Supply Chain Financial Risk Contagion and Management: A Survey

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Abstract

This survey paper comprehensively examines the interconnected processes and strategies involved in managing financial risk contagion within global supply chains. It highlights the vulnerabilities exposed by recent systemic shocks, such as the COVID-19 pandemic, and underscores the necessity for innovative risk management strategies that incorporate financial tools and technological advancements like blockchain and IoT systems. The survey provides a structured exploration of supply chain financial risk contagion, risk management strategies, supply chain finance, and systemic risk, offering insights into their impact on global economic stability. It emphasizes the role of blockchain and digital technologies in enhancing transparency, security, and operational efficiency, and discusses the integration of supply chain finance into broader risk management frameworks. Through case studies across healthcare, manufacturing, agriculture, and retail sectors, the paper illustrates practical applications of risk management strategies. Furthermore, it identifies future research opportunities, advocating for interdisciplinary approaches, advanced modeling techniques, and a focus on sustainability and resilience. The survey concludes by emphasizing the importance of adopting integrated and adaptive strategies to ensure the stability and resilience of supply chains in an increasingly interconnected global economy.

1 Introduction

1.1 Motivation for the Survey

This survey is motivated by the urgent need to tackle inefficiencies and vulnerabilities in global supply chains, exacerbated by recent systemic shocks, including the COVID-19 pandemic and geopolitical tensions such as the conflict in Ukraine. These events have underscored the limitations of traditional supply chain management practices, highlighting the necessity for innovative strategies that enhance resilience and adaptability. Research indicates that integrating dynamic capabilities, including tighter collaboration and increased flexibility, can significantly bolster supply chain resilience against external risks. Moreover, a coordinated approach to sourcing decisions can safeguard upstream suppliers during aggregate shocks, ensuring supply continuity even in challenging circumstances. This holistic understanding of supply chain dynamics is crucial for navigating the complexities and uncertainties of modern supply networks [1, 2, 3, 4, 5]. The pandemic has notably illustrated the drastic production declines due to lockdowns and the critical need for policy coordination among regions to mitigate economic losses.

Additionally, the survey aims to enhance supply chain transparency and resilience in light of global crises and regulatory developments [6]. The prevalent lack of transparency and traceability, particularly in sectors like the oil industry, hampers effective monitoring and tracking, necessitating the adoption of technologies such as blockchain to improve stability and transparency [7]. The survey also addresses the unique risks posed by IoT systems within supply chains and identifies future research directions to strengthen supply chain security [7].

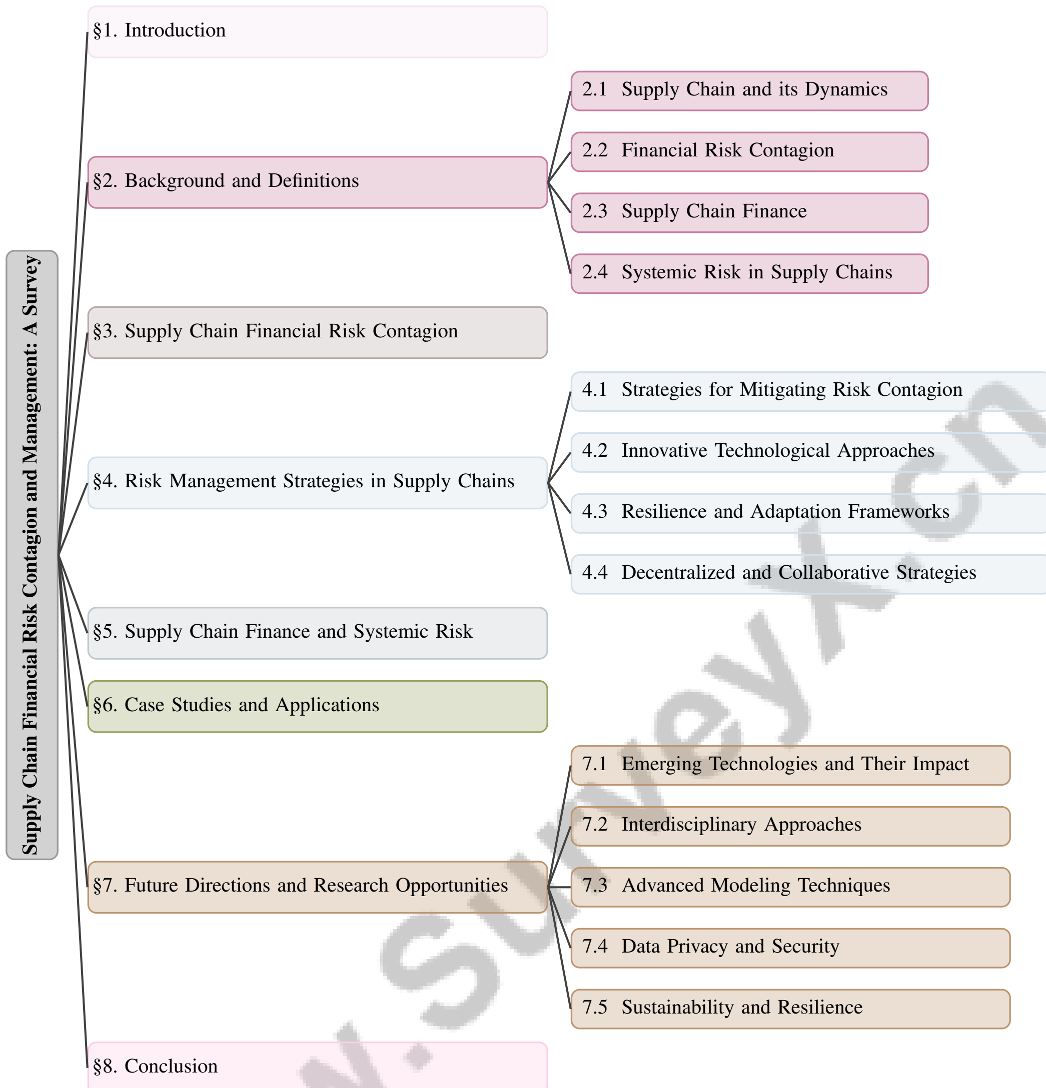

Figure 1: chapter structure

Furthermore, this survey tackles the shared challenges encountered by e-commerce and process industries, emphasizing the need for scalability, integrated decision-making, and the orchestration of human and computer-based decision-makers [8]. The complexities of international trade networks and their influence on supply chain dynamics further underscore the importance of understanding trade relationships and the impact of global events on these dynamics for developing resilient supply chains.

In response to the evolving landscape of global supply chains and the growing significance of strategic collaboration, this survey provides a comprehensive analysis of supply chain management principles. It explores critical inquiries regarding the definition of supply chain management, its role in fostering economic stability, and the foundational elements that underpin effective practices, drawing insights from recent technological advancements and procurement strategies that prioritize value creation over mere cost reduction [9, 10, 11, 12].

1.2 Structure of the Survey

This survey is meticulously structured to navigate the complex landscape of supply chain financial risk contagion and management. It begins with an **Introduction**, outlining the motivation behind the survey and its relevance to the current global economic climate. Following this, a detailed

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Background and Definitions section defines foundational concepts such as supply chain dynamics, financial risk contagion, supply chain finance, and systemic risk, providing a robust framework for subsequent discussions.

The core of the survey is divided into thematic sections, commencing with **Supply Chain Financial Risk Contagion**, which examines the mechanisms and historical instances of financial risk propagation within supply chains and its implications for global economic stability. This is followed by an exploration of **Risk Management Strategies in Supply Chains**, showcasing both traditional and innovative approaches to mitigating financial risk contagion, including technological applications and collaborative frameworks.

In **Supply Chain Finance and Systemic Risk**, the survey investigates the crucial role of financial tools and instruments in managing systemic risk, emphasizing the potential of blockchain and digital technologies. This section also discusses the integration of supply chain finance into broader risk management strategies.

The survey further enriches its analysis with **Case Studies and Applications**, presenting real-world examples across various sectors such as healthcare, manufacturing, food, and retail. These case studies illustrate how risk management strategies and supply chain finance can effectively mitigate financial risk propagation, particularly during crises like pandemics and geopolitical instabilities. By examining the intricate relationships within supply chain networks, these studies reveal the significant impact of firm failures on overall financial stability, underscoring the necessity for comprehensive risk assessments that consider the cascading effects of supply chain disruptions [13, 14, 10, 15].

Finally, the survey concludes with **Future Directions and Research Opportunities**, identifying gaps in current research and proposing areas for future exploration. This discussion encompasses the multifaceted impact of emerging technologies on supply chains, emphasizing the importance of interdisciplinary approaches that integrate insights from supply chain management, information systems, and computer science. It highlights advanced modeling techniques and the pressing challenges of data privacy and security, particularly in the context of enhancing sustainability and resilience in supply chain strategies. Additionally, it identifies future research opportunities, such as employing multi-agent systems that harmonize human and machine decision-making, to address the ongoing complexities faced by e-commerce and process industries in a competitive global landscape [8, 16].

Each section is crafted to build upon the previous one, ensuring a coherent and comprehensive narrative that equips the reader with a profound understanding of supply chain financial risk contagion and management.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Supply Chain and its Dynamics

Supply chains form the intricate backbone of global commerce, facilitating the production and distribution of goods and services through complex networks of suppliers, manufacturers, distributors, and retailers. These interconnected entities enhance supply chain efficiency and effectiveness [17]. The complexity and vulnerability of global supply chains are heightened by the need to adapt to increasing demands and disruptions [8]. A significant challenge is the integration of strategic, tactical, and operational decisions across business units and time scales to ensure seamless operations [8].

Market demand variability significantly influences supply chain dynamics, leading to the bullwhip effect, where minor consumer demand fluctuations result in substantial upstream variabilities. Advanced demand forecasting techniques and collaborative strategies are essential for managing these uncertainties, especially during promotional periods that exacerbate forecasting errors [18]. Resilience against disruptions necessitates robust designs capable of withstanding supplier failures and incorporating expedited shipments to meet uncertain customer demands [19].

Mathematical modeling is crucial for optimizing operations by alleviating bottlenecks and minimizing queue dead times, thus enhancing the flow of goods and services [20]. The time evolution of supply chains, dependent on their complex networks, requires continuous adaptation to maintain resilience amid market perturbations [17].

Technological advancements, including blockchain and digital twin technologies, offer transformative potential for enhancing supply chain visibility and risk management. Blockchain enhances transparency through secure, traceable transactions, fostering trust and accountability among participants [6]. Digital twin technology provides dynamic, real-time representations of operations, facilitating improved decision-making and operational efficiency [6].

Moreover, managing contract breaches and penalties arising from unexpected market perturbations is critical for supply chain dynamics. Implementing automated dispute resolution mechanisms can significantly bolster resilience and adaptability [21].

2.2 Financial Risk Contagion

Financial risk contagion refers to the transmission of financial disturbances across interconnected supply chain entities, potentially leading to systemic instability and widespread economic repercussions. In a globalized economy, disruptions in one segment can cascade through the network, affecting suppliers, manufacturers, and distributors. This interdependency necessitates different forecasting models based on demand series volatility, as indicated by the coefficient of variation (CoV) [18].

The COVID-19 pandemic exemplifies financial risk contagion, disrupting retail operations, altering consumer behavior, and exposing vulnerabilities within supply chains [22]. These disruptions revealed the inadequacies of traditional credit risk models, which often underestimate credit risk by neglecting supply chain shocks and focusing primarily on borrowers' financial conditions [15]. The pandemic underscored the need for models capable of detecting change-points and accounting for the effects of past events on future orders, as traditional forecasting methods relying on historical sales data have proven inadequate [23].

Collaborative forecasting, essential for effective production planning and inventory management, further complicates financial risk contagion in supply chains [24]. The lack of trust among partners exacerbates this issue, leading to reluctance in data sharing, which hinders collaboration and efficiency [25]. This reluctance can impede optimal ordering strategies in multi-echelon supply networks, where firms must balance inventory management with costs associated with production, shortages, and holding [26].

Addressing financial risk contagion requires robust models and collaborative strategies. Integrating cooperative game theory frameworks, such as partition form games, can optimize supply chain decisions under uncertainty and interdependence [27]. By overcoming the limitations of traditional forecasting methods and adopting cooperative approaches, supply chains can enhance resilience against future disruptions. Additionally, robust designs of integrated supply chain systems can effectively manage supplier disruptions while ensuring timely product delivery to meet uncertain customer demands [19].

2.3 Supply Chain Finance

Supply chain finance (SCF) plays a vital role in mitigating risks associated with supply chain operations by providing liquidity solutions and improving financial flow efficiency across the network. SCF is particularly crucial for upstream suppliers with less robust financial standing, offering necessary credit facilities to maintain operational continuity [28]. By optimizing capital flow, SCF reduces disruptions caused by cash flow constraints, essential for overall supply chain stability.

Integrating blockchain technology into SCF frameworks significantly enhances transparency, security, and efficiency. Blockchain provides a decentralized system that ensures traceability and authenticity, vital for maintaining trust among participants [29]. An analysis of 271 blockchain projects highlights the growing adoption of this technology across supply chain sectors, emphasizing its potential to revolutionize SCF by providing secure and verifiable transaction records [30]. Furthermore, combining blockchain with ANFIS and IoT technologies strengthens SCF, improving decision-making and operational efficiency, thus mitigating risks [31].

In addition to technological advancements, SCF benefits from innovative financial tools and methodologies that enhance credit assessment and improve financing access for small and medium-sized enterprises (SMEs), often operating with low credit lines [29]. Strategic supply chain formation through game-theoretic approaches aids firms in managing yield uncertainty and optimizing financial strategies, supporting the financial stability of smaller participants [32].

Moreover, implementing shared forecasting models across all supply chain parties can reduce the bullwhip effect and enhance overall performance [33]. This collaborative forecasting approach improves demand prediction accuracy, aligning financial strategies with operational needs and minimizing inventory mismatches.

The application of machine learning-based frameworks during the COVID-19 pandemic illustrates SCF's importance in optimizing supply chain decisions by identifying trending keywords, enhancing adaptability to sudden market changes [22]. Additionally, utilizing Graph Neural Networks (GNNs) combined with human expertise to predict and validate unknown supply chain links underscores SCF's role in risk mitigation by improving network visibility and accuracy [34].

2.4 Systemic Risk in Supply Chains

Systemic risk in supply chains refers to the potential for localized disruptions to escalate and affect the entire network, significantly disturbing the continuity of goods and services. The interconnected nature of modern supply chains, characterized by strategic outsourcing and lean inventory practices, increases their susceptibility to external shocks [4]. This risk is exacerbated by complex interdependencies among entities, where the failure of a single node can trigger cascading effects throughout the network [35].

The resilience of supply chains against systemic risks is significantly influenced by their design and configuration. Traditional risk management models often struggle to adapt to unexpected disruptions, particularly those outside predefined scenarios [36]. The integration of financial products, such as resMBS securities, complicates risk assessment, as demonstrated during the 2008 financial crisis [13]. Additionally, the underutilization of Big Data analytics in supply chain management (SCM) hinders the adoption of data-driven approaches necessary for improving decision-making and operational efficiency [37].

Theoretical perspectives rooted in network science provide valuable insights into how supply chain structures influence the diffusion of economic impacts [38]. Economic systemic risk (ESR) in corporate supply networks is particularly highlighted by crises like COVID-19 and natural disasters, emphasizing the need for robust risk management strategies [39]. The core challenge lies in managing risks associated with supplier unreliability and uncertain demand, crucial components of systemic risk within supply chains [40].

Technological advancements, particularly blockchain integration, offer promising solutions to enhance supply chain security and privacy. Blockchain addresses inefficiencies and security challenges by providing a decentralized system that ensures traceability and authenticity, vital for maintaining trust among participants. However, strict data privacy requirements that prevent companies from sharing internal data limit the ability to identify sources of quality variations in decentralized supply chains [41]. The development of supply chain digital twins (SCDT) also holds potential for improving resilience, although challenges remain in production, transportation, and inventory management due to the lack of a general framework and specific application methods [42].

Adaptive risk management strategies are essential to address the dynamic nature of supply chains. Social network analysis can identify critical facilities within closed-loop supply chain networks that significantly impact overall performance, addressing systemic risk [43]. Furthermore, causal machine learning (CML) methodologies provide a framework for estimating causal effects of interventions on outcomes, enabling effective decision-making in supply chain risk management [44]. The implementation of agent-based autonomous supply chains (A2SC) aims to enhance performance by integrating various processes, addressing limitations in current methods that primarily automate specific functions [45].

The integration of Internet of Things (IoT) technologies within supply chains introduces additional complexity and cyber risks, necessitating robust cybersecurity measures to safeguard against potential threats [46]. Moreover, the bullwhip effect, characterized by demand amplification across supply networks, underscores the influence of network structure and market demand volatility on systemic risk [47].

Managing systemic risk in supply chains requires a multifaceted approach combining technological innovations, optimal network design, and adaptive risk management strategies. By enhancing resilience and adaptability, stakeholders can effectively address the challenges posed by global disruptions, ensuring the stability and continuity of interconnected networks. Strategies such as substituting goods within established supply chains can mitigate supply deficits while balancing trade-offs between flexibility and operational costs. Furthermore, fostering tighter integration among supply chain echelons and increasing flexibility are critical for strengthening resilience, enabling organizations to navigate risks and reconstruct disrupted supply chains to emerge stronger than before [48, 4].

3 Supply Chain Financial Risk Contagion

Analyzing financial risk contagion within supply chains involves understanding how financial disturbances spread through interconnected networks, impacting stability and resilience. This section delves into the mechanisms of financial risk contagion, highlighting strategic interactions, network dynamics, and external shocks. As illustrated in Figure 2, the hierarchical structure of financial risk contagion in supply chains categorizes the influencing factors, key concepts, and challenges associated with these mechanisms. The figure not only emphasizes the historical examples that demonstrate the impact of contagion on global economic stability but also provides insights into the implications for robust risk management strategies. By examining these elements, we can better appreciate the intricate dynamics at play in the context of financial risk contagion.

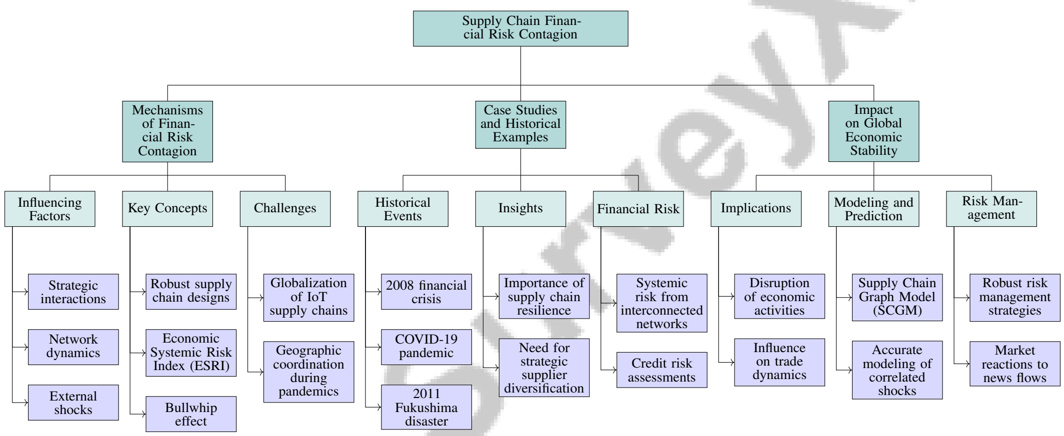
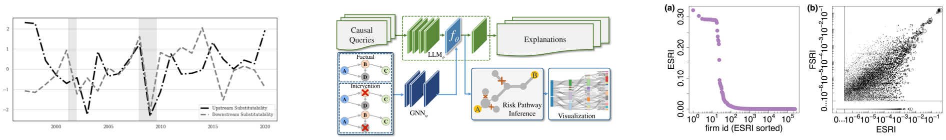


Figure 2: This figure illustrates the hierarchical structure of financial risk contagion in supply chains, focusing on mechanisms, historical examples, and their impact on global economic stability. It categorizes the influencing factors, key concepts, and challenges related to financial risk contagion mechanisms, provides insights from historical case studies, and highlights the implications for global economic stability, emphasizing the need for robust risk management strategies.

3.1 Mechanisms of Financial Risk Contagion

Financial risk contagion in supply chains is influenced by strategic interactions, network dynamics, and external shocks. The complex architecture of supply networks amplifies financial disturbances, where a single failure can trigger systemic effects. Robust supply chain designs, integrating facility location, service assignments, transportation, and inventory management, are essential for resilience [19]. The Economic Systemic Risk Index (ESRI) quantifies potential impacts on national production networks, underscoring the significance of structural features in evaluating systemic risks [39]. Firms within supply chains show stronger growth rate correlations, indicating increased potential for financial disturbances [49].

The COVID-19 pandemic illustrates how regional supply chain traits affect economic recovery, with coordinated lockdowns reducing GDP losses compared to uncoordinated ones, highlighting the need for geographic coordination [50]. The globalization of IoT supply chains presents challenges due to diverse manufacturers and suppliers, increasing uncertainties [46]. The bullwhip effect, where minor demand fluctuations cause significant upstream variabilities, remains a crucial mechanism for financial risk propagation. Advanced techniques like ESRI measure a firm's default impact on production output, offering insights into systemic financial risk contagion [51].



(a) Graph of Upstream and Downstream Substitutability over Time[52]

(b) Integrated Causal Inference and Explanation for Risk Pathway Inference[53]

(c) ESRI and FSRI Correlation Analysis[15]

Figure 3: Examples of Mechanisms of Financial Risk Contagion

Figure 3 illustrates various mechanisms of financial risk propagation. The first image shows substitutability dynamics in supply chains over time. The second image explores advances in causal inference for risk pathway delineation. The third image presents a correlation analysis between ESRI and FSRI, informing risk management strategies. These examples highlight the need for both qualitative and quantitative analyses to effectively manage financial risk contagion [52, 53, 15].

3.2 Case Studies and Historical Examples

Historical case studies provide insights into financial risk contagion in supply chains. An analysis of 16,401 firms with 178,911 links reveals how financial shocks spread across interconnected networks, emphasizing systemic risk [49]. The 2008 financial crisis demonstrated the vulnerability of supply networks to credit crunches, highlighting the need for resilient financial structures and liquidity management [13, 15].

The COVID-19 pandemic further exemplified real-time financial risk contagion, with disruptions highlighting supply network fragility and the necessity for adaptive risk management. Coordinated lockdowns resulted in lower economic losses, emphasizing geographic coordination in policy responses [50]. The 2011 Fukushima disaster showcased the cascading effects of localized disruptions on global supply chains, revealing vulnerabilities in interconnected networks [39, 54, 55, 56, 48]. This case highlighted the need for supply chain resilience and strategic supplier diversification to mitigate regional disruption impacts.

Historical examples stress the importance of understanding supply chain interconnectedness, as disruptions from tariffs, pandemics, and natural disasters can lead to significant financial risk contagion. Supply chain shocks can trigger firm failures, amplifying credit risk assessments. Integrating supply chain dynamics into financial stability evaluations is crucial for effective risk management [34, 15]. By analyzing past risk propagation, stakeholders can develop strategies to enhance supply chain resilience and stability.

3.3 Impact on Global Economic Stability

Financial risk contagion within supply chains has profound implications for global economic stability, driven by complex interdependencies and network dynamics. The spread of financial disturbances can disrupt economic activities, as demonstrated by systemic risk profiles from the Supply Chain Graph Model (SCGM), which align with empirical data [56]. This alignment highlights the critical role of supply chain structures in amplifying or mitigating financial shocks, affecting economic stability.

International trade networks are influenced by economic characteristics such as GDP, inflation, and education expenditure, affecting trade dynamics and global economic alliances [57]. Accurate modeling of correlated shocks is essential for predicting economic impacts and enhancing economic resilience [52]. Cascade dynamics within supply chains, compared to food webs, emphasize the role of covariance in influencing financial risk propagation and global stability [58].

Empirical studies identify firms posing high systemic risks, with potential defaults leading to significant economic disruptions [51]. Robust risk management strategies are necessary to prevent cascading financial distress effects that could destabilize broader economic systems. Market reactions to news flows further illustrate global economic implications, with positive news affecting stock prices and highlighting interconnected financial markets [59]. This underscores the potential for financial risk contagion to influence economic stability across regions.

4 Risk Management Strategies in Supply Chains

4.1 Strategies for Mitigating Risk Contagion

Mitigating risk contagion in supply chains necessitates a multifaceted approach that incorporates collaborative frameworks, advanced modeling techniques, and innovative strategies. The integration of multi-agent systems, as discussed by Lara et al., enhances decision-making by fostering interaction between human and machine intelligence, enabling supply chains to adapt to dynamic environments and improve operational efficiency [8].

Establishing accountability mechanisms in IoT supply chains, as proposed by Ge et al., encourages suppliers to invest in cybersecurity, thereby reducing risks and bolstering the resilience of the supply chain network [46]. This strategy is particularly vital given the increasing reliance on IoT technologies and their associated vulnerabilities.

Coordinated responses to disruptions, exemplified during the COVID-19 pandemic, highlight the significance of geographic coordination in mitigating economic losses. Inoue's study demonstrates that coordinated lockdowns can substantially lessen adverse economic impacts compared to uncoordinated efforts, underscoring the necessity for collaborative policy interventions in managing risk contagion [50].

The development of robust risk assessment tools, such as firm-level systemic risk indices, offers granular insights into potential vulnerabilities within supply chains. These advanced tools facilitate targeted risk management strategies and policy interventions by enhancing data integrity and transparency, providing a distinct advantage over traditional aggregate methods that often overlook the complexities of risk propagation [53, 60, 3, 61]. By identifying specific risk factors, stakeholders can implement more effective mitigation measures tailored to their supply networks.

Incorporating decision-makers' risk preferences into supply chain models aligns risk management strategies with stakeholders' objectives. The integration of technologies such as artificial intelligence and machine learning enhances decision-making processes by providing predictive insights and fostering collaboration. By leveraging data transparency and resource sharing, supply chains can better anticipate and respond to potential disruptions from tariffs, pandemics, and severe weather, thus improving operational resilience [54, 34, 62, 63, 64].

Optimal ordering policies, framed as stochastic control problems, represent a robust strategy for mitigating risk contagion by allowing firms to dynamically adjust orders based on real-time inventory levels and external shocks, thereby enhancing overall supply chain resilience [65, 66, 26, 67].

4.2 Innovative Technological Approaches

Innovative technological approaches are pivotal in enhancing risk management strategies within supply chains, offering advanced tools to predict, mitigate, and recover from disruptions. Blockchain technology, particularly when integrated with enterprise information systems through the Blockchain-enabled Supply Chain Method (BESCM), facilitates secure data sharing and enhances trust among supply chain partners [25]. This integration addresses data verification challenges while significantly improving operational efficiency and reducing fraud [30].

The synergy between blockchain and IoT technologies enhances supply chain capabilities by enabling advanced data collection and predictive modeling [31]. This combination supports the development of dynamic, self-adapting supply chain systems that leverage artificial intelligence and machine learning for predictive analytics, essential for the resilience of small and medium-sized enterprises (SMEs) [68].

Digital twins provide another innovative approach by offering real-time simulation and optimization of supply chain operations. This technology allows stakeholders to identify vulnerabilities and develop effective mitigation strategies, further enhancing data security when integrated with blockchain [42]. The Component-Centered Risk Assessment Model (CCRAM) employs a directed graph to represent components and suppliers, enabling the calculation of systemic risk based on interdependencies [69].

Quantum Monte Carlo methods, as introduced by Sharma, enhance efficiency in estimating probabilities in inventory management, providing a novel approach to optimize supply chain decision-making processes [40]. Bellman's recursion establishes threshold policies for inventory requests in multi-stage frameworks, optimizing ordering policies across multi-echelon supply chains [26].

The Upwind-Euler scheme, a numerical method for solving coupled PDE-ODE systems, improves the accuracy of decision-making in supply chain models [20]. Additionally, task dependency network models automate dispute resolution tasks, assessing penalties' impact on agent behavior and enhancing contract management [21].

4.3 Resilience and Adaptation Frameworks

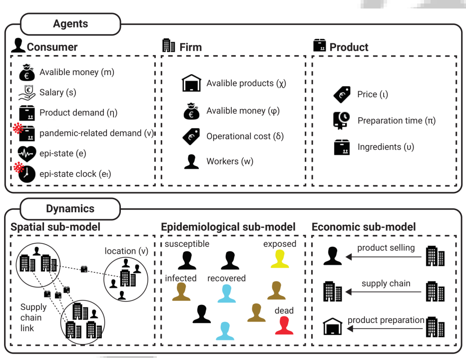
Resilience and adaptation frameworks are critical for ensuring that supply chains can withstand and recover from disruptions. The Global Robust Newsvendor Model (GRNM) exemplifies an effective framework by quantifying uncertainties and providing a structured decision-making process that minimizes risks while maximizing expected profits [66]. This model underscores the importance of robust planning in maintaining supply chain resilience under uncertainty.

Integrating multi-dimensional flexibility, as proposed by Piprani et al., enhances resilience by addressing diverse risks comprehensively [3]. This approach effectively manages the complex interdependencies between components and suppliers, allowing for a more accurate assessment of systemic risks [69].

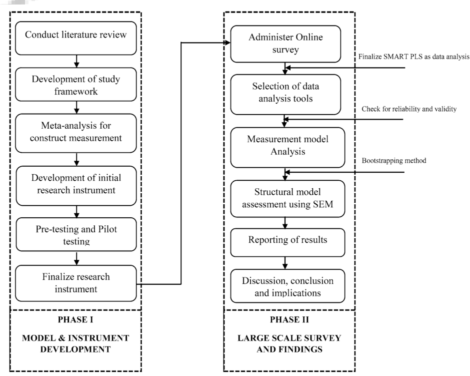
Blockchain technology, particularly through the BESCM, enhances resilience by ensuring data integrity and fostering trust among partners. Its capacity to provide a single immutable record of transactions facilitates transparency and accountability, essential for robust supply chain operations [25].

The ISO 31000 standard provides a structured approach to supply chain risk management (SCRM), harmonizing existing methodologies to enhance resilience [70]. This framework standardizes risk management practices, equipping supply chains to better handle disruptions.

Future research, as suggested by Lara et al., should focus on integrating human intuition with machine intelligence. Developing multi-agent systems and analytical methods that incorporate human input can significantly improve decision coordination and enhance supply chains' adaptive capacity [8].



(a) An Agent-Based Model for the Dynamics of a Pandemic-Related Supply Chain[71]



(b) The image depicts a flowchart outlining the steps involved in conducting a research study, specifically focusing on the development and validation of a measurement model.[3]

Figure 4: Examples of Resilience and Adaptation Frameworks

As shown in Figure 4, the exploration of risk management strategies within supply chains through resilience and adaptation frameworks illustrates how these strategies can be conceptualized and implemented. The first illustration presents an agent-based model (ABM) designed to simulate the dynamics of a supply chain during a pandemic, detailing interactions between agents such as consumers, characterized by attributes like financial resources and product demands. This ABM serves as a crucial tool for understanding how supply chains can adapt and maintain resilience amid unprecedented disruptions. Complementing this, the second illustration provides a structured flowchart delineating the methodological steps involved in developing and validating a measurement model, split into two phases: the initial phase focuses on model development, while the subsequent phase emphasizes large-scale surveys and findings analysis. Together, these frameworks underscore the importance of theoretical modeling and empirical validation in crafting robust risk management strategies that enhance supply chains' resilience and adaptability during turbulent times [71, 3].

4.4 Decentralized and Collaborative Strategies

Decentralized and collaborative strategies are increasingly recognized as vital for effectively managing financial risk contagion within supply chains, particularly in light of recent disruptions from pandemics, geopolitical instabilities, and natural disasters. These strategies not only enhance resilience against supply chain shocks but also facilitate the integration of advanced technologies like blockchain and digital twins, improving data management and transparency. By adopting these approaches, organizations can navigate the complexities of global supply networks, mitigate systemic financial risks, and foster a more adaptive and responsive supply chain environment [72, 73, 10, 15, 3]. These approaches leverage the collective capabilities of networked entities to enhance resilience and adaptability, ensuring that supply chains can withstand and recover from disruptions. The integration of decentralized frameworks allows for a distributed decision-making process, reducing reliance on centralized control and enabling agile responses to emerging risks.

The application of macroprudential policies, as discussed by Ikeda, plays a crucial role in mitigating systemic risks within the financial sector. These policies foster a collaborative environment where financial institutions work together to manage and mitigate risks, ultimately enhancing the broader economic system's stability [74]. Extending this collaborative ethos to supply chains enables stakeholders to develop more robust strategies to identify and address potential vulnerabilities.

Decentralized approaches, particularly those enabled by blockchain technology, offer significant advantages in transparency, security, and trust. Blockchain's decentralized ledger system enhances transaction verifiability and immutability, establishing a robust framework for collaborative risk management. This technology addresses critical challenges in data integrity and transparency across sectors, particularly in supply chain management, where it enables effective traceability and regulatory compliance. By eliminating central points of failure, blockchain mitigates risks associated with data tampering and vulnerabilities, fostering trust and reliability in data handling. Furthermore, its application in sustainable development initiatives underscores its potential to improve environmental performance and informed decision-making while necessitating effective governance structures to address security and privacy concerns. Thus, integrating blockchain technology enhances organizational performance and aligns with environmental, social, and corporate governance (ESG) objectives [72, 61]. This technology facilitates secure information sharing among supply chain partners, enabling more effective coordination and decision-making.

Collaborative forecasting and planning are essential components of decentralized strategies, allowing supply chain entities to share data and insights that improve demand predictions and inventory management. By cultivating a robust culture of collaboration among supply chain partners, organizations can significantly mitigate the bullwhip effect—characterized by amplified fluctuations in order quantities—and enhance overall performance. This collaborative approach facilitates efficient resource allocation through improved information sharing, decision synchronization, and trust-building, effectively addressing potential risks and fostering resilience. Research indicates that despite the recognized benefits of collaboration, many firms have yet to fully leverage these relationships, highlighting the need for strategic integration of technology and processes to optimize supply chain operations [10, 75, 4, 62, 76].

The integration of multi-agent systems further enhances the capabilities of decentralized and collaborative strategies. These advanced systems leverage artificial intelligence and machine learning techniques to simulate and analyze intricate interactions within supply chains, offering critical insights into potential risk scenarios such as disruptions from tariffs, pandemics, and climate change. By integrating predictive models, including graph neural networks and methodologies like Random Forest and XGBoost, they enhance the identification of previously unknown supply chain relationships and improve risk assessment accuracy. This facilitates the development of adaptive response strategies, ensuring operational resilience and continuity amid evolving risk landscapes [34, 63]. By combining the strengths of decentralized frameworks with collaborative practices, supply chains can achieve greater resilience and stability in an increasingly interconnected global economy.

5 Supply Chain Finance and Systemic Risk

5.1 Role of Blockchain and Digital Technologies

Blockchain and digital technologies are pivotal in transforming systemic risk management within supply chains by enhancing transparency, security, and efficiency. The Blockchain-based Supply Chain Management (BSCM) framework leverages a distributed ledger to bolster product traceability and transaction verifiability, fostering trust among participants [64]. This decentralized approach serves as a certificate authority, addressing data verification challenges and providing economic and operational benefits in systemic risk management [31, 25].

Blockchain's real-time data monitoring capability is crucial for responding to disruptions and maintaining operational continuity, especially in global supply chains where timely information is vital [77]. The evolution from startup-led initiatives to established enterprises adopting blockchain, alongside the transition from Ethereum to Hyperledger, signifies a maturing technology landscape that acknowledges blockchain's potential to address various supply chain challenges [30, 78].

Furthermore, blockchain's application in environmental impact reporting enhances data accuracy compared to traditional methods [61]. The integration of blockchain with digital technologies, such as digital twins, further improves operational efficiency and traceability, enabling supply chains to better anticipate and mitigate risks [73].

5.2 Innovative Financial Tools and Methodologies

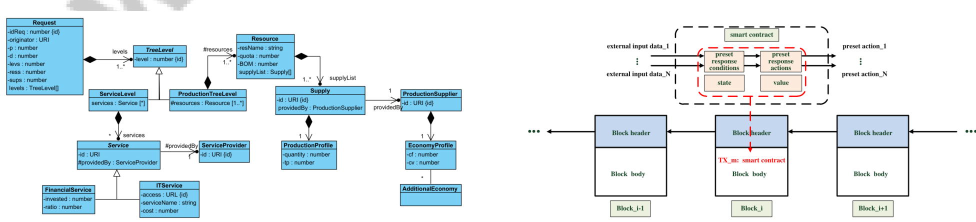
Innovative financial tools and methodologies are essential for enhancing risk management strategies in supply chains and mitigating financial contagion. The use of artificial intelligence (AI) and machine learning (ML) improves risk assessment accuracy, facilitating proactive management and bolstering resilience [63]. These technologies enable sophisticated modeling to anticipate potential disruptions, thus stabilizing supply networks.

Smart contracts within blockchain systems automate processes and enhance security, providing a reliable framework for managing transactions and minimizing fraud risks [79]. This automation ensures compliance with contractual terms without intermediaries, streamlining supply chain operations.

The Advanced Data Processing Architecture (ADPA) has proven effective across various sectors, including finance and healthcare, by optimizing data processing for better supply chain coordination [80]. Similarly, the APPA framework utilizes parallel processing and machine learning to enhance data handling efficiency [81].

Integrating game-theoretic approaches with cyber insurance in IoT supply chains creates a comprehensive risk management framework that incentivizes cybersecurity investments, thereby enhancing network resilience [46]. Additionally, the use of large language models (LLMs) and knowledge graphs (KGs) within the RC2R framework provides superior insights into financial risk contagion, surpassing traditional models in predictive capabilities [53].

Performance benchmarks indicate these innovative methodologies can reduce processing times by 50



(a) A UML class diagram representing a system with various components and relationships[82]

(b) A diagram illustrating the interaction between a smart contract and a blockchain system[83]

Figure 5: Examples of Innovative Financial Tools and Methodologies

As depicted in Figure 5, the diagrams illustrate modern approaches to managing supply chains. The first diagram, a UML class diagram, shows a system composed of various classes and their intricate relationships, highlighting the complexity inherent in supply chain systems. The second diagram focuses on technological advancements by illustrating the interaction between a smart contract and a blockchain system, detailing how external input data integrates into the blockchain. Together, these diagrams provide a comprehensive view of the innovative financial tools and methodologies reshaping supply chain finance, emphasizing both structural and technological dimensions essential for mitigating systemic risks [82, 83].

5.3 Integration of Supply Chain Finance in Risk Management

Integrating supply chain finance (SCF) into broader risk management strategies is vital for enhancing the resilience and stability of supply networks. SCF provides essential liquidity solutions that enable firms to manage cash flow effectively, reducing the risk of financial disruptions. Blockchain-based systems, such as Fabric-SCF, which utilize smart contracts and attribute-based access control (ABAC), enhance secure storage and access control, ensuring robust financial project management [29].

Incorporating knowledge graphs into risk management strategies supports effective risk identification and mitigation by enhancing transparency [6]. The ISO 31000 standard offers a structured approach to supply chain risk management (SCRM), emphasizing the selection of tools and techniques tailored to each company's unique characteristics [70].

The integration of SCF with advanced analytical models, such as the Supply Chain Network (SCN) model, facilitates a comprehensive approach to managing environmental, economic, social, and demand uncertainties [17]. This holistic perspective is essential for effective risk mitigation across supply networks.

Monitoring systemic risk at the firm level is critical for informing regulatory frameworks and enhancing supply chain resilience strategies [39]. By embedding SCF into these strategies, firms can better anticipate and respond to potential disruptions, ensuring stability and continuity within their supply networks.

The successful reconstruction of supply networks using telecommunication data provides insights into systemic risk at the firm level, underscoring the importance of integrating SCF into comprehensive risk management frameworks to bolster resilience against systemic shocks [51].

6 Case Studies and Applications

The multifaceted nature of supply chain management across various industries necessitates tailored strategies to address unique challenges and leverage opportunities. This section delves into diverse case studies and applications, focusing on risk mitigation and resilience enhancement. The following subsection highlights the pivotal role of healthcare and pharmaceutical supply chains in maintaining essential product availability during crises.

6.1 Healthcare and Pharmaceutical Supply Chains

Healthcare and pharmaceutical supply chains operate under complex dynamics requiring robust risk management to ensure uninterrupted delivery of essential goods, particularly during global disruptions. Arani et al. employed a two-stage stochastic programming model to optimize blood supply chain operations, underscoring the importance of strategic resource allocation and risk management [84]. Their study, involving multiple healthcare facilities and donor regions, highlights the need for resilient planning frameworks.

The COVID-19 pandemic emphasized adaptive strategies in healthcare supply chains, illustrated by case studies on oxygen concentrator demand, showcasing risk management's role in timely medical equipment delivery [85]. In pharmaceuticals, ensuring vaccine integrity and traceability is crucial. A case study on vaccine supply chain planning highlights the necessity of robust systems for enhancing resilience [86].

The evaluation of decentralized technologies like the dNAS framework in simulated settings reveals their potential to improve anti-counterfeiting measures and transparency in pharmaceutical supply chains [87]. Additionally, social network analysis in closed-loop supply chains identifies critical facilities impacting performance, offering insights into interdependencies and interventions to bolster resilience [43].

6.2 Manufacturing and Production Logistics

Manufacturing and production logistics demand sophisticated risk management to ensure operational efficiency and resilience. Wang et al. applied a network flow approach to optimize semiconductor wafer manufacturing, achieving significant performance gains [88]. This underscores the importance of optimizing logistics to mitigate systemic risks.

Sharma et al. demonstrated the applicability of quantum Monte Carlo methods in optimizing supply chain decisions using IBM Manufacturing Solutions data, highlighting advanced analytics' role in managing uncertainties [40]. Babaioff et al.'s concurrent auctions framework for supply chain interactions illustrates market-based mechanisms' potential to improve logistics and mitigate risks [89].

Optimal ordering policies in multi-echelon supply chains, as evaluated by Caiza et al., emphasize data-driven decision-making for inventory management amidst demand fluctuations, demonstrating their effectiveness in various scenarios [26]. The Upwind-Euler method offers flexibility in optimizing supply chain configurations [20].

Kieras's study on systemic risk in IoT-enabled manufacturing reveals strategic supplier management's role in enhancing supply chain resilience, as evidenced by an autonomous vehicle system case study [90].

6.3 Food and Agriculture Supply Chains

Food and agriculture supply chains are critical for global food security, necessitating comprehensive risk management strategies to enhance resilience. Effective integration among partners and managing perceived risks are vital. Blockchain technology offers increased transparency and efficiency, though technical and regulatory challenges remain [91, 4].

A case study on blockchain in food supply chains demonstrates its potential for enhancing traceability and transparency, crucial for food safety and quality [61]. Digital twins in agriculture supply chains provide real-time simulations, aiding in predicting and mitigating disruptions [73].

Machine learning models improve demand predictions and inventory management in agriculture, enhancing crop yield forecasts and reducing supply-demand mismatches [18]. Collaborative frameworks enhance coordination among stakeholders, improving demand predictions and inventory management, thus reducing the bullwhip effect and enhancing supply chain performance [24].

6.4 Consumer Goods and Retail Supply Chains

Consumer goods and retail supply chains require efficient risk management to maintain product flow from manufacturers to consumers. The COVID-19 pandemic exposed vulnerabilities, prompting adaptive strategies for disruption management [22].

Blockchain integration offers substantial benefits by improving transparency and traceability, essential for consumer trust and product authenticity [31]. Collaborative forecasting and planning enhance risk management by improving demand predictions and inventory management, mitigating the bullwhip effect [24].

Advanced analytics, including AI and machine learning, enable accurate demand forecasting and inventory optimization, supporting sophisticated models for managing disruptions and ensuring network stability [63]. Leveraging these technologies allows retail supply chains to better adapt to market conditions and consumer demands.

7 Future Directions and Research Opportunities

Exploring future directions in supply chain risk management highlights the transformative potential of emerging technologies, which redefine operational paradigms and enhance supply chain resilience and adaptability. The following subsections examine the specific impacts of these technologies on supply chain risk management.

7.1 Emerging Technologies and Their Impact

Emerging technologies significantly transform supply chain risk management by enhancing resilience, efficiency, and adaptability. Blockchain technology improves transparency, security, and operational efficiency. Future research should explore additional blockchain use cases, develop user-friendly tools, and improve system interoperability [25, 78]. Establishing standards and integrating blockchain with IoT are critical areas for further exploration.

Quantum computing holds promise for improving decision-making under uncertainty, potentially revolutionizing complex processes [40]. Future research should refine these techniques and assess their real-world applicability.

Machine learning applications are crucial for capturing the dynamic nature of supply chains. Studies should focus on diverse industrial contexts and enhance predictive capabilities [17, 11]. Developing hybrid models that merge theoretical insights with empirical data could improve accuracy and applicability.

Cognitive engineering and historical decision-making patterns offer promising research avenues, potentially leveraging human intuition in risk management strategies [8]. Cybersecurity remains a pressing concern, necessitating innovative regulatory approaches and robust measures to protect against emerging threats [92].

Reconstructing supply networks using enhanced methods that incorporate additional data sources and refine supply link estimations is another valuable area for exploration [51].

7.2 Interdisciplinary Approaches

Interdisciplinary research is vital for addressing complex supply chain challenges, integrating insights from supply chain management, information systems, and computer science to tackle issues like information flow security and decision-making integration. This approach enhances operational robustness and identifies innovative strategies for disruption recovery, improving business value and resilience [54, 8, 16, 10].

Network science, as explored by Perera et al., effectively models and analyzes supply chain dynamics, aiding in understanding interdependencies and identifying critical nodes [93]. Integrating machine learning and AI with cognitive science insights can bolster predictive capabilities and decision-making processes [8]. The use of quantum Monte Carlo methods exemplifies interdisciplinary approaches optimizing decision-making processes [40]. Combining blockchain with existing frameworks illustrates the benefits of merging technological innovations with economic theories, enhancing transparency and security [61].

7.3 Advanced Modeling Techniques

Advanced modeling techniques are essential for improving risk assessment and management in supply chains, providing sophisticated tools for predicting, mitigating, and adapting to disruptions. These methodologies utilize advanced stochastic processes, real-time data analysis, and cutting-edge computational techniques, enabling organizations to predict product availability and implement robust optimization strategies, thus improving flexibility in response to disruptions. Machine learning models and intelligent recommender systems help manage uncertainties and enhance operational capabilities [94, 4, 63, 81, 35].

Enhancing correlation estimation techniques is crucial for understanding interdependencies within production networks, with future improvements focusing on universal network features to deepen insights into structural dynamics and vulnerabilities [49]. The Economic Systemic Risk Index (ESRI) quantifies firm-level economic systemic risks, and future research should refine production function calibrations and dynamic aspects of supply networks to better understand external shocks [39]. In inventory management, integrating production decisions with inventory strategies enhances resilience against disruptions, including optimizing multi-echelon ordering policies [26]. Numerical methods proposed by D'Apice et al. offer flexibility in optimizing supply chain configurations, with future studies focusing on relaxing assumptions and applying adaptive mesh techniques to complex models [20].

The integration of advanced modeling techniques, real-time data analysis, and machine learning algorithms is critical for accurately capturing the dynamic nature of supply chain networks, particularly in response to disruptions from tariffs, pandemics, and climate change. This approach enhances predictive capabilities and risk mitigation strategies, leveraging technologies like graph neural networks and knowledge graphs to improve visibility and resilience [95, 34, 96, 63].

7.4 Data Privacy and Security

Data privacy and security are paramount challenges in supply chain management, especially in the context of large-scale Big Data systems. The reliance on digital technologies has intensified concerns about protecting sensitive information and the potential for data breaches. Robust frameworks are necessary to manage the complexities of real-time analytics while safeguarding against unauthorized access and cyber threats [37].

Blockchain technology presents promising solutions for enhancing data security in supply chains through its decentralized ledger system, which ensures data integrity and transparency. This system protects against tampering and vulnerabilities found in traditional databases, facilitating real-time access to verifiable information among network participants. Such capabilities are crucial for maintaining trust among stakeholders, particularly in regulated sectors requiring traceability. By leveraging blockchain's attributes, organizations can enhance monitoring processes and contribute to sustainable development initiatives. However, challenges related to network security and data privacy must be addressed through effective governance and risk management strategies [72, 61].

Implementing blockchain and other digital technologies also raises data privacy concerns. Balancing transparency with confidentiality is essential, as information sharing must not compromise individual entity privacy. Emerging technologies can enhance data transparency while safeguarding sensitive information through hybrid architectures that combine public visibility with private control, addressing data silos and communication barriers [72, 16, 96, 97, 98]. Developing encryption techniques and access control mechanisms is critical for ensuring secure information flow.

The proliferation of Internet of Things (IoT) devices introduces new vulnerabilities, necessitating comprehensive strategies that integrate hardware and software solutions, including secure communication protocols and regular security audits. Leveraging blockchain can enhance data integrity and trust among supply chain partners, addressing security challenges in complex IoT systems [25, 79, 7].

Future research should focus on sophisticated frameworks for managing data privacy and security in supply chains, particularly concerning Big Data and IoT systems. Innovative approaches to data encryption, access control, and real-time threat detection are essential for enhancing resilience against cyber threats. By effectively addressing cybersecurity challenges, supply chains can utilize blockchain technology to protect sensitive information while fostering stakeholder trust in a digitalized economy. This approach facilitates secure data transfer through smart contracts and promotes resource sharing and traceability among stakeholders, strengthening supply chain integrity and competitiveness [99, 64, 79].

7.5 Sustainability and Resilience

Sustainability and resilience are increasingly recognized as essential in future supply chain strategies, tackling environmental stewardship and operational robustness. Research indicates that supply chain resilience—defined as the capacity to recover from disruptions—can be enhanced through tighter integration among supply chain echelons and increased flexibility, improving operational capabilities and mitigating risks from environmental and market uncertainties. Effective supply chain design must balance efficiency with resilience, particularly in regions facing logistical challenges. Integrating sustainability into these frameworks prepares organizations for unforeseen events while promoting responsible resource management [100, 48, 4].

Future research should develop integrated models that account for recovery and proactive measures, exploring the interfaces between resilience and sustainability in supply chains [54]. This comprehensive approach ensures that supply chains are both resilient and environmentally responsible.

Decentralizing registration authorities and integrating privacy-preserving techniques for sensitive data can enhance sustainability and resilience [101]. By decentralizing control and protecting sensitive information, supply chains can foster trust and transparency essential for sustainable operations.

Introducing fees and incentive mechanisms to study the economic models behind decentralized trust and reputation management emphasizes the role of economic incentives in promoting sustainable practices [102]. These mechanisms encourage participants to adopt environmentally friendly practices and enhance resilience.

Knowledge exchange from product design to waste valorization within clusters highlights the importance of sustainable development in improving supply chain resilience [103]. Collaboration and innovation can optimize resource use and minimize waste, contributing to both sustainability and resilience.

Exploring the implications of perishable goods in resilient supply chains and developing back-to-normal plans post-disruption are critical areas for future research [104]. Understanding the unique challenges posed by perishable goods can inform strategies that ensure continuity while minimizing environmental impacts.

Moreover, refining accountability metrics and enhancing cyber insurance integration can improve supply chain resilience [46]. These measures protect against cyber threats and ensure robustness in the face of digital disruptions.

8 Conclusion

This survey underscores the imperative of addressing financial risk contagion within supply chains, advocating for strategies that are both integrated and adaptive to meet the demands of a globally interconnected network. Blockchain technology emerges as a pivotal tool in this context, offering enhancements in traceability, fraud prevention, and automation, despite ongoing challenges related to scalability and interoperability. The conceptualization of supply chain information as a knowledge graph is also recognized for its potential to significantly enhance transparency and resilience.

The survey highlights the necessity of interdisciplinary collaboration, particularly between computer scientists and supply chain professionals, to ensure robust information flows essential for the functionality of digital supply chains. The fusion of advanced theoretical models with practical applications is shown to enhance decision-making and operational efficiency in supply chain management. Furthermore, social network analysis is identified as a valuable approach for increasing flexibility and resilience by effectively assessing networks and identifying key facilities.

Significant insights include the adoption of collaborative procurement strategies and the strategic use of technology to foster business value. The Digital Procurement Workspace (DPW) exemplifies successful design implementation, achieving greater transparency, efficiency, and decision-making support, thereby aligning with sustainable procurement practices and the objectives of the Paris Agreement.

For practitioners and policymakers, the survey suggests a focus on innovative technologies, increased flexibility, and the cultivation of sustainable practices to uphold the resilience and stability of global supply networks. It also emphasizes the importance of establishing stricter legal definitions and obligations for companies to enhance cybersecurity measures. By employing integrated and adaptive strategies, stakeholders can effectively manage financial risk contagion, thereby safeguarding the resilience and stability of supply chains in an increasingly interconnected global economy.

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