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ORIGINAL RESEARCH

How Does Digital Intelligence Technology Enhance Supply Chain Resilience? Sustainable Framework and Agenda

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Abstract

In a highly competitive and risky business environment, firms are currently focusing on the construction and investment of sustainable supply chain. Supply chain resilience management (SCRM), as the key factor in building sustainable supply chain, is crucial for firms to gain a competitive edge and adapt to changes. SCRM involves establishing a flexible, adaptable and sustainable supply network under uncertainty and risk to ensure continuous supply and a rapid response to market demand. However, SCRM faces a series of challenging factors, including unstable market demand, natural disasters, and political uncertainty. Digital intelligence technologies, such as big data analytics, the Internet of Things, artificial intelligence, and blockchain, have strong potential to improve the visibility, forecasting capability, and decision support of the supply chain. However, despite having a plethora of literature on the instrumental role of digital intelligence technologies in building supply chain performance, the literature still lacks comprehensive thinking and a theoretical framework for the construction of digital intelligence technology applications and their empowerment mechanisms in developing SCRM. In this study, the underpinning elements and principles for the SCRM framework are first provided. Then, we analyze the empowerment mechanism and challenges of digital intelligence technology in SCRM, and put forward corresponding solutions. Afterward, some of the notable gaps are discussed, and a comprehensive direction for future research is proposed using the SCRM framework empowered by digital intelligence technology.

Keywords Supply chain management · Sustainable · Resilience · Digital intelligence technology

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1 Introduction

In recent years, increasingly complex supply networks, globalization, and external effects (e.g., natural disasters, virus outbreaks, and cyber-attacks) have repeatedly led to supply chain disruptions (Fan & Stevenson, 2018; Lechler et al., 2019; Kara et al., 2020; Gupta et al., 2021; Shen & Sun, 2023). Disruptions to supply chains can have significant economic impacts (Min, 2019; Dolgui & Ivanov, 2020). Preventing and mitigating the severe impact of these disruptions continuously remains a serious concern (Ivanov & Dolgui, 2021, 2022). For example, the unforeseen emergence of the COVID-19 pandemic has had a profound and far-reaching impact on enterprises worldwide. The rapid and massive scale of this pandemic has made it exceedingly difficult for businesses to foresee the extent of its consequences and the subsequent ripple effect (Ivanov et al., 2017; Kapoor et al., 2021; Lv et al., 2022). Consequently, global supply chains have been severely disrupted, leading to operational challenges and significantly affecting the production flow of numerous companies (El Baz & Ruel, 2021; Paul et al., 2021). To tackle such kinds of supply chain disruptions due to unexcepted events, firms are currently paying increasing attention to the construction and investment of sustainable supply chain, aiming to guard against disruptions, mitigate supply chain vulnerabilities, and control risks (Ivanov et al., 2021; Ivanov & Keskin, 2023; Yousefi & Tosarkani, 2024).

Resilience, the capacity of a system to adapt to changes and deal with emergencies while retaining the basic function and structure of the system, has emerged as an important support for building sustainable supply chain to manage supply chain risk and vulnerability (Ivanov, 2021; Ganesh & Kalpana, 2022; Ivanov, 2023; Jiang et al., 2024). Resilience encompasses various aspects of preparedness, adaptability, and recovery to effectively navigate through unpredictable and challenging circumstances, thereby ensuring seamless and efficient operations moving forward (Quayson et al., 2020). Specifically for supply chains, resilience refers to the preparedness of an organization or business to effectively manage risks, uncertainties, and disruptions that may arise from suppliers, customers or other business processes, as well as the supply chain integration mechanisms employed (Purvis et al., 2016; Min, 2019). To date, various definitions of supply chain resilience management (SCRM) are available in the literature, but researchers are not unanimous on one single definition. By summarizing existing theories (Ambulkar et al., 2015; Ali et al., 2017; Adobor & McMullen, 2018; Li et al., 2022; Rahman et al., 2022; Xue & Li, 2023), we can define SCRM as "the strategic utilization of the supply chain network to foresee disruptive events, react flexibly to these disruptions while retaining control over the structure and functionality, and ultimately transitioning to a post-event resilient operational state that may potentially surpass the pre-event conditions, thereby achieving a competitive edge." The primary objective of SCRM is to swiftly recover from unforeseen disruptions within the supply chain and ultimately restore or enhance its initial performance (Hohenstein et al., 2015; Adobor & McMullen, 2018). Therefore, firms must identify and assess the nodes for risks, their severity, and also their likelihood of occurrence to build resilient supply chains and determine how these risks can be detected (Dubey et al. 2021; Belhadi et al., 2024).

In practice, many resilience strategies have been suggested, encompassing a range of approaches, such as enhancing supplier reliability, establishing backup suppliers, fortifying critical infrastructure, maintaining reserved or excess capacity, holding safety stock, and promoting process flexibility (Zhalechian et al., 2018; He et al., 2019; Azadegan et al., 2020; Fadaki et al., 2020; Alikhani et al., 2021). Meanwhile, literature has shown that advanced digital intelligence technologies, such as artificial intelligence (AI), blockchain, big data analytics (BDA), and the Internet of Things (IoT), have provided a new way for organizations to enhance their resilience (Belhadi et al., 2019; Min, 2019; Govindan et al., 2020; Ivanov et al., 2021; Koot et al., 2021; Ivanov & Dolgui, 2022; Kayikci et al., 2022; Singh et al., 2022; Ivanov, 2023). An increasing number of firms have been employing advanced digital intelligence technologies in their supply chains to enhance their capacity for effective prediction, competence, transparency, and the capability to make quick decisions (Chen et al., 2015; Saberi et al., 2019; Gu et al., 2021). Numerous initiatives highlight the significance of digital-enabled technologies solutions in enhancing resilience (Ivanov et al., 2019; Koot et al., 2021; Spieske & Birkel, 2021; Dubey et al., 2023). For example, the application of IoT technology increases the intelligence of logistics and inventory management, enables real-time tracking of the location and status of goods, and improves the visibility and transparency of the supply chain (Birkel & Hartmann, 2020; Qader et al., 2022). AI and machine learning algorithms enable companies to automate many repetitive tasks and improve the efficiency of production and logistics (Gupta et al., 2021; Ganesh & Kalpana, 2022). The application of blockchain technology contributes to increasing the security and trust of the supply chain, reducing information asymmetry and prohibiting fraud (Singh & Singh, 2019; Belhadi et al., 2021; Li et al., 2022).

Despite the benefits of digital intelligence technologies in SCRM, many firms are encountering obstacles stemming from substantial investments and challenges associated with their deployment and integration (Stank et al., 2019; Hennelly et al., 2020; Etemadi et al., 2021), data privacy, security, and accuracy (Belhadi et al., 2024). For example, supply chain management involves the collection and sharing of a large amount of sensitive data, such as the data about the supplier's operations, the retailer's retailing/marketing and also the data about customer preference/profile in one supply chain. The parties in a supply chain will lose the edge on competition once the data are leakaged. Therefore, data security and privacy protection measures must be strengthened to prevent data leakage and abuse. In 2021, Bridewell Consulting revealed that during the previous year, approximately 86% of critical national infrastructure organizations encountered cyber-attacks targeting their industrial control systems. To ensure the protection of sensitive information and avoid negative consequences on economic, social, and political levels, it is essential for a geographically dispersed supply chain to incorporate a cyber-secure supply chain (Melnyk et al., 2022). In addition, supply chains involve multiple links and participants; thus, addressing issues such as technical standards, data formats, and system compatibility is necessary to achieve the integration and collaborative work of digital and intelligent technologies (Brintrup et al., 2020; Iftikhar et al., 2024).

The development of digital intelligence technologies is vital for research and practitioners alike because resilience will be expected of every business practice and company in the near future, and will be strongly connected to digital technologies and SCRM (Brintrup et al., 2020; Dolgui & Ivanov, 2020; Cui et al., 2023; Ning et al., 2023). However, to date, despite having a plethora of literature on the instrumental role of digital intelligence technologies in building supply chain performance, the literature still lacks comprehensive thinking and a theoretical framework for the construction of digital intelligence technology applications and their essential role in developing SCRM. We fill this gap to create a foundation for the current research state. The following two significant questions will be investigated in our study: (i) What are the underpinning elements and principles of building the SCRM framework? (ii) What is the role of digital intelligence technologies in uplifting SCRM? (iii) What are the knowledge gaps and limitations of existing literature, and what future research opportunities can be derived to advance knowledge in the field of digital intelligence technologies?

To examine the above questions, we use the critical thinking and theoretical framework of SCRM enabled by digital intelligence technology. First, we introduce the background and significance of SCRM, and focus on the underpinning elements and principles for building the SCRM framework. Then, we illustrate the empowerment mechanisms and challenges of digital intelligence technologies in SCRM and propose corresponding solutions. Afterward, we explore the future development trend and present possible innovation directions. Through the research and discussion in this study, we comprehensively understand the opportunities and challenges of digital intelligence technology enabling SCRM and provide useful enlightenment and suggestions for firms to build a strong and flexible supply chain in an uncertain market environment.

The paper is organized as follows. Section 2 describes the underpinning elements and principles of the SCRM framework. Section 3 illustrates the empowerment mechanisms and challenges of digital intelligence technologies and provides solutions accordingly. Section 4 elaborates on the further frontier research directions. Finally, Section 5 concludes this study.

2 Underpinning elements and principles for SCRM framework

Based on the aforementioned, we define SCRM as "the ability to proactively leverage the supply chain network for anticipating unexpected disruptive events, to respond adaptively regarding disruptions while maintaining control over structure and function such that transcending to a post-event robust state of operations, if possible, more favorable than the one prior to the event, thus gaining competitive advantage" (Ivanov et al., 2019; Li et al., 2023; Xue & Li, 2023). This section aims to explore and discuss the underpinning elements and principles essential for a comprehensive SCRM framework. An analysis of the current study was developed in accordance with the principles and elements described by previous literature to extend their proposal (Kamalahmadi & Parast, 2016; Thomé et al., 2016; Ali et al., 2017; Chowdhury & Quaddus, 2017; Kochan & Nowicki, 2018; Stone & Rahimifard, 2018; DuHadway et al., 2019; Hosseini et al., 2019; Vishnu et al., 2019; Conboy et al., 2020; Duong & Chong, 2020; Goldbeck et al., 2020; Shashi, Centobelli et al. 2020; Tucker et al., 2020; Ekanayake et al., 2021; Kaur & Singh, 2021; Nguyen et al., 2021; Paul et al., 2021; Ruel et al., 2021; Furstenau et al., 2022; Ivanov, 2022; Parast, 2022; Liu et al., 2023; Wu et al. 2022; Xue & Li, 2023; Zamani et al., 2023). Specifically, our proposal consists of four principles, each of which comprises various elements: (1) Absorptive (belief, readiness, velocity, and visibility); (2) Reactive (flexibility, contingency design, and diversification); (3) Restorative (reversibility, adaptability, and robustness); (4) SCRM(strategic leadership, understanding, collaboration, and learning and skill development). The relationship framework between elements and the principles is shown in Fig. 1.

The principle of absorptive entails the ability to absorb and endure unforeseen disruptions while mitigating the negative outcomes of such disturbances with minimal resources prior to the occurrence of disruptive events. Thus, the principle of absorptive reflects four

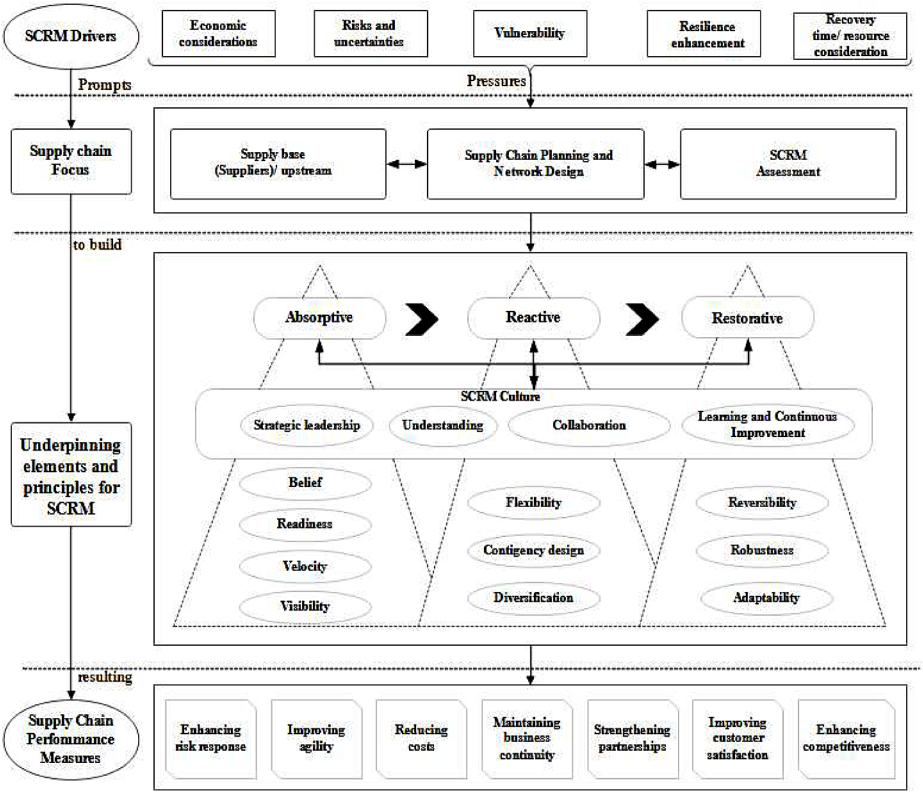

Fig. 1 Underpinning Elements of Supply Chain Resilience Framework. Based on Ali et al. (2017), Hosseini et al. (2019), Spieske and Birkel (2021), and Ganesh and Kalpana (2022)

elements: readiness, velocity, belief and visibility. In specific, readiness reflects to the capability of the supply chain firms to be prepared for all measures in the pre-disruption state suitable to reduce the probability of supply chain disruption and absorb its negative impact. Velocity refers to the capability of the supply chain to promptly detect potential issues and implement appropriate preventive and responsive actions to prevent or minimize their potential impact. Belief refers to the situation in which the supply chain members believe that their partners are willing and capable of fulfilling their responsibilities and making mutually beneficial decisions, thereby taking necessary actions proactively before the occurrence of any disruptive event. Visibility refers to that SCRM requires firms to be aware of the real-time situation of the entire supply chain, such that firms can make decisions and respond to risks in a timely manner by increasing the visibility of the supply chain.

The principle of reactive involves promptly adapting the course of actions and distribution of resources in response to potential risks, ensuring a proper response to disruptive events. This implies that firms possess the knowledge and capability to promptly modify their regular operations in order to effectively counter uncertainties in a volatile market environment. Therefore, the principle of reactive embodies three elements: flexibility, contingency design and diversification. Specifically, flexibility in SCRM requires firms to adjust their supply chain network and resource allocation quickly, including flexible production capacity, inventory management, and logistics transportation. Contingency design is the capability to resist the disturbing event by designing and managing the density, complexity, and node criticality of the supply network or replacing critical nodes in the presence of a disruptive event. Diversification refers to that supply chain firms should avoid over-reliance on one single supplier or region and instead build multiple supply sources and partnerships. When one supplier or region shuts down, firms can still acquire the necessary resources from other sources to reduce the influence of supply chain disruptions. Moreover, a diversified supply chain network helps reduce operational risk and enables companies to adapt to market changes and fluctuations in demand effectively.

The principle of restorative pertains to cost-effectively returning to its initial operational state by employing optimal strategies for promptly addressing risk shocks during the later phases of their occurrence. When absorptive and reactive cannot sustain the original operational state, it becomes imperative to promptly reinforce the principle of restoration. Therefore, the principle of restorative embodies three elements: reversibility, adaptability and robustness. Specifically, reversibility means that SCRM requires firms are capable to recover from a shock by applying various operations, including backup plans, alternative suppliers, and diversified supply chain strategies. Adaptability is the capability of the supply chain to formulate competitive strategies in response to market demands, potentially influenced by disruptions, enables it to regain or enhance its previous market share and overall position. Robustness is the capability of the supply chain to maintain its functions normally after the occurrence of a disruptive event.

The principle of SCRM culture is considered to be transversal to the development of resilient capabilities in supply chains, which reflects four elements: strategic leadership, understanding, collaboration, and learning and skill development. In specific, strategic leadership is the capability to lead the formulation, implementation, and assessment of risk mitigation tactics, engaging all essential teams within the organization to ascertain their advantages. Understanding refers to the capability of the supply chain to identify critical paths and potential bottlenecks, which can be achieved through modeling and mapping techniques. Collaboration means that SCRM requires close relationships with suppliers, partners, and customers. Firms can effectively cope with uncertainty through information sharing, risk sharing, and resource integration. Moreover, learning and skill development is the capability of the supply chain to analyze disruptive events thoroughly, including understanding their root causes and impacts, and implementing proactive measures to prevent their reoccurrence.

The principles and elements of resilience encompass a wide range of actions that supply chain should adopt when confronted with a disruptive event. The strategic implementation of these measures holds utmost significance in ensuring the recovery and stability of the supply chain. Supply chain firms can enhance their ability to adapt, recover, and thrive regardless of disruptions by understanding and implementing these elements and principles in SCRM. Moreover, firms can cope with various uncertainties and impacts, maintain normal operations, and provide customer value. The specific summary in this study is presented as follows.

1) Enhancing risk response: SCRM can help firms cope with various risks and uncertainties. Enterprises can reduce their dependence on one single source of supply by establishing a diversified supplier network and reasonable inventory management, thereby

reducing the risks caused by supply interruptions. In addition, supply chain resilience can help identify and assess potential risks in advance and take corresponding prevention and mitigation measures.

2) Improving agility: SCRM enables firms to adjust their supply chain processes quickly to adapt to market changes and demand fluctuations. Moreover, firms can quickly adjust product combinations and delivery methods to meet customer needs by adopting flexible production and logistics solutions. This flexibility can help firms gain advantages in a fiercely competitive market environment and quickly seize market opportunities.
3) Reducing costs: SCRM enables firms to better manage supply chain risk, reducing the risk of production disruptions and inventory overhangs, which helps reduce costs and improve the competitiveness of firms.
4) Maintaining business continuity: SCRM can help ensure business continuity of firms. Specifically, when a disruption event occurs at a certain node of supply chain, such as supplier bankruptcy or transportation interruption, a resilient supply chain can use alternative suppliers or transportation channels to ensure the continuous operation of the supply chain, thereby avoiding production disruptions and customer order delays.
5) Strengthening partnerships: SCRM requires firms to establish close cooperative relationships with suppliers and partners. Firms can enhance partnerships and improve the efficiency and effectiveness of the entire supply chain by jointly addressing risks and challenges.
6) Improving customer satisfaction: SCRM can ensure the timely delivery of products and meet customer expectations. Enterprises can provide excellent customer service and enhance customer loyalty and satisfaction by optimizing supply chain processes, reducing delivery time, and improving delivery accuracy. This improvement is crucial for the long-term success and sustainable development of firms.
7) Enhancing competitiveness: Establishing a resilient supply chain can provide a competitive advantage for firms. When other competitors are troubled, resilient firms can effectively cope with challenges and quickly recover to normal operations, which helps to enhancing the reputation of firms, increasing market share, and attracting additional partners and customers.

3 Digital intelligence technology and supply chain resilience

Digital intelligence technologies, such as BDA, IoT, AI, and blockchain, have strong potential to enhance supply chain visibility, predictive power, and decision support. Supply chain firms can successfully identify risks, optimize resource allocation, enhance collaboration, and enable rapid response and flexible adjustment by applying these technologies (Ivanov et al., 2019, 2021; Wu et al., 2020; Etemadi et al., 2021; Ganesh & Kalpana, 2022; Gupta et al., 2023; Ivanov, 2023). However, most firms currently face difficulties due to the costly investments and challenges related to their deployment and integration, privacy and security issues, data quality, and reliability. In this section, we investigate how digital intelligence technology empowers SCRM, challenges faced by digital intelligence technology empowering SCRM, and proposes corresponding solutions. The proposed framework for SCRM empowered by digital intelligence technology is illustrated in Fig. 2.

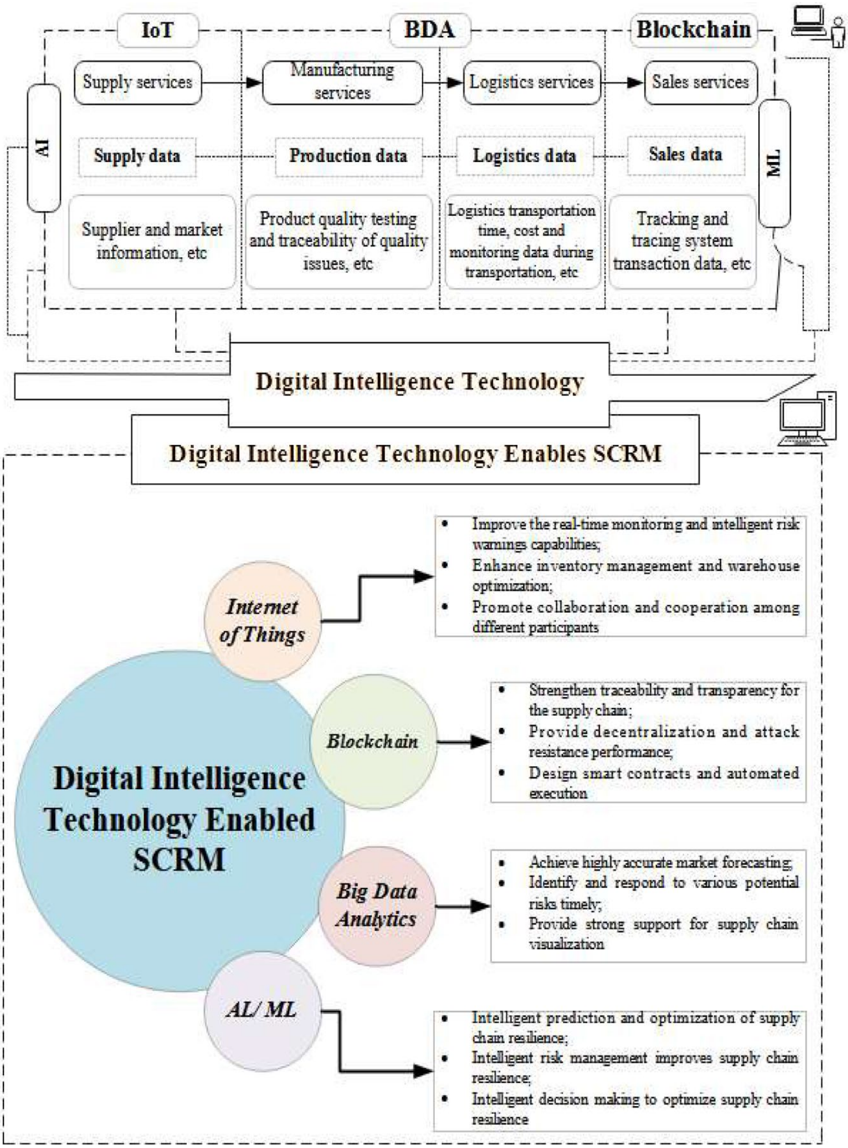

Fig. 2 Conceptual Framework of SCRM Empowered by Digital Intelligence Technology. Based on Ganesh and Kalpana (2022) and Modgil et al. (2022)

3.1 Digital intelligence technology enables SCRM

Digital intelligence technology empowers supply chain managers with unprecedented insights and capabilities, enabling them to effectively deal with risks and uncertainties in SCRM (Kara et al., 2020; Koot et al., 2021; Kayikci et al., 2022; Belhadi et al., 2024). Their combination provides companies with improved visibility, rapid decision-making, and opportunities for collaboration, thereby increasing the resilience and responsiveness of supply chains (Mandal, 2019; Min, 2019; Li et al., 2022; Modgil et al., 2022; Iftikhar et al., 2024). With the continuous advancement of technology, the potential for digital intelligence in SCRM is infinite. This subsection focuses on how digital intelligence technologies promote SCRM.

3.1.1 Internet of things (IoT)

IoT refers to a network system that connects various physical devices through the Internet and achieves data exchange and communication through technologies such as sensors, software, and networks (Birkel & Hartmann, 2020; Koot et al., 2021; Qader et al., 2022; Dubey et al., 2023). The application of IoT technology has shown remarkable potential, especially in the area of SCRM. Some key advantages of the IoT technology in SCRM are presented below.

First, IoT can improve the real-time monitoring and intelligent risk warnings capabilities of the supply chain. SCRM requires a timely understanding of the dynamics of each link in the supply chain to quickly respond to potential risks. IoT technology has brought innovations in real-time data monitoring and intelligent risk warnings systems to the supply chain. By installing sensors at key nodes, IoT devices can track and monitor key parameters such as storage conditions, temperature and humidity, and product status in real time. These data can be uploaded to the cloud platform in real time for analysis and processing. Supply chain managers can obtain real-time monitoring information through intelligent dashboards, discover abnormal situations in time and take corresponding measures. In addition, IoT technology can be combined with predictive analysis to provide early warning of potential supply chain risks and help companies make sufficient preparation, thereby enhancing the resilience of the supply chain.

Second, IoT can improve inventory management and warehouse optimization. Traditional warehousing and logistics processes often face issues such as information opacity and low logistics transportation efficiency, which can easily lead to supply chain disruptions or delays. IoT technology achieves intelligent warehousing and logistics management by labeling goods and logistics equipment and connecting them to the network. In such circumstance, logistics equipment can automatically identify goods and transmit their status information in real-time to a central database. Supply chain managers can track and manage the real-time location and status of goods through cloud platforms, thereby achieving visual monitoring of the entire process. In addition, IoT technology can be combined with artificial intelligence to optimize logistics path planning, improve distribution efficiency, reduce uncertainty in supply chain operations, and enhance supply chain resilience.

Third, IoT can promote collaboration among different participants in the supply chain. Suppliers, manufacturers, logistics service providers, and retailers can share real-time data through the IoT system. Such collaboration helps optimize processes and resource allocation in the supply chain and improve overall efficiency and responsiveness. For example, when a problem with the supply of a critical raw material emerges, the IoT system can automatically send a request to the supplier and coordinate solutions with them, thereby alleviating potential supply bottlenecks.

Overall, the application of IoT in SCRM provides organizations with increased real-time monitoring, intelligent warning, inventory management and warehouse optimization and collaboration among different participants. Through IoT technology, supply chain managers can effectively cope with unforeseen risks and challenges, reducing production interruptions, inventory waste, and delivery delays.

3.1.2 Blockchain technology

The traditional SCRM method may face several challenges, including information asymmetry, data tampering, middlemen abuse of power, and other issues. Blockchain, as a decentralized, transparent, and traceable technology, has the potential to play an important role in SCRM (Saberi et al., 2019; Li et al., 2022; Singh et al., 2022; Manzoor et al., 2024). This subsection explores how blockchain technology can improve the robustness and elasticity of the supply chain and illustrates its potential applications in SCRM.

First, transparency and traceability: Each link in the supply chain involves multiple participants, such as suppliers, manufacturers, logistics companies, and retailers. Traditional SCRM can easily lead to data silos and make it difficult to obtain a global data perspective. Blockchain can record and store various links and transaction information in the supply chain, ensuring transparency among all parties involved in the supply chain, such that everyone can view and verify transaction records, thereby reducing the risk of information asymmetry. Meanwhile, blockchain technology can provide a complete transaction history, increasing the reliability and efficiency of traceability and tracking in the supply chain.

Second, decentralization and attack resistance: In traditional supply chain management, the centralized control structure is easily affected by attacks or failures, paralyzing the entire supply chain. The decentralized nature of blockchain technology can distribute control to multiple nodes, improving the resilience and attack resistance of the supply chain. Even if one node is attacked, other nodes can continue to operate, ensuring the normal operation of the supply chain. For example, by building a decentralized logistics network, transportation companies can directly cooperate with suppliers and customers, avoid communication and costs in intermediate links, and improve logistics efficiency and flexibility.

Third, smart contracts and automated execution: Blockchain can achieve automated execution in the supply chain through smart contracts. A smart contract is a contract written in code that can automatically perform predetermined operations when specific conditions are met. The order, payment, and delivery processes in the supply chain can be automated through smart contracts, reducing human error and potential fraud risks and improving the efficiency and reliability of the supply chain. For instance, smart contracts can be used to automate logistics and shipping processes. When a certain condition is met (e.g., the goods arrive at the designated location or pass the quality inspection), the smart contract can automatically trigger the payment operation without human intervention, reducing the risk of payment delays. In addition, smart contracts can track and record key data such as temperature and humidity in the supply chain in real time to ensure the safety and quality of products during transportation.

Overall, the emergence of blockchain technology has introduced revolutionary changes to supply chain management. The distributed, transparent, and tamper-resistant characteristics of this technology endow the supply chain with robustness and resilience. Through functions such as transparency, traceability, and smart contracts, blockchain technology is expected to continue to derive innovation and development in SCRM.

3.1.3 Big data analytics (BDA)

In practice, BDA provides accurate and real-time data support for SCRM, helping enterprises respond quickly to changes and risks (Ivanov et al., 2021; Koot et al., 2021; Qader et al., 2022; Jiang et al., 2024). This subsection characterizes how BDA enables SCRM, including demand forecasting, risk identification and response, supply chain visualization, and decision support, to provide some practical ideas and methods for supply chain managers.

First, SCRM requires supply chain firms to quickly adapt to changes in market demand. Traditional forecasting methods are usually based on historical sales data and empirical judgments. However, such method is susceptible to interference from unexpected events, market fluctuations, and other factors especially in big data era. BDA, on the one hand, can comprehensively mine massive historical and real-time data; on the other hand, by applying advanced analytics methods like Large Language Model (LLM), BDA can better utilize the collected data so as to predict future demand trends. For example, a more accurate forecasting on market demand enables firms to take corresponding measures in advance, such as increasing raw material procurement, adjusting production plans, and optimizing inventory management, to better respond to market fluctuations.

Second, BDA can provide strong support for supply chain visualization. By integrating various types of data involved in the supply chain, such as supplier information, logistics and transportation data, inventory levels, etc., firms can monitor the operation of the supply chain in real-time and detect abnormal situations in a timely manner. For example, when the delivery delay or production failure of a key supplier occurs, the supply chain visualization system can immediately remind enterprise managers, enabling them to take timely response measures to avoid problem escalation. Moreover, supply chain visualization can help firms optimize and design their supply chain networks. By analyzing data from various links in the supply chain, firms can identify potential bottlenecks and risk points, optimize the structure and layout of the supply chain, and enhance overall resilience and risk resistance.

Third, SCRM requires timely identification and response to various potential risks to reduce losses and business interruption. BDA plays an irreplaceable role in this regard. By collecting and analyzing data from various links in the supply chain, firms can comprehensively understand the vulnerable links and key risk points of the supply chain. BDA can help firms build supply chain risk models and simulate and predict various possible risk events. These risk events may include natural disasters, raw material shortages, supplier failures, etc. Once a risk event occurs, firms can use BDA to monitor and evaluate the risk impact in real time, respond quickly, launch emergency plans, and find alternative supply channels to minimize the risk of supply chain disruption. For instance, in the event of an emergency, BDA can help firms quickly assess the scope and extent of the risk and formulate corresponding response strategies, such as adjusting supplier selection, altering inventory strategies, or starting backup supply chains.

Overall, employing BDA can help firms achieve highly accurate forecasting, timely risk identification and response, supply chain visualization, and decision support. Therefore, firms can improve the flexibility, adaptability, and responsiveness of their supply chains, thereby increasing supply chain resilience and addressing uncertainties. However, the role of BDA in SCRM must be completely developed. Therefore, firms should continuously improve data collection, storage, and analysis capabilities and closely integrate BDA with actual business to achieve optimization and innovation.

3.1.4 Artificial intelligence (AI) and machine learning (ML)

In the fast-moving world toward a digital future, AI/ML plays an essential role as one of the most prominent technologies (Gupta et al., 2021, 2023; Zamani et al., 2023). In recent years, research in SCRM has started reaping the benefits of AI-driven applications. An intelligent risk management methodology should aid an automated decision-making approach related to SCRM goals. Therefore, in this subsection, we discuss the empowerment mechanisms of AI/ML in SCRM and analyze its impact on supply chain efficiency, risk management, and decision support.

First, a key application of AI/ML in SCRM is intelligent forecasting. By utilizing ML algorithms, AI/ML can predict and optimize every link in the supply chain. For example, through the analysis of historical sales data, future demand trends can be accurately predicted, thereby helping firms rationally arrange production and inventory, and avoid supply chain breaks caused by demand fluctuations. In addition, AI/ML can optimize the transportation and distribution links in the supply chain. By monitoring traffic conditions and weather conditions in real time, the intelligent system can make real-time adjustments according to the actual situation to avoid logistics delays caused by traffic jams or bad weather. At the same time, the intelligent distribution system can perform intelligent sorting according to the order priority and address location, improve distribution efficiency, shorten delivery time, and increase the flexibility and rapid response capabilities of the supply chain.

Second, risks in SCRM are inevitable, such as interruption of raw material supply, natural disasters, changes in policies and regulations, etc. AI/ML can help firms better deal with these risks and improve the resilience of supply chains. In specific, AI/ML can discover potential risk factors in a timely manner through data analysis and prediction. By monitoring and analyzing data from various links in the supply chain, AI/ML can identify abnormal situations and issue timely warnings, enabling firms to take measures in advance to address potential risks. Moreover, AI/ML can evaluate the performance of the supply chain in the face of different risks through simulation and prediction. Firms can use AI/ML technology to establish a virtual model of the supply chain, test different response strategies in simulated scenarios, find the optimal solution, and improve the risk resistance of the supply chain.

Third, decision-making in SCRM is complex and changeable, and multiple factors and variables need to be considered comprehensively. AI/ML can provide intelligent decision-making support for SCRM, optimize the decision-making process, and improve the resilience of the supply chain. AI/ML can provide more comprehensive and accurate information to firms through data mining and analysis to help decision makers make informed decisions. For example, in procurement decisions, AI/ML can make a comprehensive assessment based on market demand, supplier stability, cost and other factors to provide the optimal procurement plan for enterprises. Moreover, AI/ML can optimize resource allocation and operational processes. For example, an intelligent scheduling system can automatically optimize production plans and logistics routes based on real-time data and algorithms, improve resource utilization, reduce waste, and enhance the adaptability and flexibility of the supply chain.

3.2 Challenges and solutions

Digital intelligence technology has remarkable potential in SCRM, providing real-time visualization, accurate forecasting and optimization, comprehensive risk management, and other functions. However, digital intelligence technology also faces some challenges in SCRM, such as data quality and reliability, privacy and security issues, data/information silos, and data integration. This subsection explores these challenges and proposes corresponding solutions.

1) Data quality and reliability: Digital intelligence technology relies on a considerable amount of data collection and analysis. However, issues with data quality and reliability are often encountered in the supply chain, which poses challenges to the application of digital intelligence technology. For example, dataset may contain errors or inaccuracies (e.g., record missing, data outliers), which will dilute the value generated by digital intelligence technology. However, regarding this issue, how to find a more efficient method on data validation and verification is quite challenging. Moreover, the data sources in the supply chain are diverse. The data formats and standards may also be inconsistent, leading to difficulties in data integration and analysis. Therefore, the following solution mechanisms are proposed in this study.

- Establishing a data quality management mechanism: Firms can establish a comprehensive data quality management mechanism, including data collection, verification, validation to ensure the accuracy and reliability of data;
- Promoting data standardization: Collaborate with suppliers and partners to develop unified data standards and formats, promoting data consistency and integration;
- Introducing intelligent data analysis tools: Utilizing technologies such as AI and machine learning to develop intelligent data analysis tools that can automatically detect and correct data errors, improving data quality and reliability.

2) Security and privacy protection: With the widespread application of digital intelligence technology, data and information involved in the supply chain face high-security risks and threats of privacy leakage. Each link in the supply chain involves sensitive business information, customer data, and personal privacy. Therefore, ensuring data and information security becomes an important challenge in SCRM. Hence, the following solutions are proposed in the current study.

- Strengthening network security measures: Adopting advanced network security technologies, including firewalls, intrusion detection systems, and data encryption, to protect data and information in the supply chain from malicious attacks and unauthorized access;
- Establishing permission and access control mechanisms: Establishing strict permission management and access control mechanisms to restrict access to data and information, ensuring that only authorized personnel can access and use relevant data;
- Compliance with privacy regulations and policies: Ensuring that businesses comply with relevant privacy regulations and policies, protect customer data and personal privacy, and avoid leakage and abuse.

3) Data/information silos and data integration: The supply chain involves multiple links and actors, each of which may use different intelligent technology tools and data systems. This phenomenon leads to a large number of data silos in the supply chain; thus, realizing effective integration and sharing of data from different links is difficult. Data silos may also lead to information lag, inaccurate decision-making, and low coordination efficiency. Therefore, the following solutions are proposed in this study.

- Data integration platform: Use a data integration platform or data lake technology to centrally store and manage the data of each link in the supply chain to facilitate data integration and access;
- Data sharing agreement: Reach a data sharing agreement with supply chain participants, clarify the scope, method, and security measures of data sharing, and promote information sharing and cooperation.

4) Technology dependency and system vulnerability: SCRM relies on complex technical systems and software applications. Vulnerabilities or attacks on these technical systems could lead to disruption of supply chains, loss of information, or the dissemination of false data. Thus, technology dependencies and systemic vulnerabilities are the major risks to supply chain resilience. Therefore, the following solution mechanisms are proposed.

- Diversified technology suppliers: Instead of heavily relying on a single technology supplier, choose a variety of technical solutions to reduce the risk of a single point of failure;
- Flexibility cultivation: Cultivate flexibility and resilience within the organization to enable quick adjustments and decision-making in the face of technical failures;
- Emergency Response Plan: Establish a robust emergency response plan to respond to system attacks or failures quickly and minimize losses.

5) Intelligent risk management: The wide application of intelligent technology in the supply chain increases its complexity and introduces new risks. For example, automated decision-making can lead to wrong decisions due to inaccurate data or flawed algorithms. In addition, smart sensors and IoT devices in the supply chain may face hardware failure or malicious attacks, thereby affecting their operation. Therefore, we propose the following solutions.

- Establish a risk assessment model: Develop a comprehensive intelligent supply chain risk assessment model, including data, technical, and operational risks, and corresponding countermeasures;
- Establish a risk identification and assessment mechanism, including regular risk inspections and an early warning system, to detect and assess supply chain risks in advance;
- Adopting diversified risk management strategies, such as diversified supplier selection, stocking, and backup supply chains, to reduce supply chain risk;
- Backup and recovery plan: Establish a data backup and recovery plan to ensure rapid recovery in the event of system damage or attack.

Overall, the application of digital intelligence technologies can improve the visibility, accuracy, and response speed of the supply chain, allowing firms to cope with uncertainty and shocks effectively. However, with the continuous advancement of technology, supply chain firms may face challenges such as data privacy, security, and integration. Therefore, firms should formulate a clear digital intelligence strategy to maximize the opportunities of digital intelligence technology in SCRM.

4 Frontier research agenda

The literature on SCRM is growing, but the understanding of this topic is far from mature, and numerous problems must be addressed, especially in the digital era. As described above, the elements of the SCRM framework and the challenges of digital intelligence technology enable SCRM and correspond to different risk categories. In this section, considering SCRM design and optimization, we discuss some of the notable gaps and propose further research directions.

4.1 Digital twin and supply chain resilience

With the rapid development of information technology, digital twin technology has been gradually applied in supply chain management to improve the resilience of supply chains. A digital twin is a technology that reflects and simulates a physical entity or system in real time through a digital model. In the field of supply chain management, digital twins can simulate the operation of all links in the supply chain, from suppliers to manufacturers, distributors, and final consumers, helping enterprises grasp the dynamics of the supply chain in real time to deal with uncertainties and shocks effectively. In future research, we can explore the relationship between digital twins and SCRM and the use of digital twins to improve supply chain resilience.

First, intelligent digital twin supply chain modeling and optimization: With the continuous development of digital intelligence technology, future digital twin supply chain modeling will be highly intelligent and refined. Traditional supply chain models are often based on static data and lack the capability to adapt to real-time data and dynamic changes. Future research should explore how real-time data and sensor information can be integrated into a digital twin model for real-time monitoring and prediction of supply chain status. The digital twin model can automatically optimize and make decisions using AI technology, thereby improving the response speed and resource utilization efficiency of the supply chain and enhancing its resilience.

Second, data security and privacy protection: With the gradual expansion of the application of digital twins in the supply chain, a considerable amount of sensitive data will be collected and processed. This data collection includes information on product production, transportation, inventory, and sales. Supply chain participants must share data to ensure the effectiveness of digital twins. However, this sharing strategy is risky for data security and privacy. Therefore, future research should focus on protecting the security and privacy of data in digital twins and using encryption technology, multilevel access control, and other means to reduce the risk of data leakage and abuse. Simultaneously, finding a balance between data sharing and privacy protection is also necessary. This balance allows different participants in the supply chain to share information reasonably while protecting their respective business secrets and intellectual property rights.

Third, cross-organizational collaboration and intelligent decision support: The supply chain usually involves collaboration among multiple organizations, including suppliers, manufacturers, and logistics companies. Digital twin technology can realize real-time data sharing and communication between these organizations, thereby achieving a high degree of synergy in the supply chain. Future research should focus on building a cross-organizational digital twin platform to facilitate information sharing and communication between parties. In addition, digital twins can provide highly accurate and real-time decisions through data analysis and intelligent decision support systems, helping supply chain managers make informed choices in the face of emergencies or risks.

4.2 Financial risk and supply chain resilience

With the continuous development of the global economy and the improvement of the degree of globalization, the impact of financial risks and supply chain resilience on firms has become increasingly prominent. This subsection aims to explore the relationship between financial risk and SCRM and propose future research directions.

First, correlation and measurement of financial risk and supply chain resilience: In a globalized and complex business environment, supply chain resilience is increasingly becoming a key factor for business success. However, the relationship between financial risk and supply chain resilience is not fully understood. Therefore, a notable direction of in-depth research lies in exploring the relationship between financial risk and supply chain resilience and quantifying their impact. This research can be conducted from the following aspects. (1) Analyzing the impact of financial risks on supply chain resilience, including but not limited to currency fluctuations, interest rate risks, credit risks, and other factors: By establishing a comprehensive indicator system, companies can effectively understand the resilience of their supply chains and assess potential threats to supply chain stability from financial risks. (2) Exploring the transmission of financial risk through various links in the supply chain, affecting the operation and resilience of the entire supply chain: Research can include the impact of financial risks on suppliers, logistics partners, and customers and how financial market turmoil can trigger ripple effects in supply chains. (3) Studying the effect of different risk buffer strategies on improving supply chain resilience: These strategies may include financial risk management tools (e.g., insurance and foreign exchange hedging), diversification of suppliers and customers, and building close partnerships. Companies can be provided with effective suggestions to improve supply chain resilience by comparing different risk buffer strategies.

Second, a global perspective on financial risk and supply chain resilience: Globalization will continue to develop comprehensively, and frequent international trade and investment activities will increase the interdependence of financial risks and supply chain resilience. Therefore, future research must explore the relationship between financial risk and supply chain resilience from a global perspective. This research can be conducted on the basis of the following aspects. (1) Cross-border risk transmission analysis: Analyze the transmission mechanism of financial risks among different countries and explore the linkage and interaction of global supply chains under financial risks. (2) Transnational financial regulation and coordination: Explore the cooperation mechanism of global supply chain finance regulation, strengthen international information sharing and cooperation, and reduce the systemic risk of global supply chain finance risks. (3) Supply chain diversification strategy: Research how companies can reduce financial risks through diversification of supply chain strategies, such as establishing a backup supplier network and reducing dependence on a single supply chain.

Third, technological innovation empowers financial risk and supply chain resilience: The introduction of new technologies will help improve the supervision and risk management of the financial system and improve the stability of the financial market. For example, blockchain technology can provide highly transparent and secure supply chain finance transactions; smart contracts can help simplify the contract fulfillment process; and big data analysis and forecasting technology can provide highly accurate supply chain finance risk prediction. However, technological innovation also introduces new risks and challenges. For example, the rise of virtual currencies and digital payment systems may cause financial regulatory complexity and regulatory loopholes, thereby increasing the instability of the financial system. The widespread adoption of AI and automation technologies could lead to mass unemployment and social instability, which, in turn, could affect the resilience of supply chains. Therefore, future research must deeply explore the dual impact of technological innovation on financial risk and supply chain resilience and propose corresponding policy recommendations and risk management strategies.

4.3 Emergency management and supply chain resilience

With the deepening of globalization and the rapid development of the economy and society, the impact of emergencies on the supply chain has become increasingly prominent. Emergencies may be natural disasters, war conflicts, public health crises, or even failures within the supply chain. These events will cause serious disruption and impact supply chain. The research on emergency management and supply chain resilience becomes crucial to ensuring the stable operation of the supply chain.

First, data-driven forecasting and decision support systems: Future research should focus on building highly accurate and efficient data-driven predictive models. Through technologies such as big data, AI, and machine learning, historical emergency, supply chain, and macroeconomic data can be comprehensively analyzed, and the type, time, and location of possible emergencies can be predicted in advance. Simultaneously, researchers should also develop corresponding decision support systems for different types of emergencies to help enterprises make rapid and accurate decisions in the face of emergencies to minimize losses and impacts.

Second, optimization of supply chain diversification and flexibility: Future research on supply chain resilience should focus on the optimization of supply chain diversification and flexibility. A diversified supply chain structure can reduce the risk of a single point of failure and improve the resilience of the supply chain. For example, multiple suppliers and production bases could be explored to address risks from a single supplier or region. Simultaneously, the improvement of the flexibility of the supply chain, including the rapid adjustment of production lines, the optimization of inventory management, and the flexible response to logistics and transportation, is crucial. Future research should focus on improving the diversification and flexibility of the supply chain with the goal of ensuring its efficiency.

Third, the establishment of cooperation and information-sharing mechanisms: Resilience in supply chains does not depend solely on internal preparations within the enterprise but also requires the support of external partners. Future research could explore establishing an information-sharing mechanism among supply chain partners. This mechanism includes information sharing with suppliers, logistics companies, government agencies, and other stakeholders. Through the timely delivery of information, emergencies can be effectively predicted and responded to. Simultaneously, studying the risk-sharing mechanism among partners to form a joint defense system for the supply chain makes it possible to respond to emergencies jointly. A close cooperative relationship can be formed on the basis of information and risk sharing, and the overall resilience of the supply chain can be improved.

4.4 Environmental sustainability and supply chain resilience

With the development of human society and the acceleration of globalization, environmental pollution, climate change, and resource depletion are becoming increasingly serious, which introduces considerable challenges to the stability and sustainability of the supply chain. This paper will explore the relationship between environmental sustainability and supply chain resilience and propose some research questions to provide implications for future supply chain management and environmental protection.

First, how does environmental sustainability affect supply chain resilience? Against the backdrop of increasingly severe global climate change, supply chains usually face risks such as natural disasters, resource shortages, and policy changes. The lack of environmental sustainability may lead to supply chain disruptions and delays, affecting the operations and profits of enterprises. Therefore, researchers can explore how supply chains can construct resilient strategies and measures under environmental uncertainty.

Second, how does supply chain resilience promote environmental sustainability? Enterprises with strong supply chain resilience can effectively adapt to and recover from external shocks without long-term or irreversible damage to the environment. These enterprises may prefer to adopt green and renewable resources to reduce carbon emissions and promote the circular economy. This preference aims to minimize the environmental burden while ensuring the stability of the supply chain. Researchers can explore the relationship between supply chain resilience and environmental protection and analyze the performance of resilient supply chains in environmental sustainability.

Third, how can policies and institutions promote the combination of environmental sustainability and supply chain resilience? Governments and international organizations play an important role in promoting environmental protection and supply chain management. For example, formulating and implementing environmental protection laws and regulations can help control the behavior of enterprises and promote the construction of green supply chains. Simultaneously, the stability and consistency of policies can also help improve the resilience of supply chains, enabling companies to cope with external risks effectively. Researchers can explore the interplay between different national or regional policies, supply chain resilience, and environmental sustainability.

Finally, the application of technological innovation in environmental sustainability and supply chain resilience: With the advancement of science and technology, several new technologies, such as the IoT, blockchain, and AI/ML, have been applied in supply chain management and environmental protection. These technologies can help improve the transparency and flexibility of the supply chain, reduce the waste of resources and energy, and help build an environmentally friendly and resilient supply chain network. Therefore, researchers can explore the application cases and effects of technological innovations on environmental sustainability and supply chain resilience.

5 Conclusion

With the continuous expansion and complexity of global supply chains, SCRM has become a key capability for firms when facing uncertainties and risks. Digital intelligence technologies, such as BDA, IoT, blockchain, and AI/ML, provide new solutions to achieve strong and flexible supply chain resilience. Digital intelligence technologies introduce numerous advantages to SCRM. However, despite having a plethora of literature on the instrumental role of digital intelligence technologies in building supply chain performance, the literature still lacks comprehensive thinking and a theoretical framework for the construction of digital intelligence technology applications and their empowerment mechanisms in developing SCRM. In this paper, we use critical thinking and a theoretical framework of SCRM enabled by digital intelligence technology. Specifically, we first propose the underpinning elements and principles for building the SCRM framework. Then, we illustrate the empowerment mechanisms and challenges of digital intelligence technology in SCRM and provide corresponding solutions. Afterward, we explore the future development trend and propose possible innovation directions. The research and discussion in this study aim to provide useful enlightenment and suggestions for firms to build strong, flexible and sustainable supply chains in uncertain market environments.

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