Supply Chain Resilience and Digital Transformation: A Survey

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Abstract

This survey paper explores the interconnected concepts of supply chain resilience, digitalization, enabling theory, digital techniques, digital transformation, and resilience strategy, emphasizing their collective impact on modern supply chain management. The integration of Industry 4.0 technologies, such as the Internet of Things (IoT) and artificial intelligence (AI), is highlighted as crucial for enhancing supply chain resilience through real-time monitoring and data-driven decision-making. The paper underscores the transformative potential of digital techniques, including blockchain and AI, in optimizing supply chain operations and addressing challenges like traceability and trust. It further discusses the significance of digital transformation in reshaping business models and processes, enhancing operational efficiency and resilience across various sectors. The survey identifies key challenges in digital integration, such as technological, human, and data management issues, while proposing future research directions to address these obstacles. Case studies illustrate successful digital transformation applications, demonstrating the role of digital tools in enhancing supply chain transparency, efficiency, and resilience. The findings emphasize the necessity of balanced resilience strategies and the strategic implementation of digital technologies to achieve sustainable competitive advantages in an increasingly volatile business environment. By leveraging digitalization and digital transformation, organizations can build robust supply chains capable of navigating vulnerabilities exposed by global disruptions.

1 Introduction

1.1 Interconnected Concepts Overview

The interconnectedness of supply chain resilience, digitalization, enabling theory, digital techniques, digital transformation, supply chain management, and resilience strategy forms a critical foundation for modern supply chain dynamics. Industry 4.0 technologies, including the Internet of Things (IoT) and artificial intelligence (AI), enhance supply chain resilience through real-time monitoring and data-driven decision-making [1]. Digitalization, which integrates digital technologies into business processes, significantly shapes the skills required for future work environments, influencing professional and practice-based learning [2]. This transformation is vital for operational efficiency and fostering a culture of continuous improvement and innovation within organizations [3].

AI applications in reverse supply chain management (RSCM) exemplify digital techniques' potential to optimize operations, particularly in product return management [4]. Blockchain technology also addresses global supply chain challenges like traceability and stakeholder trust, thus enhancing transparency and compliance [5]. Advanced digital techniques optimize supply chain flexibility, especially in industries such as poultry, by managing uncertainties in delivery times and reorder processes [6].

Digital transformation is closely linked to economic development, influencing business processes and competitiveness [7]. The societal impacts of digitalization highlight the necessity of integrating

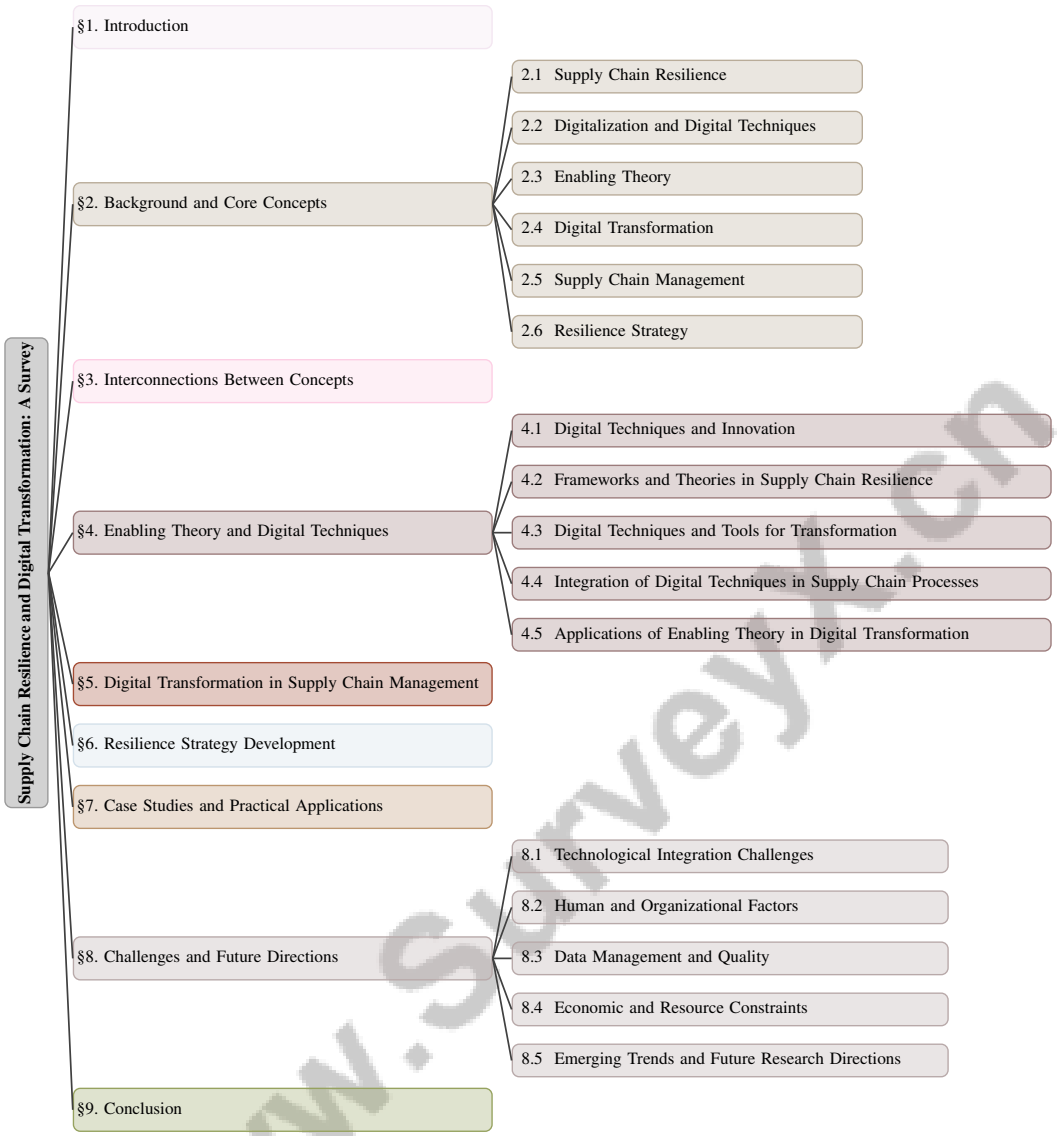


Figure 1: chapter structure

digital technologies into professional and social spheres to improve governance and social well-being, particularly in industrialized societies [8]. Furthermore, the fourth industrial revolution is transforming quality management, with emerging technologies enhancing product and service quality [9].

Understanding the structure of supply chain digitalization research is essential for identifying key topics and areas needing further exploration [10]. The integration of these core concepts not only enhances supply chain robustness and flexibility but also ensures sustainable operations amidst evolving challenges. By leveraging digitalization and transformation, organizations can build resilient supply chains capable of navigating vulnerabilities exposed by global economic disruptions. This survey aims to consolidate fragmented digital transformation literature and clarify the theoretical positioning of the constructs involved [11].

1.2 Relevance in the Current Business Environment

In today's business landscape, marked by rapid technological advancements and increased market volatility, digital transformation is crucial for enhancing supply chain resilience. The integration of digital technologies is essential for reshaping business models, processes, and customer experiences,

thereby strengthening supply chains [11]. As organizations increasingly depend on data-driven innovation, facilitated by digitalization, machine learning, and AI, they can develop adaptive capabilities and foster collaboration across supply chains.

The significance of digital transformation spans various sectors, including business and healthcare, emphasizing its essential role in modern economic contexts. For small and medium-sized enterprises (SMEs), overcoming digital transformation challenges is vital for enhancing digital maturity and leveraging capabilities [12]. Aligning digital transformation initiatives with organizational culture and employee mindset is critical for enhancing supply chain resilience and promoting a culture of innovation and continuous improvement [13].

The COVID-19 pandemic has highlighted the necessity of resilient supply chains, particularly in critical sectors such as healthcare, where efficient management is crucial for vaccine production and distribution [14]. Industry 4.0 technologies have played a key role in mitigating pandemic-induced disruptions, underscoring the importance of digital transformation for maintaining operational continuity [1]. Understanding digitalization metrics and their impact on supply chain management practices is essential for organizations aiming to enhance resilience and adapt to the dynamic business environment [10].

Moreover, the pandemic has accelerated the demand for digital maturity and resilience, as organizations strive to bridge knowledge gaps and navigate uncertainty [15]. Continuous learning and adaptation in educational curricula are necessary to equip the workforce with skills essential for thriving in a digital economy [2]. Digital transformation not only provides tools and methodologies to tackle modern supply chain complexities but also ensures sustainable operations and long-term strategic advantages. The increasing frequency and impact of supply chain disruptions necessitate a comprehensive understanding of these dynamics, as highlighted in recent surveys addressing existing knowledge gaps [16].

1.3 Structure of the Survey

This survey is meticulously organized to explore the interconnected concepts of supply chain resilience and digital transformation comprehensively. The initial section introduces these core concepts, underscoring their relevance and significance in the current business environment, and sets the stage for understanding the pivotal roles of digitalization, enabling theory, digital techniques, and resilience strategies in modern supply chain management.

The second section delves into the background and core concepts, providing detailed explanations and definitions from existing literature, establishing a foundational understanding of how these concepts are framed and their significance in supply chain management.

Subsequently, the third section explores the interconnections between these concepts, examining relationships and interdependencies that highlight how digitalization and transformation enhance supply chain resilience and management.

The fourth section focuses on enabling theory and digital techniques, discussing their roles in integrating digital tools into supply chain processes and highlighting specific methods that facilitate digital transformation and improve resilience.

In the fifth section, the survey analyzes digital transformation within supply chain management, assessing its impact on operational efficiency, resilience, and organizational agility, while presenting case studies of successful initiatives.

The sixth section addresses resilience strategy development, discussing strategies for enhancing supply chain robustness and flexibility, emphasizing digital transformation's role in supporting these strategies.

The seventh section presents case studies and practical applications, showcasing examples of organizations effectively integrating digital transformation and resilience strategies, providing insights into outcomes and lessons learned.

Finally, the eighth section identifies challenges and future directions in integrating digital transformation and resilience strategies, discussing potential research avenues and emerging trends, offering a forward-looking perspective on the evolution of supply chain resilience and digital transformation.The following sections are organized as shown in Figure 1.

AI-generated, for reference only.

2 Background and Core Concepts

2.1 Supply Chain Resilience

Supply chain resilience embodies the ability to prepare for, respond to, and recover from disruptions, ensuring operational continuity and performance during challenges [17]. This capability is vital across sectors, particularly in mitigating risks from unforeseen events [16]. The COVID-19 pandemic highlighted vulnerabilities in supply chains, emphasizing the need for resilient strategies to maintain operations, notably in critical areas like vaccine supply chains [10, 14].

Technological advancements, especially Industry 4.0 solutions, enhance supply chain resilience through real-time data analysis and informed decision-making [1]. AI optimizes operations, especially in reverse logistics, crucial for recovery options [4]. The Material-Inventory Transportation (MIT) problem exemplifies how production failures can escalate costs, highlighting resilience's role in mitigating disruptions [18].

However, digital transformation faces challenges like limited technical expertise and resources, particularly for SMEs [19]. These challenges, exacerbated by external uncertainties, necessitate comprehensive digital strategies and effective knowledge transfer between academia and industry [20]. Organizational resilience at the individual level significantly enhances collective supply chain resilience, especially during extreme weather events [21]. Leveraging internal enablers such as organizational strategy and sustainable technology capabilities, firms can develop resilient supply chains to withstand diverse disruptions [22].

2.2 Digitalization and Digital Techniques

Digitalization, the integration of digital technologies into business operations, is fundamental to modern supply chain management, transitioning from traditional processes to digital records and transactions for enhanced efficiency and transparency [5]. In the European Union, digitalization optimizes business processes and enhances competitiveness [7]. Adopting digital techniques like AI, blockchain, robotics, cloud computing, and IoT is crucial for modernizing supply chain operations [23].

Blockchain technology enhances traceability and integrity in supply chain management, addressing inefficiencies and transparency challenges [24]. Integrating blockchain with ANFIS proposes a decentralized finance protocol that improves transparency and reduces transaction times [6]. Blockchain smart contracts and decentralized storage facilitate stakeholder connections, automating processes and improving service delivery [25].

Challenges persist, including data quality, integrity, and security issues like low data quality, missing data, and lack of standardization, hindering the full adoption of data-driven technologies in operations and supply chain management (OSCM) [26]. In remanufacturing, the varied conditions of returned products and the complexity of managing multiple return types necessitate effective decision-making models, underscoring the need for sophisticated digital techniques [4].

Digitalization and blockchain technology enhance efficiency, accuracy, and trustworthiness in data collection and supply chain management, providing a robust foundation for digital transformation [27]. Process Mining (PM) techniques support this transformation by discovering, monitoring, and improving real processes through knowledge extraction from event logs available in today's information systems [28]. Quantum computing techniques, like Quantum Monte Carlo methods, optimize decision-making in inventory management under uncertainty, offering new avenues for enhancing supply chain resilience [29].

The application of Industrial IoT (IIoT) and Industry 4.0 technologies in smart manufacturing contexts underscores the potential of digitalization to revolutionize supply chain operations [30]. However, slow adoption in industries like the European Steel Industry poses challenges in ensuring reliable quality information exchange, highlighting the need for strategic implementation of these technologies [31]. As organizations navigate digital transformation complexities, strategically deploying digital techniques is essential for achieving resilient and competitive supply chains.

2.3 Enabling Theory

Theoretical frameworks are crucial for understanding and facilitating digital transformation in supply chains, providing insights into the effective integration of digital technologies to enhance efficiency and resilience. A significant framework categorizes digital technologies by adoption levels and impacts on business processes and employee roles, emphasizing the transformative potential of digital systems in organizations [32]. This framework highlights aligning digital initiatives with organizational strategies to optimize supply chain operations.

Blockchain technology, a cornerstone of digital transformation, is analyzed through various theoretical lenses to understand its implications for supply chain management. A comprehensive framework based on four established economic theories—principal agent theory (PAT), transaction cost analysis (TCA), resource-based view (RBV), and network theory (NT)—provides a detailed analysis of blockchain's capabilities in reducing transaction costs, mitigating information asymmetry risks, and leveraging network effects to enhance supply chain operations [33]. This perspective emphasizes blockchain's potential to provide secure, immutable, and decentralized contract execution, crucial for modern supply chains [34].

Integrating blockchain and digital twins in supply chain management addresses traditional challenges related to security, efficiency, and data management. Frameworks focusing on these challenges highlight the role of smart contracts and cybersecurity measures, stressing the importance of robust data management systems. Moreover, applying Bitcoin's data structures and incentive mechanisms enhances transparency and traceability in supply chain systems, showcasing the potential of decentralized platforms [35].

A proposed architecture for supply chain management (SCM) incorporates cloud computing and IoT, emphasizing real-time data processing and analytics capabilities essential for agile and responsive supply chains [36]. This architecture aligns with frameworks categorizing the roles of blockchain and IoT devices in achieving SCM objectives, emphasizing enhanced tracking and verification processes [37].

Furthermore, a taxonomy categorizes industrial challenges and corresponding enabling technologies, providing a structured approach to understanding and addressing these issues [20]. This taxonomy is instrumental in identifying key resources and capabilities necessary for digital transformation, highlighted in the nomological net framework, which categorizes existing research into an input-process-output framework [11].

Theoretical frameworks and architectures provide critical insights into integrating digital technologies in supply chains, revealing the complex and transformative effects of digital transformation on organizational structures and processes. Key technologies such as AI, robotics, cloud computing, and IoT are reshaping business models and operational efficiencies while presenting managerial challenges and barriers to digitization. This evolution enhances supply chain performance and creates substantial opportunities for value creation across industries, underscoring the necessity for organizations to adapt to these changes or risk obsolescence [23, 10]. These frameworks are essential tools for researchers and practitioners aiming to navigate digital transformation complexities and enhance supply chain resilience.

2.4 Digital Transformation

Digital transformation (DT) involves strategically integrating digital technologies to fundamentally alter organizational operations, business models, and value propositions [38]. In supply chain management, DT is pivotal for improving operational efficiency, responsiveness, and resilience, particularly in the face of disruptions. This transformation is characterized by advanced modeling techniques, like the Integrated Hybrid Simulation Framework, enhancing supply chain responsiveness to demand fluctuations [39].

Successful digital transformation requires both technological advancements and significant organizational and cultural shifts. It necessitates reevaluating traditional practices and aligning digital initiatives with strategic business goals to optimize supply chain processes [13]. Despite its critical importance, many digital transformation initiatives fail to deliver expected benefits, highlighting the complexity and challenges involved in their execution [40]. The Dynamic Capability View

(DCV) theory underscores the necessity of developing flexible capacities to respond to environmental changes, essential for navigating digital transformation complexities [41].

Digital transformation significantly enhances decision-making capabilities within supply chains. The MARE semantic disruption management framework exemplifies integrating data across all decision-making process steps, facilitating monitoring, modeling, assessment, recovery, and evaluation of disruptions using semantic technologies [42]. This integration allows organizations to address inadequacies in traditional forecasting paradigms and better manage modern supply chains' complexities [43].

Moreover, digital transformation technologies support contextualization in cyber-physical production systems, addressing challenges of information integration and interpretation [44]. The Digital Twin Interface Model (DT-IM) enhances supply chain operations by representing Process-Aware Information Systems (PAIS) entities and updates, enabling analysis of the impacts of updates on business processes [45].

Incorporating digital technologies such as blockchain and smart contracts facilitates real-time monitoring and traceability, enhancing transparency and trust in supply chain operations [46]. This integration improves operational efficiency and fosters innovation by leveraging data science, machine learning, and AI to inform strategic decision-making [47]. For instance, implementing cloud-based routing and scheduling systems optimizes urban freight transportation by utilizing real-time data, underscoring digital transformation's role in enhancing supply chain operations [48].

Digital transformation represents a holistic change in societal norms and behaviors, leading to a concept termed 'Digital Transfiguration,' significantly altering lifestyles [8]. The survey focuses on understanding and assessing digital transformation maturity in organizations, specifically how different maturity models capture this concept [3]. Moreover, the trend from RFID to big data as the primary research focus indicates a shift towards data-driven supply chain management [10]. This transformation is further supported by software engineering, which plays a critical role in enabling effective digital transformation across sectors [49]. Understanding the enablers that facilitate digital transformation is crucial, particularly in SMEs, which face unique challenges compared to larger firms [19].

Digital transformation serves as a dynamic capability that enhances supply chain operations by promoting agility, optimizing efficiency, and equipping organizations to adeptly manage contemporary business complexities. This transformation is driven by integrating advanced digital technologies, such as AI, big data analytics, and IoT, enabling companies to innovate processes and business models. By fostering a culture of risk-taking and adaptability, organizations can leverage these technologies to create new products and services, streamline operations, and achieve a competitive advantage in an increasingly turbulent environment. Successful implementation of digital transformation initiatives requires a clear digital strategy and strong leadership support to navigate potential challenges, including data security and interoperability issues [3, 50, 23, 51]. It necessitates a holistic approach integrating technological innovations with organizational restructuring and cultural adaptation to achieve sustainable competitive advantages.

2.5 Supply Chain Management

Integrating digital techniques into traditional supply chain management (SCM) practices is essential for addressing the complexities and dynamic nature of globalized markets. The increasing complexity of supply chains necessitates effective management strategies capable of handling uncertainties and rapid changes [18]. Traditional SCM frameworks, such as the Value Chain Operations Reference (VCOR) model, provide a unified approach by integrating product development, supply chain management, and customer success to enhance performance across the value chain [52]. However, these models must evolve to incorporate digital techniques that enhance efficiency and responsiveness.

Digital transformation (DT) in SCM is often misconceived as primarily focused on technology, while the actual challenges lie in organizational structures and processes [40]. This misconception can lead to failures in implementing DT initiatives, underscoring the need for a strategic approach that aligns digital initiatives with organizational goals. The Collaborative Supply Chain Management (CSCM) framework facilitates process integration and information sharing among supply chain partners, enhancing overall efficiency and responsiveness [53].

The application of AI in reverse supply chain management (RSCM) exemplifies digital techniques' transformative potential in optimizing operations, particularly in managing product returns [4]. Blockchain technology plays a pivotal role in enhancing transparency and security in supply chains, addressing inefficiencies and fostering trust among stakeholders [5]. This technology enables seamless integration of digital techniques into SCM practices, ensuring robust and transparent operations.

Key obstacles in digital integration include managing big data, establishing standardized representations for digital artifacts, ensuring trustworthiness in digital models, and addressing the skills gap in the workforce [54]. These challenges necessitate focusing on developing digital skills and establishing trust in digital models to optimize supply chain processes. Moreover, the inadequacy of current SCM strategies to handle unprecedented demand, such as during a global pandemic, underscores the importance of integrating digital techniques to enhance resilience and adaptability [14].

The hybrid approach to Business Process Management (BPM), which combines centralized management of high-value processes with decentralized improvement efforts for lower-value processes, offers a strategic framework for integrating digital techniques into SCM [55]. This approach allows organizations to optimize supply chain operations by leveraging digital tools and methodologies.

Integrating digital technologies, such as AI, blockchain, and IoT, into traditional SCM practices is essential for significantly improving operational efficiency, enhancing transparency, and building resilience against disruptions. This transformation leverages advanced analytics and automation to streamline processes, foster innovation, and create new value propositions, enabling organizations to adapt to rapidly changing market dynamics and achieve competitive advantages [23, 51]. By adopting strategic frameworks and addressing key obstacles, organizations can effectively navigate the complexities of modern supply chains and achieve sustainable competitive advantages.

2.6 Resilience Strategy

Developing resilient supply chains necessitates a strategic approach incorporating proactive and reactive measures, enabling organizations to effectively handle disruptions and long-term challenges. Integrating internal processes with external supply chain partnerships enhances responsiveness and adaptability, offering a significant advantage over traditional methods [56]. Proactive strategies focus on anticipating potential disruptions and implementing measures to mitigate their impact, while reactive strategies emphasize effective responses once disruptions occur [57].

A comprehensive framework categorizes supply chain resilience strategies into proactive and reactive approaches, emphasizing the importance of innovation, empowerment, and risk management to enhance overall resilience [58]. The ability to anticipate, adapt, respond, recover, and learn are identified as five core capabilities essential for supply chain resilience (SCRES), crucial for navigating modern supply chain complexities [59]. Architectural strategies such as composition, adaptation, and dispersion are vital for developing robust and flexible supply chains in response to demand fluctuations [60]. Enhancing flexibility within existing supply chain structures allows for the substitution of goods, mitigating shortages and improving resilience [61].

The conflicting objectives of achieving immediate financial gains and establishing long-term resilience present a significant challenge, as existing methods often fail to address these dual goals effectively [62]. This tension underscores the need for a nuanced approach that incorporates both short-term and long-term considerations in resilience strategy development. Tailored trust management solutions, such as the Decentralized Trust and Reputation Management (DeTRM) system, are essential for enhancing data integrity and ensuring reliable information flow across supply chains [63].

The reliance on centralized databases for traceability data introduces vulnerabilities and high operational costs, highlighting the need for innovative resilience strategies [64]. Blockchain technology offers solutions to these challenges by providing decentralized and secure data management systems, although practical implementation and interoperability among various blockchain platforms remain significant hurdles [65]. Moreover, the complexity of modern software supply chains, insufficient visibility into components, and the integration of numerous third-party services complicate monitoring and securing each element, necessitating advanced resilience strategies [66].

The COVID-19 crisis highlighted the critical role of reactive strategies, particularly for food sector small and medium-sized enterprises (FSMEs), in maintaining supply chain continuity during disruptions [67]. These strategies include diversifying supplier bases, enhancing inventory manage-

ment practices, and leveraging digital technologies to improve supply chain visibility and agility. A data-driven culture in manufacturing is crucial for enhancing supplier selection processes, enabling organizations to make informed decisions based on real-time data and analytics [68].

Organizations face significant challenges in shifting from traditional business models to digital ones, overcoming organizational inertia, and adapting existing strategies to exploit new business opportunities. These challenges are compounded by issues related to data quality and availability, integration challenges between blockchain and existing systems, and the complexity of managing multi-level decision models [69]. Addressing these obstacles requires a strategic focus on building digital capabilities and fostering a culture of continuous improvement and innovation.

Key challenges include the difficulty in replicating and scaling pilot projects, the need for further validation of technology readiness levels, and the complexity of developing tailored strategies for different industrial contexts [70]. Additionally, integrating digital engineering practices within existing information assurance frameworks is crucial to enhancing security, compliance, and risk management [71].

Ensuring the reliability of quality information, supervising compliance with specifications, and customizing data exchanges to meet individual order requirements present primary challenges in supply chain resilience [31]. Furthermore, studies related to natural gas supply chain resilience highlight the importance of addressing disruptions, optimization techniques, and resilience strategies specific to this sector [72].

In recent years, the landscape of supply chain management has undergone significant transformations, driven by advancements in technology and evolving market demands. A critical examination of these changes reveals the intricate relationships between various key concepts that underpin effective supply chain strategies. As illustrated in Figure 2, the figure elucidates the interconnections among these concepts, emphasizing the pivotal role of digitalization in enhancing resilience. It further explores how digital transformation impacts organizational agility, while blockchain technology contributes to supply chain efficiency. Additionally, the figure highlights the influence of data analytics on decision-making processes. Each main category is meticulously detailed, encompassing aspects such as technological integration, organizational impact, and the challenges faced, thereby providing a comprehensive overview of the relationships and contributions that shape the overall supply chain strategy.

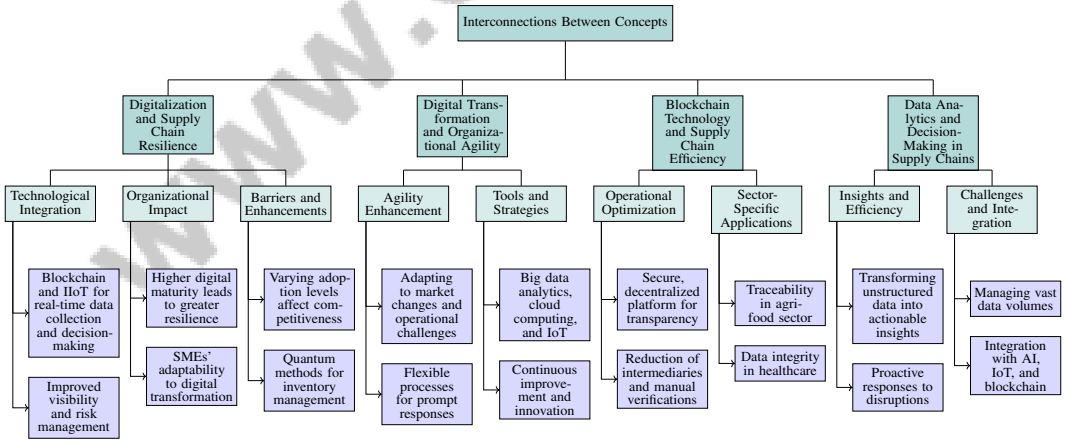


Figure 2: This figure illustrates the interconnections between key concepts in supply chain management, highlighting digitalization's role in enhancing resilience, digital transformation's impact on organizational agility, blockchain technology's contribution to supply chain efficiency, and data analytics' influence on decision-making. Each main category is further detailed with technological integration, organizational impact, and challenges, providing a comprehensive overview of the relationships and contributions to the overall supply chain strategy.

3 Interconnections Between Concepts

3.1 Digitalization and Supply Chain Resilience

Digitalization enhances supply chain resilience by integrating technologies like blockchain and IIoT, which enable real-time data collection, validation, and decision-making. These technologies improve visibility and risk management, helping organizations anticipate and mitigate disruptions, such as production failures and inventory shortages [17, 18]. Blockchain fosters collaboration by enhancing transparency and trust among partners, which is crucial for maintaining continuity [73]. Organizations with higher digital maturity exhibit greater resilience and flexibility, underscoring the link between digitalization and supply chain resilience [15]. Digital transformation extends beyond technology; it requires structured approaches to drive societal change and cultivate innovation [8, 11]. SMEs demonstrate unique adaptability to digital transformation, crucial for resilient supply chains [19]. However, varying adoption levels in the EU hinder competitiveness and resilience [7]. Addressing these barriers is essential for maximizing digitalization's benefits. Quantum methods can further enhance inventory management, improving decision-making tools for supply chain resilience [29].

3.2 Digital Transformation and Organizational Agility

Digital transformation is crucial for enhancing organizational agility, allowing enterprises to adapt swiftly to market changes and operational challenges. Integrating digital technologies fosters flexible processes, enabling prompt responses to disruptions and evolving demands. JD.com's successful navigation of COVID-19 complexities through digital strategies illustrates this potential [74]. The impact on diversification strategies varies with execution channels, highlighting the need for alignment with organizational goals to optimize agility [75]. Digital transformation catalyzes agility by promoting continuous improvement and innovation. Adopting tools like big data analytics, cloud computing, and IoT enhances resilience and adaptability, allowing organizations to navigate uncertainties and seize opportunities [76, 77, 51, 1].

3.3 Blockchain Technology and Supply Chain Efficiency

Blockchain technology enhances supply chain efficiency by providing a secure, decentralized platform that improves transparency and trust. Its tamper-proof ledger optimizes operations by reducing intermediaries and manual verifications [33]. This decentralization mitigates single points of failure, common in traditional systems [78, 79]. In the agri-food sector, blockchain enhances traceability, reduces fraud, and improves efficiency [80, 24]. In global supply chains, it enhances visibility and security, crucial for sectors like healthcare where data integrity is paramount [5, 25]. Despite its potential, blockchain implementation faces security challenges that must be addressed for effective deployment [79]. Overcoming these challenges can significantly improve data management, transparency, and efficiency in supply chains, fostering sustainable and competitive operations.

3.4 Data Analytics and Decision-Making in Supply Chains

Data analytics is vital for enhancing decision-making in supply chains by transforming unstructured data into actionable insights, improving operational efficiency and strategic planning [81, 82]. Advanced analytics techniques provide deeper insights into supply chain dynamics, enabling proactive responses to disruptions [83]. Effective data management strategies emphasize data quality and continuous monitoring, crucial for reliable decision-making [69]. The challenge lies in managing vast data volumes across processes, necessitating advanced systems and tools [36]. Overcoming these obstacles enhances decision-making capabilities, leading to improved performance and competitive advantage. By integrating analytics with digital technologies like AI, IoT, and blockchain, organizations can optimize operations, reduce costs, and enhance resilience [10, 23, 37, 36, 83].

4 Enabling Theory and Digital Techniques

4.1 Digital Techniques and Innovation

Innovative digital techniques are pivotal in transforming supply chains, enhancing efficiency, agility, and resilience. Blockchain technology and smart contracts automate and secure contractual agree-

ments, providing a robust framework for managing complex supply chain processes through reliable data exchanges [34, 79]. Blockchain's decentralized architecture significantly enhances data security, underscoring its transformative potential.

Machine learning solutions bolster supply chain resilience by offering predictive tools that manage disruptions effectively, such as those from the COVID-19 pandemic and geopolitical conflicts. These tools facilitate accurate product availability forecasting and enhance decision-making, reducing transportation and inventory costs. By employing regression models like Random Forest and Gradient Boosting Machine, organizations can navigate uncertainties, optimize logistics, and implement proactive risk management strategies, minimizing disruption impacts [1, 16, 61, 68, 84]. Additionally, multi-objective optimization models enhance decision-making in complex reverse supply chain networks, showcasing artificial intelligence's strengths in supply chain transformation.

Causal Machine Learning (CML) techniques provide innovative solutions, offering clear causal insights that inform strategic decision-making in supply chains. Grounded in Data Governance (DG) principles, CML enhances data usability and facilitates informed decision-making in Operations and Supply Chain Management (OSCM) by addressing challenges like data quality and accessibility. By integrating DG practices, organizations can leverage data-driven insights for improved operational efficiency and strategic planning in the context of Industry 4.0 [10, 23, 85, 26, 86].

Smart contracts within blockchain frameworks streamline collaboration by reducing intermediaries and enhancing transparency. The categorization of enablers into factors influencing digital transformation underscores the strategic importance of aligning digital initiatives with organizational goals. Training in ICT skills is vital for enterprises to leverage digital technologies effectively [7].

Digitalization metrics enable organizations to assess their digital progress and investment effectiveness, highlighting techniques that drive performance improvements. By implementing these tools strategically, organizations can achieve greater efficiency and resilience, supporting long-term objectives in a digitalized world. Categorizing current methods into stages like information sampling, integration, and causal reasoning emphasizes the need for technologies that support cognitive activities, further enhancing digital techniques' transformative potential [44].

The strategic implementation of digital techniques such as blockchain, machine learning, and smart contracts is crucial for driving transformation in supply chains. These innovations enhance operational efficiency and resilience while supporting organizations in achieving long-term strategic objectives in a digitalized world. A comprehensive framework for understanding digital transformation aligns stakeholders in the process, facilitating a cohesive approach to adopting digital innovations [8].

4.2 Frameworks and Theories in Supply Chain Resilience

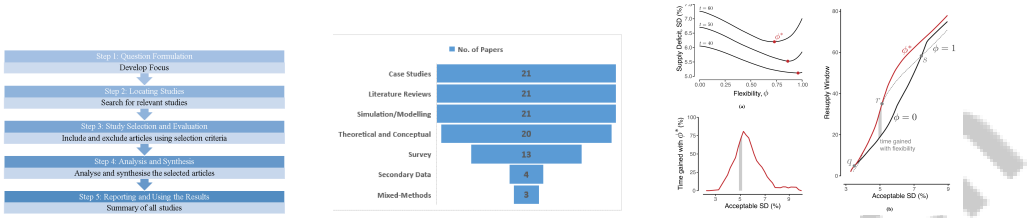
Theoretical frameworks are essential for understanding and enhancing supply chain resilience, providing structured methodologies to navigate modern complexities. The Resource-Based View (RBV) and Contingency Theory suggest that resource effectiveness in enhancing resilience is context-dependent [22], emphasizing the need to align resources with specific environmental conditions for optimal resilience strategies.

Dynamic Capability Theory highlights the importance of flexibility and adaptability in building resilience, advocating for organizations to develop capabilities to respond swiftly to changes and disruptions [87]. This aligns with 'extreme supply chain management' (ESCM), which categorizes research and practices in supply chain management to address extreme conditions and enhance resilience [88].

Holistic models integrating technological and managerial aspects are crucial for developing resilient supply chains. These models advocate for incorporating cultural attributes into digital transformation processes to ensure comprehensive resilience strategies [3]. Frameworks emphasizing interdependencies within supply chains highlight how resilience elements can vary across nodes, necessitating tailored approaches [21].

System-based and operation-based strategies enhance supply chain resilience, offering insights into diverse approaches necessary to address systemic and operational challenges [72]. These strategies underscore the need for a multifaceted approach, integrating high-level strategic planning with detailed operational adjustments for robust performance.

The discussed theoretical frameworks provide critical insights into supply chain resilience dynamics, outlining methodologies that enhance adaptability, flexibility, and robustness. They emphasize substituting goods within established supply chains to mitigate disruptions, as demonstrated through a comprehensive analysis of the US opioid distribution system. Essential resilience capabilities—anticipation, adaptation, response, recovery, and learning—are identified alongside managerial practices that support these capabilities, equipping policymakers and practitioners with tools to navigate supply chain disruption challenges [61, 59, 16]. Integrating these frameworks into strategic planning enables organizations to develop more resilient and sustainable supply chains.



(a) Steps in Conducting a Systematic Review[89]

(b) Research Methodologies in Education: A Comprehensive Analysis[59]

(c) Optimal Resupply Window and Supply Deficit in a Supply Chain with Flexibility[61]

Figure 3: Examples of Frameworks and Theories in Supply Chain Resilience

As illustrated in Figure 3, the integration of enabling theories and digital techniques forms a crucial foundation for developing robust frameworks in supply chain resilience. The first image outlines a systematic review process essential for synthesizing knowledge and identifying gaps in the literature, guiding future research directions. The second image categorizes various research methodologies, emphasizing the diversity of approaches applicable to studying supply chain resilience. The third image illustrates the interplay between flexibility and supply deficit, highlighting adaptability's critical role in enhancing resilience. Together, these examples showcase how theoretical frameworks and digital techniques can be harnessed to navigate and mitigate supply chain disruptions effectively [89, 59, 61].

4.3 Digital Techniques and Tools for Transformation

The integration of advanced digital techniques and tools is central to the digital transformation of supply chains, enhancing efficiency, transparency, and adaptability. The Material-Inventory Transportation (MIT) model minimizes production and transportation costs by optimizing material flows based on inventory levels across factories [18], exemplifying how digital techniques streamline operations through optimal resource allocation.

Blockchain technology enhances supply chain security and transparency. Private blockchain architectures combined with smart contracts and IoT devices significantly improve traceability and monitoring capabilities [46]. This integration facilitates efficient operations and ensures transaction integrity, supporting a more transparent supply chain process. The UAV and blockchain-based inventory management system (UBIMS) further exemplifies digital techniques' potential in transforming inventory management processes, ensuring operational transparency [27].

Quantum Monte Carlo methods, which integrate decision-maker risk preferences, enhance inventory management's accuracy and efficiency, demonstrating digital techniques' transformative potential in optimizing decision-making processes [29]. Process Mining (PM) techniques assess pre- and post-intervention phases, supporting continuous improvement and adaptation in supply chain processes [28].

Digital Twins of Organizations (DTOs) quantitatively assess the impacts of updates in Process-Aware Information Systems (PAIS) [45], enabling organizations to simulate and evaluate changes in real-time. The Service-Oriented Architecture (SOA) for the Quality4.0 platform emphasizes integrating various components to manage quality data effectively, ensuring data integrity and compliance [31].

Advanced simulation frameworks, such as the Integrated Hybrid Simulation Framework, combine system dynamics and discrete event simulation to model supply chains under non-stationary demand conditions, enhancing organizations' ability to anticipate and respond to fluctuating demand patterns

[39]. This framework underscores specific digital techniques' role in facilitating transformation through effective demand management.

The strategic integration of advanced digital technologies—such as blockchain, digital twins, and sophisticated simulation frameworks—is crucial for transforming supply chains. These technologies enhance data management, storage, and sharing while addressing critical SCM challenges like security, efficiency, and transparency. By leveraging blockchain's capabilities to increase accountability and reduce risks, alongside digital twins for process optimization, organizations can navigate modern supply chain complexities and drive innovation in smart manufacturing and logistics. This transformation is essential for companies seeking to remain competitive in a digital economy [90, 23, 37].

4.4 Integration of Digital Techniques in Supply Chain Processes

Method Name	Digital Integration	Information Architecture	Adaptability and Resilience
CSCM[53]	Information Technology	Communication Protocols	Dynamic And Flexible
FSC[61]	-	-	Supply Chain Resilience
BSCM[35]	Bitcoin Principles	Bitcoin's Data Structures	Adapt TO Disruptions

Table 1: Comparison of Digital Integration, Information Architecture, and Adaptability in Supply Chain Management Methods. This table delineates the specific digital technologies and strategies employed by various supply chain management frameworks, highlighting their focus on integration, information dissemination, and resilience. The methods examined include CSCM, FSC, and BSCM, each demonstrating unique approaches to enhancing supply chain operations through digital means.

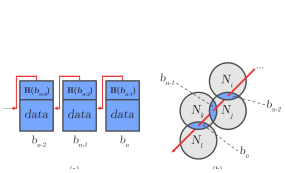
Integrating digital techniques into supply chain processes is pivotal for enhancing efficiency, flexibility, and resilience. Modern supply chains rely on advanced digital tools for real-time data sharing and collaborative decision-making, as emphasized by the Collaborative Supply Chain Management (CSCM) framework [53]. This framework highlights the importance of leveraging Information Technology to enable seamless communication and coordination among supply chain partners, optimizing operations and responsiveness.

A key aspect of integration involves categorizing information distribution strategies into architectures that support optimal dissemination. The Optimal Distributed Architecture (ODA) and the Optimal Distributed Architecture considering communicating Products (ODAP) provide structured approaches to managing information flow, ensuring efficient data sharing across the supply chain network [91]. These architectures are essential for maintaining data transparency and accuracy, crucial for informed decision-making and risk management.

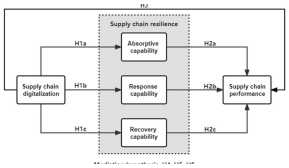
A survey of current methods in supply chain management underscores the necessity of flexibility, collaboration, and redundancy, particularly for food sector small and medium-sized enterprises (FSMEs) [67]. Organizing methods into stages of readiness, response, recovery, and adaptation emphasizes the need for dynamic strategies to accommodate changing conditions and disruptions. This approach aligns with relaxing upstream preferences of distributors to accept substitute goods, enhancing supply chain adaptability and resilience [61].

Integrating digital techniques into supply chain processes requires a multifaceted strategy encompassing advanced information technologies—such as AI, IoT, and blockchain—alongside frameworks designed for effective information dissemination and collaboration. This approach enhances coordination among supply chain stakeholders, optimizing operations through data sharing and advanced analytics, ultimately leading to improved efficiency and competitive advantage in the industry [53, 23, 10]. By adopting these techniques, organizations can enhance supply chain operations, improve resilience, and achieve sustainable competitive advantages in a digitalized world. Table 1 presents a comparative analysis of different supply chain management methods, focusing on their digital integration, information architecture, and adaptability to disruptions.

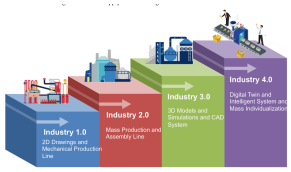
As illustrated in Figure 4, the integration of digital techniques in modern supply chain management is increasingly pivotal for driving efficiency and resilience. The first image captures the intricate dynamics of neural networks, highlighting machine learning's potential in refining supply chain operations. The second image presents a flowchart hypothesizing the interconnectedness of supply chain resilience with digitalization and capabilities such as absorptive, response, and recovery, emphasizing digital integration's multifaceted nature in enhancing performance. Lastly, the third



(a) Learning to Learn: A Deep Dive into the Dynamics of Neural Network Training[35]



(b) The image depicts a flowchart or diagram illustrating a hypothesis about the relationship between supply chain resilience and various components, including supply chain digitalization, absorptive capability, response capability, recovery capability, and supply chain performance.[92]



(c) The Evolution of Manufacturing Industry[90]

Figure 4: Examples of Integration of Digital Techniques in Supply Chain Processes

image traces the transformative journey from Industry 1.0 to Industry 4.0, showcasing the shift to sophisticated digital twins and intelligent systems, illustrating digitalization's profound impact on manufacturing and supply chain processes. Together, these visual examples encapsulate theoretical and practical advancements in digital supply chain integration, offering insights into future industry practices [35, 92, 90].

4.5 Applications of Enabling Theory in Digital Transformation

The practical applications of enabling theory in digital transformation underscore the strategic integration of digital technologies to enhance organizational resilience and sustainability. Enabling theory provides a framework emphasizing the socio-technical aspects of digital transformation, highlighting the importance of aligning digital initiatives with organizational culture and strategic objectives for optimized outcomes [13]. This alignment fosters a culture of continuous digital transformation and resilience planning, particularly within Industry 4.0 contexts [15].

Digital transformation initiatives benefit from enabling theory by incorporating cultural dimensions, such as those identified by Hofstede, to understand how digitalization influences strategic behaviors within organizations [75]. This understanding is essential for developing strategies that enhance resilience and promote environmental sustainability. The integration of decentralized data management and secure transaction protocols, exemplified by Bitcoin principles, illustrates enabling theory's practical application in supply chain management, enhancing transparency and efficiency [35].

Moreover, enabling theory supports the shift from predicting digital carbon footprints to focusing on mitigation strategies, emphasizing proactive environmental management in digital transformation initiatives [93]. This proactive approach is crucial for addressing questions regarding new digital technologies' integration into resilience strategies and understanding long-term disruption effects on supply chain performance [16].

Future research should develop robust frameworks for continuous digital transformation and resilience planning, emphasizing interdisciplinary collaboration to tackle scalability, privacy, and reliability challenges in digital initiatives [94]. Exploring the interplay between digitalization, consumer preferences, and sustainable practices in supply chains can provide valuable insights into digital transformation's broader impacts [95]. Establishing a data-driven culture within organizations is critical for sustaining digital transformation efforts, necessitating further exploration of data governance frameworks and emerging technologies' integration [26].

5 Digital Transformation in Supply Chain Management

5.1 Impact on Operational Efficiency and Resilience

Digital transformation significantly enhances operational efficiency and resilience in supply chains by integrating advanced technologies that streamline processes and improve decision-making. Industry 4.0 technologies, such as UAVs and blockchain systems, enable real-time inventory data collection, increasing speed and accuracy, which leads to cost savings and operational improvements [27, 28]. Blockchain technology enhances the reliability, traceability, and automation of business interactions, crucial for operational efficiency [34]. In healthcare supply chains, blockchain addresses data management challenges, fostering a patient-centric ecosystem that boosts efficiency and resilience [25]. The combination of blockchain with smart contracts ensures secure and efficient data management, strengthening the reliability and transparency of supply chain operations.

The Material-Inventory Transportation (MIT) model illustrates digital techniques' potential to optimize resource allocation, reducing production and transportation costs, thus enhancing efficiency and resilience [18]. Additionally, the Quality4.0 platform promotes reliable quality information exchange, fostering customer trust and providing a competitive edge in the European Steel Industry [31]. Quantum Monte Carlo methods improve decision-making under uncertainty by efficiently processing complex probabilistic models, vital for optimizing supply chain operations [29]. This optimization is crucial for achieving resilience in production, storage, and transportation activities [72].

Digital transformation acts as a catalyst for operational efficiency and resilience in supply chains by leveraging technologies such as artificial intelligence, big data analytics, IoT, and blockchain. These tools streamline processes and enhance communication, allowing organizations to adapt to disruptions like those experienced during the COVID-19 pandemic. By fostering capabilities such as absorptive, response, and recovery, digitalization improves performance in uncertain environments, enabling businesses to create value, mitigate risks, and maintain a competitive advantage [1, 10, 23, 92, 51]. Strategic implementation of these technologies, coupled with a culture of continuous improvement, positions organizations to navigate modern supply chain complexities effectively.

5.2 Role of Digital Skills and Data Integration

Digital skills and data integration are essential for transforming supply chains, enabling organizations to leverage advanced technologies and optimize operations. The integration of information and communication technologies (ICT) enhances data collection, processing, and sharing capabilities, which supports workforce development of digital skills necessary for managing and utilizing digital tools effectively [76]. The significance of digital skills in transformation processes is profound, as they empower employees to adapt to new technologies and contribute to continuous operational improvement. Organizations prioritizing digital competencies are better positioned to adopt advanced technologies like blockchain and artificial intelligence, which enhance operational efficiency and resilience. Research shows that digital transformation initiatives improve financial performance by streamlining processes and reducing costs, while blockchain offers promising applications in enhancing cybersecurity and privacy in decentralized systems. The interplay between digitalization and organizational agility highlights the importance of big data analytics and IT capabilities in navigating complex environments, thereby fostering a more adaptable and competitive framework [78, 38, 50, 9, 79]. Moreover, digital skills enable effective data analysis and interpretation, leading to informed decision-making and strategic planning.

Data integration is crucial for ensuring seamless information flow across supply chain networks, promoting collaboration and coordination among stakeholders. By consolidating data from various sources, organizations gain comprehensive insights into their operations, allowing for the prompt identification of bottlenecks and corrective measures. This approach enhances transparency and accountability, cultivating trust among partners through advanced technologies like blockchain, which provides a tamper-proof digital ledger for tracking product movement and transactions. Effective data governance practices address challenges of data integrity and traceability, fostering a more efficient and trustworthy supply chain environment [64, 24, 85].

5.3 Case Studies of Successful Digital Transformation

Successful digital transformation initiatives across industries illustrate the transformative potential of advanced technologies in enhancing supply chain operations. Walmart's use of blockchain for food traceability exemplifies this, significantly reducing the time needed to trace the origin of food products compared to traditional methods, thus improving transparency and consumer trust [37]. The Trading Agent Competition Supply Chain Management (TAC SCM) platform serves as another case study, offering a simulated environment where multiple agents operate, facilitating exploration of multi-agent architectures and their impact on supply chain management. This platform provides insights into how digital transformation can optimize decision-making and resource allocation in dynamic market conditions [96]. Moreover, integrating blockchain technology in IoT security and identity management presents significant opportunities for enhancing supply chain transparency and efficiency by addressing key security challenges, ensuring data integrity and authenticity across interconnected devices [79].

These case studies highlight a wide range of applications and benefits of digital transformation across industries, emphasizing how the strategic integration of technologies—such as artificial intelligence, blockchain, IoT, and cloud computing—can significantly enhance supply chain operations. These innovations streamline processes and create new value opportunities, driving substantial improvements in efficiency, responsiveness, and overall performance within the supply chain ecosystem [23, 10]. By leveraging these advancements, organizations can bolster their resilience, competitiveness, and adaptability in an increasingly digitalized business landscape.

6 Resilience Strategy Development

6.1 Balanced Resilience Strategies

Balanced resilience strategies are vital for sustaining operational stability in supply chains amid market fluctuations. Multi-sourcing dispersion enhances flexibility by diversifying supply sources, mitigating risks related to supplier dependency and market volatility [60]. This approach effectively manages disruptions, ensuring continuity in operations. In urban freight logistics, advanced cloud-based systems facilitate real-time decision-making and cost efficiency, optimizing resource allocation and streamlining operations [48]. The Material-Inventory Transportation (MIT) model illustrates the balance of resilience and efficiency by optimizing transportation planning, addressing inventory shortages and production failures [18]. In healthcare, resilience strategies focus on optimizing resource allocation and enhancing user engagement through personalized interventions [97].

A comprehensive approach integrating flexibility, efficiency, and adaptability is essential for balanced resilience strategies. Leveraging technologies such as big data analytics and cyber-physical systems, alongside strategic planning, enhances supply chain resilience through improved visibility and velocity. This ensures sustainable operations and competitive advantages in volatile markets, emphasizing anticipation, adaptation, response, recovery, and learning, particularly in light of disruptions like the COVID-19 pandemic [59, 1].

6.2 Blockchain and Decentralized Models

Blockchain technology plays a crucial role in developing decentralized resilience models within supply chains, enhancing transparency, traceability, and stakeholder coordination. It significantly reduces paperwork and improves tracking efficiency, particularly in international logistics [37]. In the food supply chain, blockchain tackles product traceability challenges, ensuring secure information flow [24]. The use of private blockchain technology and smart contracts in the oil supply chain exemplifies secure and traceable transactions, enhancing operational resilience and efficiency [46]. This approach automates processes and reduces intermediary needs, fostering trust among partners.

Decentralized resilience models are supported by the Income Sharing method, which utilizes blockchain for improved coordination among SMEs, enhancing adaptability to disruptions [98]. However, challenges in establishing trust and effective governance are crucial for industry-wide adoption of blockchain-based models [99].

6.3 Innovative Supplier Selection and Data Analytics

Data analytics enhances innovative supplier selection by providing insights for informed decision-making. Integrating data analytics into supply chain management allows systematic evaluation of supplier performance, aligning with strategic objectives [83]. In industries with complex dynamics, such as remanufacturing, data analytics aids in evaluating suppliers based on their capacity to manage diverse return types and product recovery processes [4]. This proactive approach to supplier management provides real-time insights into performance and market trends, enhancing resilience and agility [82].

6.4 Flexibility and Architectural Changes

Flexibility and architectural changes are critical for developing resilience strategies in supply chains, enabling adaptation to market conditions and effective disruption management. These strategies enhance operational flexibility and maintain competitiveness [41, 61, 59, 76]. Architectural changes involve integrating advanced technologies and innovative frameworks for real-time data analysis and decision-making. For example, a semantic-driven approach to maintenance digitalization improves activity robustness and compliance with GMP requirements [100].

Blockchain technology facilitates architectural changes by enabling decentralized systems that enhance transparency and traceability [64, 24, 10]. Leveraging blockchain and IoT enables resilient supply chains capable of withstanding disruptions and maintaining continuity through real-time monitoring and data sharing.

6.5 Collaboration and Information Sharing

Collaboration and information sharing are pivotal in enhancing supply chain resilience, offering advantages such as increased visibility, improved responsiveness, and strengthened partnerships. The Collaborative Supply Chain Management (CSCM) framework emphasizes seamless communication and coordination among partners, optimizing operations and responsiveness [53]. AI integration in reverse supply chain management exemplifies the transformative potential of collaboration, enhancing management of product returns and sustainable practices [4]. Transitioning from individual to collaborative resilience strategies improves overall supply chain performance [21].

Leveraging Industry 4.0 technologies, such as big data analytics and cyber-physical systems, significantly enhances visibility and responsiveness in supply chains. These advancements enable firms to anticipate, adapt, respond, recover, and learn from disruptions, fostering robust supply chains capable of withstanding challenges like those posed by the COVID-19 pandemic [16, 1, 59, 53, 41].

7 Case Studies and Practical Applications

Innovative technologies are essential for enhancing operational efficiency and decision-making in supply chain management. This section explores the practical applications of such technologies, particularly the integration of blockchain and digital twin technologies in Business Decision Modeling (BDM), which enhances interoperability and real-time data exchange, establishing a resilient and transparent supply chain framework.

7.1 Blockchain and Digital Twin Integration in BDM

The integration of blockchain and digital twin (DT) technologies in BDM represents a significant advancement in supply chain management, improving interoperability and real-time data exchange crucial for operational efficiency and informed decision-making. Case studies demonstrate how these technologies optimize business decision-making and revolutionize supply chain operations [101]. Blockchain's decentralized ledger enhances transparency and security, with smart contracts automating transactions to ensure compliance and reduce intermediaries, fostering trust among partners [102]. Complementing blockchain, digital twin technology enables real-time monitoring and scenario simulations, enhancing predictive accuracy in logistics and product availability through big data analytics and machine learning [84, 1]. The synergy of DT and blockchain ensures secure data collection from physical assets, offering a comprehensive view of supply chain activities. Diverse

industry case studies, such as a beverage company's bottling plant and a multinational wind energy firm, illustrate the transformative potential of integrating blockchain and DT in fostering efficiency and resilience [26].

7.2 Real-Time Resiliency Management During COVID-19

The COVID-19 pandemic posed unprecedented challenges to global supply chains, necessitating agile approaches for maintaining operational continuity. Digital technologies facilitated real-time data analysis and decision-making, enabling swift responses to emerging challenges [1]. Industry 4.0 technologies, such as IoT and AI, were pivotal in enhancing supply chain resilience, optimizing resource allocation, and fostering collaboration among partners [17, 41]. Blockchain improved transparency and traceability, crucial for monitoring goods and ensuring compliance with safety protocols, particularly in healthcare for vaccine distribution [5, 14]. The pandemic accelerated digital platform use for remote work and virtual collaboration, supporting operational resilience and laying the groundwork for robust future supply chains [15].

7.3 Implementation of CSCM Frameworks

Collaborative Supply Chain Management (CSCM) frameworks are vital for enhancing supply chain efficiency and responsiveness. These frameworks promote process integration and information sharing, optimizing operations and improving performance [53]. CSCM emphasizes collaboration, enabling organizations to leverage shared resources to achieve common goals. Advanced technologies like cloud computing and IoT support real-time data exchange and decision-making, enhancing visibility and transparency [36]. Blockchain technology secures data exchanges, providing a tamper-proof record that fosters trust among partners [37]. Case studies, such as in healthcare and the agri-food industry, illustrate successful CSCM framework implementations and their impacts on supply chain performance [25, 24].

7.4 Blockchain-Based Traceability in Olive Oil Production

Blockchain technology enhances traceability in olive oil production, ensuring transparency and accountability throughout the supply chain [80]. Blockchain's decentralized ledger provides a secure record of transactions, addressing food fraud and quality assurance challenges. This is crucial for consumer trust, as authenticity and quality are essential in olive oil production. Digital technologies, including machine learning and blockchain, enhance transparency and reliability of product quality information [9, 10, 31]. Implementing blockchain involves smart contracts that automate processes, ensuring adherence to regulatory conditions and reducing tampering risks. This fosters collaboration among partners, promoting sustainable and ethical practices in olive oil production, ultimately benefiting the agri-food sector through improved product quality assessment and stakeholder engagement [24, 80].

7.5 Digital Transformation and Resilience at JD.com

JD.com exemplifies how digital transformation enhances organizational resilience, particularly in response to COVID-19 disruptions. The company leveraged its digital infrastructure for operational continuity, investing in technologies that enabled real-time data analysis and decision-making [74]. AI and IoT integration improved supply chain efficiency and responsiveness, streamlining processes and facilitating real-time data analysis [23, 38]. JD.com's experience highlights the critical role of digital transformation in building resilient supply chains capable of withstanding disruptions. Despite its success, gaps remain in understanding the environmental impacts of digital transformation, necessitating further research for sustainable strategies [11]. JD.com's response to the pandemic illustrates the impact of digital technologies on supply chain resilience, highlighting advancements in big data analytics, automation, and real-time data integration [23, 74, 1].

7.6 Optimization of Water Sampling Processes at Merck Serono

The optimization of water sampling processes at Merck Serono demonstrates the practical application of digital transformation frameworks in enhancing supply chain operations. A semantic-driven approach to maintenance digitalization improved the robustness and efficiency of water sampling,

leveraging advanced digital techniques to streamline activities, reduce errors, and ensure compliance [100]. Real-time monitoring and data analysis facilitate proactive maintenance and decision-making, enhancing accuracy and reliability. This optimization reinforces the facility's commitment to sustainable practices and regulatory standards, ensuring a resilient supply chain capable of responding effectively to uncertainties [72, 101, 103, 10]. By implementing innovative frameworks like DataOps and integrating advanced technologies, organizations can significantly enhance operational resilience, fostering agility and risk-taking essential for competitive advantages [50, 59, 11, 51, 104].

7.7 Diverse Industry Applications

Digital transformation and resilience strategies have been widely adopted across various industries, enhancing operational efficiency and sustainability. In healthcare, blockchain integration improves data management and patient care by ensuring secure and transparent transactions [25]. In the agri-food sector, blockchain enhances traceability and accountability, addressing food fraud and quality assurance challenges [80]. The manufacturing sector benefits from advanced simulation frameworks and process mining techniques, optimizing production efficiency and resilience. Technologies like AI and IIoT empower manufacturers to adapt swiftly to market demands through real-time data integration [105, 23, 31, 9, 4]. In logistics, cloud-based systems and IoT devices enhance supply chain efficiency and responsiveness [48]. By integrating advanced digital technologies with strategic frameworks, organizations enhance efficiency, transparency, and resilience, fostering innovation and agility in navigating the digital landscape [38, 50, 9, 77, 51].

8 Challenges and Future Directions

8.1 Technological Integration Challenges

Integrating emerging technologies into supply chains involves complex challenges that affect the scalability and effectiveness of digital transformation. A significant hurdle is aligning new technologies with existing systems, which often requires extensive modifications [30]. Standardization and interoperability among diverse IoT devices and platforms are essential for seamless operations, yet remain challenging [30]. Decentralized data storage and incomplete information further hinder effective risk management and decision-making [17]. Disparities in digital adoption and cybersecurity threats within the EU exacerbate these issues, leading to vulnerabilities in supply chain networks [7]. Additional barriers include data overload on blockchain systems and high initial investment costs [24].

In the healthcare sector, integrating blockchain with existing infrastructures is challenging, particularly due to stringent regulatory requirements [25]. Organizations with lower digital maturity struggle with rapid technological advancements, highlighting the need for strategic planning and investment in digital capabilities [15]. Real-time data integration and inventory tracking across multiple factories demand sophisticated systems for seamless operations [18]. The use of technologies like UAVs and blockchain in Industry 4.0 also requires robust positioning systems, considering potential environmental signal interference [27].

Process Mining (PM) techniques offer insights into process inefficiencies, yet challenges remain in digitizing contracts, ensuring data privacy, and addressing poorly written smart contracts [28, 34]. High computational costs associated with implementing quantum algorithms add complexity [29]. Addressing these challenges requires a comprehensive approach that considers supply chain complexities, invests in digital maturity, and leverages advanced technologies to enhance resilience and competitive advantage. Unresolved issues with quality data exchange standardization and diverse data source integration also pose significant challenges [31]. Researchers continue to grapple with modeling uncertainties and disruptions, complicating supply chain performance analysis [72].

8.2 Human and Organizational Factors

Human and organizational factors significantly influence the successful implementation of digital transformation in supply chains. Resistance to change is a major obstacle, often intensified by psychological barriers and a lack of understanding of digital transformation benefits [53, 13]. Organizational culture, if not supportive of innovation, can further hinder progress [106]. The complexity of integrating diverse IT systems presents another challenge, compounded by the absence of formal procedures

for correcting data inaccuracies [44, 69]. Poor-quality data can lead to inaccurate predictions and ineffective solutions [107].

Slow adoption of agile methodologies and insufficient technology integration limit flexibility and responsiveness, particularly in sectors like public administration and SMEs [108]. These challenges are exacerbated by low data literacy levels among employees, necessitating extensive training. Future research should focus on developing frameworks that address these challenges, emphasizing supportive organizational cultures and enhanced data literacy. Addressing resistance to change and improving digital technology integration can significantly enhance organizational capacity to manage digital transformation complexities. A clear digital strategy supported by leadership is crucial for leveraging these technologies to drive efficiency and personalize customer experiences, achieving higher market valuations compared to competitors without a robust digital vision [109, 51].

8.3 Data Management and Quality

Data management and quality are critical challenges in supply chain operations, directly impacting decision-making reliability and overall performance. High-quality data availability is often constrained by fragmented supply chain networks and disparate systems [83]. This fragmentation leads to inconsistencies, complicating data integration and analysis. The complexity of supply chain models exacerbates these challenges, requiring comprehensive and accurate data inputs, often limited by organizational silos and lack of standardized practices. Poor data quality can result in erroneous conclusions and suboptimal decisions, with issues like data duplication and outdated information impeding efficiency and increasing costs [16, 10, 23, 59, 41]. Organizations must implement robust data governance frameworks to establish clear data collection, validation, and maintenance protocols.

Advanced technologies like blockchain and AI offer solutions to data management issues, enhancing transparency and integrity. Blockchain serves as a decentralized ledger, improving data traceability and integrity, particularly in Industry Cyber-Physical Systems (ICPS) [78, 65, 80, 64, 79]. AI automates data cleaning and analysis, reducing human error and enhancing data quality. Together, these technologies streamline supply chain management processes, fostering efficiency and consumer confidence through tamper-proof records and real-time auditing capabilities.

8.4 Economic and Resource Constraints

Economic and resource constraints pose significant challenges to digital transformation initiatives in supply chains. The substantial initial investment required for technologies such as blockchain, AI, and IoT is a primary economic barrier, encompassing procurement, deployment, maintenance, training, and system upgrades [7]. This financial burden can be prohibitive for SMEs lacking the capital for cutting-edge solutions [19]. Resource constraints also include the availability of skilled personnel to manage these technologies, with the digital skills gap being a critical issue [15]. This shortage impedes effective technology implementation and integration, limiting their potential impact on supply chain efficiency and resilience.

Economic constraints are exacerbated by the need to balance short-term financial pressures with long-term strategic goals. A focus on immediate cost savings can lead to underinvestment in digital transformation projects, which require sustained commitment to realize full benefits [12]. This tension between short-term performance and long-term investment presents a significant challenge for organizations aiming to enhance supply chain resilience through digital transformation.

8.5 Emerging Trends and Future Research Directions

Emerging trends in supply chain resilience and digital transformation emphasize integrating advanced technologies like AI, blockchain, and IIoT to enhance efficiency and decision-making. Future research should develop standardized protocols for IIoT, explore AI and machine learning implications in predictive maintenance, and examine digital transformation's socio-economic impacts in manufacturing [30]. Investigating mobile service frameworks for automation in supply chain processes is promising for enhancing efficiency.

Research should also focus on coopetition dynamics, automation's labor impact, and public-private partnerships to enhance resilience. Developing cross-industry blockchain standards and exploring interoperability solutions are crucial for seamless integration across diverse networks [16]. Empirical

validation of digital transformation models and exploring digital transfiguration implications across sectors can provide valuable insights.

Investigating resilience strategies in different contexts and industries, alongside collaborative approaches' effects on SCRES, is essential [16]. Agent-based modeling and simulation can enhance MIT model predictive capabilities in complex environments. Testing and validating digital transformation enablers and expanding literature reviews to include major conference papers can enrich understanding.

Exploring emerging digital technology trends and their economic implications is vital for understanding their impact on supply chain resilience and transformation. Future research should focus on developing standardized IT solutions for quality data exchange and innovative real-time data processing methods [31]. By addressing these trends and research directions, scholars and practitioners can contribute to developing resilient supply chains equipped to navigate modern business complexities. Additionally, applying Process Mining (PM) methodology across government departments can explore further improvements in service delivery efficiency [28].

9 Conclusion

The survey emphasizes the vital role of integrating digital transformation with resilience strategies to strengthen supply chain robustness and adaptability. It underscores the necessity for evolving management practices that leverage insights from recent disruptions to enhance resilience and foster innovation. Emerging technologies such as blockchain hold transformative potential across various applications, influencing broader supply chain management practices and offering promising solutions to inefficiencies. Effective data governance emerges as crucial for optimizing operations and enhancing decision-making, with recommendations aimed at improving governance frameworks. The survey also identifies opportunities for continuous improvement within the long tail of business processes, which traditional approaches often overlook. Addressing privacy and security challenges is paramount in the realm of digital transformation, necessitating robust strategies to mitigate associated risks.

The conclusion advocates for a shift in the software industry towards sustainability and responsibility, highlighting the need for internal reform to address unsustainable practices. A structured taxonomy is proposed to better understand and implement Industry 4.0 technologies in industrial settings, facilitating collaboration between academia and industry. Future research should explore the applicability of proposed frameworks across diverse cultural and economic contexts, developing more nuanced strategies for digital transformation. Additionally, the application of advanced data analytics, including knowledge graph completion methods, is emphasized for enhancing supply chain management and resilience. Key findings suggest that improving digital maturity is essential for organizational resilience and flexibility, enabling effective navigation of future crises.

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