply Chain Resilience in the Manufacturing Sector

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doi.org/10.51505/IJEBMR.2025.91022 URL: https://doi.org/10.51505/IJEBMR.2025.91022

Received: July 23, 2025 Accepted: Aug 06, 2025 Online Published: Oct 24, 2025

Abstract

The COVID-19 pandemic has fundamentally reshaped how supply chain resilience (SCR) is understood and operationalized. This study synthesizes key resilience strategies and re-examines the conceptual foundations of SCR in light of prolonged global disruption. Drawing from a comprehensive analysis of recent literature, the findings identify ten core dimensions of resilience—robustness, visibility, flexibility, agility, collaboration, situation awareness, security, knowledge management, redundancy, and contingency planning. These dimensions are explored through technological, organizational, and relational lenses, highlighting the role of digitalization, strategic redundancy, and cross-functional coordination. The study finds that resilience is no longer limited to recovery capabilities but must be viewed as a proactive, dynamic, and integrative capability embedded across supply chain design, operations, and governance. Furthermore, the pandemic has catalyzed a shift from cost-efficiency to resilience-efficiency, urging firms to reconsider lean paradigms and embrace strategic slack, digital tools, and learning cultures. The findings advance the theoretical discourse on SCR and offer actionable insights for managers seeking to future-proof their supply chains.

Keywords

- Supply Chain(SC) Resilience
- SC Disruption Management
- SC Flexibility and Agility
- SC Digitalization

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- SC Collaboration
- SC Contingency Planning
- SC Redundancy
- SC Knowledge Management
- SC Visibility
- SC Organizational Learning
- SC Risk Mitigation Strategies

Introduction

The significance of supply chain management has reached unprecedented levels as the global economy faces intensified challenges, particularly during the COVID-19 pandemic. In recent years, supply chain resilience (SCR) has emerged as a crucial research area, focusing on the survival and adaptability of supply chains in the face of increasing uncertainty and frequent disruptions (A. Kumar et al., 2020).

The COVID-19 outbreak in 2019 triggered widespread supply chain disruptions due to border closures, labor shortages, demand fluctuations, and shifts in consumer behavior. Manufacturing supply chains were particularly affected, as industries reliant on manufacturing faced production halts due to cascading downstream disruptions (Juergensen et al., 2020; Seetharaman, 2020; Belhadi et al., 2021). Notably, at least 51,000 companies (including 163 Fortune 1000 firms) had Tier 1 suppliers in affected regions, while over five million companies (including 938 Fortune 1000 firms) relied on Tier 2 suppliers located in similarly impacted areas (Dun & Bradstreet, 2020). Consequently, the global economy saw a 27% decline in trade (World Investment Report, 2020), with the WTO forecasting a drop between 13% and 32% (World Trade Organization, 2020).

Although prior disasters—such as the 2003 SARS outbreak, the 2011 earthquake and tsunami in Japan, and Hurricane Isaac in 2012—had global ramifications, their impact on supply chains was relatively limited in scale and duration. By contrast, COVID-19 induced prolonged and widespread disruptions unprecedented in peacetime (Xu et al., 2020).
Many scholars emphasize the need for improved resilience and strategic restructuring of supply chains in response to the pandemic. This paper investigates the concept of SCR in the COVID-19 context, focusing on the strategies manufacturing firms have implemented to enhance resilience.

Pandemic-Induced Disruptions

To contain the spread of the virus, governments worldwide enforced varying degrees of embargoes, causing sudden supply shocks. Wuhan, the initial epicenter of the outbreak, is a critical hub for automotive and semiconductor manufacturing, supplying companies like Volkswagen, General Motors, Hyundai, and Toyota (A. Kumar et al., 2020). Plant closures in China led to cascading disruptions globally, forcing manufacturers to suspend operations (Eldem et al., 2022; Ivanov, 2020). Labor shortages, caused by illness and quarantine, further

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exacerbated the situation (Ma et al., 2021). Nearly all industrial sectors experienced shutdowns due to workforce and material shortages, leading to production and employment declines surpassing those of the 2008 financial crisis (Paul & Chowdhury, 2020; Sheth, 2020).

Small and medium-sized enterprises (SMEs) were especially vulnerable, struggling to maintain supply continuity and safe working conditions. Insufficient working capital led to bankruptcies and significantly lower recovery rates compared to larger firms (Cai & Luo, 2020; Juergensen et al., 2020).

Demand Shocks and Shifts in Consumer Behavior

The pandemic drastically altered consumer demand patterns. Products such as masks, personal protective equipment, hand sanitizers, and disinfectants experienced surging demand, while industries like automotive and aviation saw sharp declines. Remote work and online learning increased demand for technology, while fashion and luxury goods suffered due to lockdowns. Home-based fitness and food preparation surged, resulting in greater demand for home workout equipment, snacks, and baking ingredients (Ardolino et al., 2022; Paul & Chowdhury, 2020; Rahman et al., 2021; Sharma et al., 2020; Telukdarie et al., 2020). Companies were compelled to revise production processes and re-engineer supply chains to adapt.

Transformation of the Workplace

Government-imposed social distancing mandates forced many manufacturers to transition to remote work (Kanda & Kivimaa, 2020). Compliance with distancing and mask requirements posed operational challenges, requiring spatial reconfiguration and technological investment for remote work (Garlick et al., 2020; Okorie et al., 2020). These changes affected productivity due to reduced in-person interaction and the need for rapid upskilling (Ali Abdallah, 2021; Sharma et al., 2020).

Transportation Challenges and Cost Increases

Approximately 50–60% of global airfreight is typically transported in the cargo holds of passenger aircraft. The suspension of commercial flights to curb virus transmission caused a drastic 95% reduction in passenger flights in 2020, severely constraining cargo capacity (Xu et al., 2020). This bottleneck hindered global trade and significantly raised airfreight costs (Zhu et al., 2020).

Strategic Implications for Supply Chain Resilience

The pandemic exposed latent vulnerabilities in global manufacturing supply chains, especially in volatile, uncertain, complex, and ambiguous (VUCA) environments (Christopher & Lee, 2004). It underscored the necessity for resilience as a key performance driver and the importance of agile recovery plans (Fan et al., 2021). COVID-19 served as a wake-up call, prompting firms to explore innovative strategies and long-term solutions for supply chain continuity and adaptability (Bala, 2014; Deshmukh & Haleem, 2020).

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This paper aims to identify strategies and necessary underlying capabilities employed by manufacturing companies to mitigate the short- and long-term impacts of COVID-19 and improve supply chain resilience.

Supply Chain Risks and the Role of Resilience: Concepts, Classifications, and Strategic Approaches

The increasing complexity and globalization of supply networks, driven by intensified cooperation between manufacturing, distribution, and logistics partners, has significantly heightened exposure to supply chain risks (Christopher & Lee, 2004; Waters, 2015). Such risks arise from growing supply and demand volatility, shorter product life cycles, and technological acceleration. According to Waters (2015), supply chain risk refers to any unexpected event that disrupts the flow of goods from suppliers to end customers, while disruptions denote realized events with immediate adverse consequences such as delivery delays, cost escalations, and reputational damage.

Tang (2006) distinguishes between operational risks—stemming from everyday uncertainties like fluctuating demand—and disruption risks—originating from major events such as natural disasters, cyber-attacks, or labor strikes. These categories form the basis of disruption as a manifestation of broader supply chain risk (DuHadway et al., 2019).

Supply chain risk management (SCRM) involves the identification, assessment, and mitigation of potential threats through proactive and reactive strategies (Ho et al., 2015; Jüttner, 2005; Manuj & Mentzer, 2008). Key risk mitigation strategies include improved end-to-end visibility and the cultivation of supply chain confidence, which enhance adaptability and recovery capacity—foundational elements of resilience (Christopher & Lee, 2004).

Resilience, originally studied in ecology and psychology, has become a focal concept in supply chain research due to its relevance in today's uncertain business environment (Ponomarov & Holcomb, 2009). Rice and Caniato (2003) first contextualized resilience within SCM following the 9/11 attacks, defining it as an organization's ability to react and recover from disruptions more effectively than competitors. Flexibility and redundancy were identified as core enablers.

Later studies expanded the definition of supply chain resilience (SCR) as the adaptive capability to maintain continuous operation, preserve structural integrity, and restore performance levels following disruptions (Christopher & Peck, 2004; Hosseini et al., 2022). Researchers have described SCR in terms of elements (Christopher & Peck, 2004), capabilities (Pettit et al., 2013), and enablers (Pereira, 2009), among others.

Christopher and Peck (2004) proposed four strategic principles to enhance SCR:

1. **Supply Chain Reengineering** – Reconfiguring networks to reduce vulnerabilities.
2. **Collaboration** – Promoting information sharing to improve visibility and reduce uncertainty.

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3. **Agility** – Enabling rapid responses to change through speed (velocity) and transparency (visibility).
4. **Risk Awareness Culture** – Embedding resilience at all organizational levels.

In contrast to traditional lean approaches focused solely on cost-efficiency, modern supply chains must strike a balance between efficiency and resilience. Strategic use of slack, alongside robust network understanding—including pinch points and critical nodes—can significantly improve resilience.

In terms of temporal dynamics, Ponomarov and Holcomb (2009) introduced a three-phase resilience model:

1. **Readiness** – Preparing for disruption.
2. **Response** – Implementing immediate measures post-disruption.
3. **Recovery** – Returning to or surpassing pre-disruption performance.

Kamalahmadi and Parast (2016) extended this framework by dividing readiness into:

- **Anticipation** – Risk identification and contingency planning, and
- **Resistance** – Preventing escalation during early disruption stages.

Subsequent stages include response and recovery, with the latter potentially resulting in **resilience growth**—the enhancement of supply chain capabilities beyond prior performance levels due to post-disruption learning (Pettit et al., 2013; Tukamuhabwa et al., 2017).

Methodology

In this paper, the methodology of a Systematic Literature Review (SLR) was used. It has its roots in the medical sciences and has found widespread use in the management and organizational sciences to bridge the research-practice gap (D. Denyer & D. Tranfield, 2011; Rousseau, 2006). The approach taken in this paper builds on the five-step framework developed by Tranfield et al. (Tranfield et al., 2003) (figure 1).

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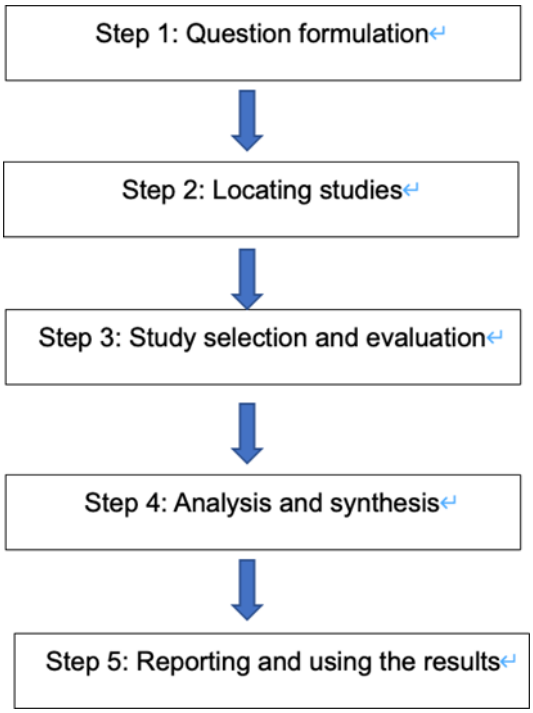

Figure 1: Step for conducting a SLR (D. Denyer & D. Tranfield, 2011; Tranfield et al., 2003)

Locating studies

For the literature search 'Web of Science' was chosen as database for bibliometric analysis. According to Singh et al (Singh et al., 2021) it is most widely used and has the most selective journal coverage (Singh et al., 2021). Retrieving title, abstract and keywords of literature under the category "topic" was selected and the following keywords were identified to build the initial database based on the review questions and basic literature. The first group of keywords used was related to COVID-19, including "COVID-19", "pandemic", "coronavirus", "outbreak", "epidemic". The second group of keywords is "supply chain". The third group of keywords related to resilience includes "resilien*", "recovery", "disruption", "flexible", "adaptable", "risk mitigation", using * instead of the related terms resilience, resilient and resiliency. The fourth group of keywords using "manufacturer*" restricts the discussion to manufacturing industry, same as before, using * instead of the related terms of keywords including "manufacturing industry" or "manufacturing companies" or "manufacturing firms" or "manufacturer". These four sets of keywords are connected internally with "or", as only one of them from each group needs to appear in the topic due to the similarity of meaning. While "and" links between group means that all four groups must appear in the topic at the same time in order to be considered as closely pertinent to the review question. 271 peer-reviewed journal articles were identified, published during and in the aftermath of the pandemic.

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Study selection and evaluation

The title, abstract and keywords were read with a focus on whether the study's findings pointed out practices of organizations to improve supply chain resilience during the pandemic, or at least involved approaches related to supply chains recovering from disruptions caused by the pandemic. Only Studies that included the keywords "supply chain", "resielien*" and "manufactur*" in their title or abstract were moved to the full-text review stage. Further articles were excluded after reading for reasons of deviating research focuses and possible duplications.

Sample description

The geographic focus of 73 research articles spreads over 22 different regions. Amongst these 10 different strategies to achieve or improve supply chain resilience were identified relying on various approaches and capabilities. These strategic approaches will be discussed in the following.

Findings

Robustness

Robustness refers to the ability of a supply chain to maintain stable operations despite disruptions (A. Ali et al., 2017). This characteristic must be embedded into the supply chain design proactively. A variety of strategic measures have been identified in the literature to enhance robustness. Among these, digitalization plays a key role. For large enterprises, comprehensive investments in digital technologies—ranging from cloud-based systems to advanced automation—are seen as prerequisites for resilience (Yin & Ran, 2022). Small and medium-sized enterprises (SMEs) can benefit from adopting digital platforms that support virtual collaboration and remote operations, thereby reducing vulnerability to external shocks like the COVID-19 pandemic (Ferreira et al., 2021).

Omni-channel distribution strategies, which integrate physical retail with digital channels, help ensure operational continuity by enabling companies to maintain customer access during lockdowns and logistical disruptions (Ahmed et al., 2022). Equally important is supply chain mapping, a process involving the analysis of network structures and potential bottlenecks prior to disruption events. When coupled with digital twins—virtual simulations of supply chain networks—mapping allows firms to identify critical nodes and test recovery strategies (Paul et al., 2021; Lv et al., 2022).

Organizational measures such as establishing a dedicated resilience team further bolster robustness. These specialized units are tasked with risk assessment, contingency planning, and coordinating response actions during crises (Paul et al., 2021). Technological innovations such as cloud manufacturing, additive manufacturing, and automation also enhance robustness by reducing dependence on human labor and enabling more decentralized and adaptive production models (Belhadi et al., 2021; Butt, 2022; Muhammad et al., 2022).

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In addition to digital and organizational measures, structural strategies such as regionalization and diversification are frequently discussed. Sourcing and manufacturing within the same region can help localize disruptions and prevent them from affecting other areas of the supply chain (Belhadi et al., 2021; Moktadir et al., 2023). Regionalization also benefits from distributed manufacturing networks and is supported by advanced manufacturing technologies that mitigate cost differentials across regions (Free & Hecimovic, 2021).

Supply chain diversification, particularly of suppliers and customers, is another critical mechanism to reduce dependency and enhance robustness. Strategies include geographic distribution of suppliers, the use of multiple transportation methods, and diversified material sourcing (Vieweg, 2021; Lin et al., 2021). The "China Plus One" strategy exemplifies how firms actively seek to avoid overreliance on a single sourcing region (Zhu et al., 2020).

Finally, servitization—shifting from product sales to service-oriented business models—offers financial stability and operational continuity. By offering repair services or product-as-a-service models, firms can smooth revenue streams and build customer loyalty during disruption events (Zhang & Qi, 2021; Rapaccini et al., 2020). A high liquidity ratio also contributes to robustness, allowing firms to absorb short-term losses and maintain operations (Jingze Chen et al., 2022).

Visibility

Supply chain visibility refers to the ability to monitor operations in real time and anticipate disruptions. It encompasses the transparent flow of information across the supply network and is critical for proactive risk management (A. Ali et al., 2017). Enhanced visibility is closely linked to collaboration and communication between supply chain partners. Regular information exchange facilitates swift decision-making and allows for rapid adaptation during crises (Juan et al., 2022; Dohale et al., 2022).

Technological advancements are central to improving visibility. Forecasting systems, integrated with customer and supply chain data, improve the accuracy of risk detection (Münch & Hartmann, 2023). Technologies such as blockchain ensure transparency and traceability, while GPS tracking, sensor systems, and the Internet of Things (IoT) offer granular insights into material flows and workforce health (Ivanov, 2022; Bastas & Garza-Reyes, 2022; Hussain et al., 2021).

Digital transformation efforts are foundational to visibility. The use of Big Data Analytics and Artificial Intelligence enables the collection, interpretation, and application of real-time data to support dynamic scenario planning (Khan et al., 2022; Belhadi et al., 2021). Digital Twins, in particular, allow companies to simulate operational responses and test potential disruptions in a risk-free environment (Lv et al., 2022).

An important human dimension complements technological capabilities. The managerial experience and social capital of supply chain leaders greatly influence the ability to interpret signals and act decisively in response to disruptions (Nikookar & Yanadori, 2022a). Moreover,

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internal systems such as real-time risk reporting and cross-organizational communication channels further increase transparency and responsiveness (Münch & Hartmann, 2023).

Flexibility

Flexibility denotes the capacity of a supply chain to adapt to changes in demand, supply conditions, or operational constraints. This adaptability is crucial during disruption events and also contributes to efficient operations in stable periods (A. Ali et al., 2017). Technological tools such as automation, 3D printing, and cloud manufacturing significantly enhance flexibility by enabling swift shifts in production and decentralized operations (Butt, 2021; Ekren et al., 2023; NIARI et al., 2022).

Flexibility is also supported by structural adaptability. The reconfiguration of facilities, procurement processes, and even workplace setups allows firms to adjust to new circumstances (Paul et al., 2021; Dwaikat et al., 2022). Remote work infrastructure, augmented reality (AR) tools, and cloud-based platforms help maintain continuity under physical access restrictions (AMBROGIO et al., 2022).

Moreover, flexibility is reinforced by collaborative practices and shared innovation with partners. Firms that maintain close integration with suppliers are better able to coordinate responses, adjust production, and fulfill changing customer requirements (Siagian et al., 2021; Juan et al., 2022). Emergency production, temporary shifts, and strategic product redesigns have also proven effective in maintaining flexibility during crisis periods (Vieweg, 2021; Ekren et al., 2023).

Finally, managerial competencies—particularly those related to coordination and improvisation—play a decisive role. Experienced managers with strong interpersonal networks can mobilize resources more quickly and navigate uncertainties more effectively (Nikookar & Yanadori, 2022a).

Agility

Agility in the supply chain context refers to the ability to respond rapidly and effectively to unforeseen disruptions. This responsiveness minimizes downtime and mitigates negative impacts on operations and customer satisfaction. The literature emphasizes that agility, while often associated with speed, is fundamentally grounded in preparedness and adaptability.

One frequently mentioned strategy is the use of emergency procurement plans. Such plans enable companies to bypass disrupted suppliers and reestablish material flows quickly by switching to alternative sources, thereby maintaining production continuity (Jingzhe Chen et al., 2021; Jingze Chen et al., 2022). Regionalization further enhances agility by enabling firms to rely on locally situated suppliers, thereby shortening lead times and reducing logistical uncertainties (M. Kumar et al., 2022; Phillips et al., 2022; Belhadi et al., 2022).

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Product redesign also supports agile responses by facilitating the modification of goods or their components to adapt to changes in demand or resource availability. Repurposing production capacity—shifting temporarily to new market segments—has emerged as a key agile measure during crises such as the COVID-19 pandemic (Dwaikat et al., 2022). In this context, investment in research and development (R&D) and digital technologies is crucial. The integration of AI, cloud computing, and Digital Twins fosters faster decision-making and real-time problem solving (Lv et al., 2022; Ivanov, 2022).

Organizational culture also plays a decisive role in agility. Firms with established learning cultures and strong internal knowledge-sharing practices are more capable of responding flexibly to disruptions. This includes dynamic information exchange across departments, enabling fast adjustments to inventory, logistics, and customer service strategies (Eryarsoy et al., 2022; Tarigan et al., 2021). Social embeddedness and inter-organizational trust networks further accelerate these adaptive capabilities (Nikookar & Yanadori, 2022b).

Collaboration

Collaboration has proven to be a central determinant of supply chain resilience. It supports flexibility, agility, visibility, and robustness by fostering coordination and trust among partners. Close collaboration enables the sharing of resources, information, and responsibilities, allowing supply chains to function more effectively during crisis situations (I. Ali & Gölgeci, 2019; Juan et al., 2022).

Collaborative arrangements include joint product development, shared contingency plans, and mutual capacity utilization. Ferreira et al. (2021) point out that collaboration encourages innovation and helps firms find more creative and effective solutions to disruptions. Supplier collaboration, especially beyond Tier-1 partners, was shown to be essential for enhancing robustness and reducing delays (Paul et al., 2021; Yang et al., 2022).

Information technology plays a critical role in strengthening collaboration. Digital platforms and cloud-based tools improve communication, ensure information parity, and support collective decision-making (Li et al., 2022; Balakrishnan & Ramanathan, 2021). Trust is another crucial element of collaboration. It reduces the need for monitoring and control mechanisms, thereby increasing the efficiency and effectiveness of joint action (Dohale et al., 2022).

Social capital and the relational competencies of supply chain managers also influence the success of collaborative initiatives. Strong interpersonal relationships facilitate smoother negotiations and quicker consensus during disruptions (Nikookar & Yanadori, 2022b).

Situation Awareness

Situation awareness refers to the capacity to identify, monitor, and interpret early signals of potential supply chain disruption. It acts as an enabler of proactive risk management by extending the reaction time available to decision-makers (A. Ali et al., 2017).

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Technological tools such as big data analytics, artificial intelligence, and digital twins have been shown to enhance situation awareness significantly. These tools allow companies to analyze patterns, predict disruption probabilities, and simulate countermeasures (Ivanov, 2022; Khan et al., 2022; Lv et al., 2022). Furthermore, Industry 4.0 technologies facilitate real-time monitoring of demand trends, customer behavior, and production performance, enabling more accurate assessments of emerging risks (Zhang & Qi, 2021).

Close cooperation with supply chain partners is another key source of situational insight. Shared monitoring systems and regulatory tracking practices help firms stay informed about policy changes or geopolitical events that may influence supply continuity (Belhadi et al., 2021; Frieske & Stieler, 2022).

Security

Security in the supply chain context refers to safeguarding assets, data, and operations from deliberate threats such as cyber-attacks or counterfeiting (A. Ali et al., 2017). Security is increasingly understood as an integral component of resilience.

Firms are advised to develop integrated supply chain risk management frameworks that encompass cybersecurity, data protection, and inventory control. These plans should involve all partners and not remain confined to the focal firm alone (Belhadi et al., 2021). Investments in intrusion detection and prevention systems (IDS/IPS) are particularly critical in digitalized supply chains (Eldem et al., 2022). Big data analytics, when aligned with the supply chain structure, can help anticipate and prevent security breaches (Bag et al., 2021; Free & Hecimovic, 2021).

Security is also linked to logistics control and contingency design. By aligning logistics flows with performance objectives and backup capabilities, organizations can protect critical operations from internal or external threats (Velayutham et al., 2021).

Knowledge Management

Knowledge management ensures that employees are equipped with the skills and information needed to respond to disruptions. It encompasses both pre-disruption learning and post-disruption knowledge retention (A. Ali et al., 2017). A resilient supply chain depends on the continuous education of its workforce and the integration of new knowledge into practice.

Collaborations with academic institutions, cross-functional training, and ambidextrous learning systems are cited as crucial enablers (Paul et al., 2021; Xie et al., 2022). During crises, firms may also need to reallocate human resources to critical areas or recruit temporary staff to stabilize operations, an option that is contingent on sufficient financial reserves (Jingze Chen et al., 2022; Bastas & Garza-Reyes, 2022).

Furthermore, the ability to manage technological knowledge, such as collecting and using data from digital systems, is essential for leveraging Industry 4.0 tools effectively (Hsu et al., 2022).

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Post-disruption phases should focus on reviewing what worked and what failed in order to inform future readiness strategies.

Redundancy

Redundancy refers to built-in excess capacities in the supply chain—such as safety stock, backup suppliers, or alternative transport routes—that allow companies to absorb shocks and maintain continuity (A. Ali et al., 2017).

Multiple sourcing and maintaining strategic inventory buffers were among the most widely applied strategies during the COVID-19 pandemic (Min, 2022; Butt, 2021). Safety stocks, while traditionally viewed as cost centers, have proven to be effective short-term buffers and are especially beneficial in closed-loop supply chains (Katsoras & Georgiadis, 2022). The use of global stockpilers—intermediaries that aggregate and store goods from multiple suppliers—has also gained traction as a redundancy-enhancing measure (Phillips et al., 2022).

The effectiveness of redundancy is contingent on strong collaboration and communication, ensuring that suppliers also hold buffer stocks and that emergency logistics are available (Tarigan et al., 2021; Butt, 2022).

Contingency Planning

Contingency planning involves the proactive development of scenarios and predefined response actions for potential disruptions. Such planning is essential to ensure resilience at both operational and strategic levels (A. Ali et al., 2017).

Plans may vary in scope, from targeted measures (e.g., emergency procurement) to comprehensive continuity plans including cross-functional crisis teams (Münch & Hartmann, 2023). The use of digital twins and simulations allows organizations to test the feasibility and effectiveness of these plans under virtual conditions (Lv et al., 2022).

Dynamic and iterative contingency planning, which evolves in response to new data and changing threats, is critical in environments characterized by uncertainty and complexity (Paul & Chowdhury, 2020). Lifeline maintenance—prioritizing the continuity of essential business functions—has emerged as a core objective in such plans (Belhadi et al., 2021).

Discussion of Findings

The findings from this study underscore the multifaceted nature of Supply Chain Resilience (SCR), emphasizing that resilience is not a singular capability but a complex constellation of interrelated competencies, structures, and behaviors. Drawing from the domains of robustness, visibility, flexibility, agility, collaboration, security, knowledge management, redundancy, situation awareness, and contingency planning, the results reveal that resilience extends far beyond mere recovery capacity. It is, instead, an adaptive, anticipatory, and strategic orientation that permeates every layer of supply chain design and governance.

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Expanding the Understanding of Supply Chain Resilience

Traditionally, supply chain resilience has been viewed through a narrow operational lens—defined largely as the capacity to return to a steady state after disruption (Christopher & Peck, 2004). This reactive understanding emphasized recovery, buffer stock, and redundancy as core mechanisms. However, the empirical insights synthesized here reflect a more nuanced and evolved conceptualization. Resilience is now increasingly interpreted as a **dynamic capability**—one that allows a supply chain not only to absorb shocks but also to adapt, evolve, and even thrive under conditions of uncertainty (Pettit et al., 2013; Hosseini et al., 2022).

The pandemic has been a catalyst in broadening this perspective. COVID-19 did not simply test resilience in terms of operational uptime—it exposed fundamental weaknesses in globalized supply networks, revealed hidden dependencies, and redefined risk parameters. Disruptions were no longer linear or localized; they were systemic, simultaneous, and enduring. As a result, firms began to shift from **resilience as a risk response** to **resilience as strategic preparedness and opportunity creation**.

In this broader view, **resilience becomes inherently proactive**, encompassing forward-looking competencies such as scenario planning, digital twin simulations, regional diversification, and learning cultures. It also implies **transformational potential**, as organizations use disruption as a springboard for redesigning supply chain models, exploring alternative markets, and accelerating technological innovation.

Interdependencies Among Resilience Dimensions

The findings further suggest that resilience cannot be cultivated in isolated silos. For instance, digitalization underpins not only visibility but also agility, flexibility, and collaboration. Technologies such as AI, Big Data, blockchain, and IoT enable real-time monitoring, predictive analytics, and seamless communication—all of which support agile and coordinated responses to volatility. However, these tools are only effective when embedded within a supportive organizational culture that values transparency, trust, and knowledge sharing.

Similarly, robustness and flexibility—often seen as opposing forces in lean paradigms—must be reinterpreted as complementary. A robust system resists failure; a flexible one adapts to it. Together, they provide a dual shield against disruption. Supply chains that balance **structural redundancies (e.g., multi-sourcing, safety stock)** with **adaptive capabilities (e.g., reconfiguration, workforce redeployment)** are better positioned to respond to a wide spectrum of threats.

Collaboration emerges as both a facilitator and a product of resilience. High levels of trust and integration among supply chain partners enable joint problem-solving and shared contingency planning. This is particularly important in complex, multi-tier supply networks where disruptions may be invisible to focal firms unless upstream transparency is secured.

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Resilience as a Socio-Technical Capability

An important theme that emerges from the findings is the **human dimension of resilience**. Technological solutions are only as effective as the people who design, implement, and interpret them. The competence, experience, and relational capital of supply chain managers influence not only the success of digital tools but also the effectiveness of cross-functional collaboration, decision-making under pressure, and post-disruption learning. The pandemic revealed that resilience is as much about **organizational learning and adaptability** as it is about physical or digital infrastructure.

Furthermore, knowledge management—often overlooked in resilience discussions—was shown to be crucial in both pre- and post-disruption phases. Training, ambidextrous learning, and the institutionalization of crisis response experiences enable continuous improvement. In this light, resilience becomes a **cultural attribute**, not just a strategic or operational one.

From Cost Efficiency to Resilience Efficiency

Perhaps the most significant shift illuminated by the findings is the move away from **cost-centric** supply chain models toward **resilience-centric** design. For decades, lean and just-in-time (JIT) philosophies dominated, emphasizing minimal inventory, limited supplier bases, and global optimization. The pandemic laid bare the fragility of such systems.
In contrast, resilience-centric models accept a certain level of **redundancy and slack** as strategic assets rather than inefficiencies. Firms now increasingly weigh the trade-offs between efficiency and resilience, recognizing that a marginal increase in operational costs may yield exponential gains in continuity, brand equity, and long-term viability.

Implications for Theory and Practice

From a theoretical perspective, this study contributes to the expanding body of literature that frames SCR as a **multidimensional and integrative capability**. It validates calls for a systems-oriented approach that accounts for both tangible resources (e.g., inventory, technology) and intangible assets (e.g., trust, learning, adaptability).

From a practical standpoint, the findings offer actionable insights for managers and policymakers. Investments in digital infrastructure must be matched with efforts to cultivate collaboration, build flexible processes, and develop human capital. Resilience should be embedded in strategic planning, not relegated to crisis response units. Cross-sector collaboration, public-private partnerships, and regulatory harmonization will also be critical in building global supply chain resilience in the post-pandemic world.

Conclusion

This study has examined the multidimensional components of Supply Chain Resilience (SCR) through a comprehensive synthesis of empirical strategies and conceptual frameworks. It has become evident that resilience is no longer to be understood merely as the capacity to recover

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from disruptions, but rather as a strategic capability that enables supply chains to anticipate, absorb, adapt to, and even grow in the face of adversity. The findings confirm that SCR encompasses an integrated system of technological, organizational, and relational capabilities, which must work in concert to withstand increasingly complex and systemic risks.

In particular, the COVID-19 pandemic has catalyzed a paradigmatic shift in the understanding and operationalization of resilience. No longer viewed as a reactive buffer, resilience has emerged as a proactive and dynamic competency—a new lens through which to design, govern, and evolve global supply chains. This expanded view not only challenges the legacy of lean and cost-centric supply chain models but also introduces new priorities for supply chain managers, policymakers, and scholars alike.

Ultimately, the study underscores that resilience is not built through isolated interventions. It is the product of long-term strategic thinking, technological investment, collaborative networks, and organizational learning—each reinforcing and amplifying the other. Future disruptions, whether pandemic-related or climate-induced, will test the robustness of these systems. The findings presented here serve as a guide for building more intelligent, responsive, and sustainable supply chain architectures in a volatile world.

Managerial Implications

For supply chain practitioners, the evolving nature of SCR has several practical implications:

1. **Strategic Integration of Resilience**: Managers should embed resilience planning into corporate strategy rather than treating it as an operational afterthought. This includes aligning investments in digital infrastructure with scenario planning and strategic redundancy.
2. **Rebalancing Efficiency and Resilience**: Firms must reconsider lean paradigms. Strategic slack—whether in the form of safety stock, redundant suppliers, or distributed manufacturing—should be embraced where appropriate to ensure business continuity.
3. **Investing in Digital Capabilities**: Technologies such as Digital Twins, Big Data Analytics, and AI must be leveraged not only for visibility and prediction but also for scenario simulation and collaborative planning across supply chain tiers.
4. **Strengthening Supply Chain Relationships**: Collaboration, trust, and transparent communication with supply chain partners are critical. Joint decision-making, supplier development, and long-term relational investments can improve both operational performance and disruption response.
5. **Building Organizational Learning and Talent**: Resilience requires human capital. Managers should invest in training, cross-functional coordination, and knowledge-sharing systems that enable faster learning and better decision-making during and after disruptions.
6. **Redesigning Global Footprints**: Regionalization and nearshoring are no longer merely cost-driven considerations—they are resilience strategies. Managers should re-evaluate supplier networks with geographic diversification and localized production capacity in mind.

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