**How Does Enterprise Digital Transformation Impact Supply Chain Resilience: A Multi-case Study from China**

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**Abstract**

**Purpose -** Inspired by the paradoxical debate surrounding the impact of enterprise digital transformation (EDT) on supply chain resilience (SCR), this study categorizes EDT into two dimensions: depth and breadth, and investigates their respective impact mechanisms on SCR.

**Design/methodology/approach -** Based on the complex adaptive system (CAS) theory, this study conducts a multi-case analysis to construct a conceptual framework exploring the relationship between EDT and SCR.

**Findings -** This study identifies a conceptual framework that explains how EDT influences SCR through key internal and external factors. Specifically, the depth of EDT enhances SCR through empowerment capability, but this relationship is contingent on the alignment between EDT and environmental adaptability. When there is a misalignment, empowerment capability is weakened. The breadth of EDT plays a crucial role in strengthening SCR by fostering supply chain collaboration. This relationship is further enhanced by supply chain learning, where stronger learning capabilities amplify the positive impact of EDT breadth on collaboration. Furthermore, empowerment capability not only directly enhances SCR but also contributes indirectly by improving collaboration across the supply chain.

**Originality/value -** By differentiating between the depth and breadth of EDT, this study enhances comprehension of EDT and offers novel adaptive strategic approaches for enterprises to cultivate SCR. This study enriches the CAS theory and also offers a theoretical reference for elucidating the connection between EDT and SCR.

**Keywords:** Enterprise digital transformation; supply chain resilience; complex adaptive system theory; multi-case study

**Paper type:** Research paper

**1. Introduction**

In recent times, supply chains have faced escalating uncertainty due to external disruptions like the COVID-19 pandemic, the Sino-US trade conflict, and the Russia-Ukraine war, posing unparalleled challenges to supply chain operations and management (Chen et al. 2024). In response, enterprises are enhancing the supply chain resilience (SCR) through various measures to withstand potential impacts. SCR refers to the capacity to anticipate unforeseen events, respond to disruptions, and recover from them, ensuring the continuity of operations at the desired level of connectivity and control over structure and function (Ponomarov and Holcomb, 2009).

In the context of the digital economy, EDT has emerged as a fundamental tool for strengthening SCR (Faruquee et al. 2021). Specifically, EDT emphasizes the creation and capture of additional value through the integration of various digital technologies (Shi et al. 2024). Consequently, EDT can enhance the ability to perceive potential risks, enabling companies to effectively navigate various uncertainties. For instance, Procter & Gamble (P&G) employs advanced analytics and AI-powered tools to monitor supplier performance, track inventory levels, and identify potential risks (The Code Work Team, 2023). This enables the company to respond swiftly to unforeseen events, such as natural disasters and supply chain disruptions, thereby substantially strengthening SCR. However, practical evidence suggests that the impact of EDT on SCR varies significantly across companies. A McKinsey report indicates that despite the widespread adoption of digital technologies prior to the COVID-19 pandemic, only 21% of companies successfully established resilient supply chain networks (Li et al. 2022). A notable case is that of the confectionery manufacturer Haribo, which invested billions of dollars in 2018 to implement EDT solutions, such as SAP, into its business processes. However, due to the failure to assess the alignment between business processes and digital systems in a timely manner, the company experienced diminished flexibility and adaptability. As a result, Haribo faced challenges including distribution network breakdowns and inaccurate inventory management, ultimately rendering its supply chain more vulnerable. These disruptions led to a sales decline of approximately 25%, with periods in 2018 during which its products were unavailable in the market (Global Leaders Today, 2022).

From a theoretical perspective, there exists considerable debate among scholars regarding the impact of EDT on SCR. On one hand, many scholars argue that EDT can positively affect SCR. For example, Zhao et al. (2023) suggest that EDT enhances a supply chain’s absorptive and recovery capabilities, thereby promoting higher resilience levels. Additionally, digital technologies, as a critical element of EDT, can improve SCR by enhancing transparency, visibility, and responsiveness (Alvarenga et al. 2023). On the other hand, some studies express concerns that EDT may undermine SCR. For instance, Faruquee et al. (2021) argue that EDT may negatively impact joint problem-solving efforts, thus hindering the improvement of SCR. Furthermore, Yang et al. (2021) highlight that the integration of digital technologies could exacerbate supplier opportunism, weakening the collaborative capabilities between upstream and downstream supply chain entities, which ultimately impedes resilience during disruptions.﻿ Despite these varying perspectives, the mechanisms through which EDT influences SCR remain insufficiently understood, revealing a critical gap in the current literature. The complexity of constructing SCR through EDT necessitates a deeper and more comprehensive exploration of these mechanisms to fully grasp how EDT can both enhance and potentially hinder SCR.

Building on the aforementioned practical cases and theoretical discussions, this study seeks to address the following research questions: What are the specific mechanisms through which EDT influences SCR? Furthermore, how can EDT be effectively leveraged to enhance SCR? To bridge this research gap, we adopt Complex Adaptive Systems (CAS) theory as a theoretical lens to gain a deeper understanding of this intricate relationship. CAS theory explains the evolution of complex systems through continuous interactions among system entities and their environment, paralleling how enterprises navigate internal operational risks and external disruptions. Based on this framework, we focus on three key characteristics of CAS that manifest in the interaction between EDT and SCR: adaptation, self-organization, and emergence. First, in line with the adaptation principle of Complex Adaptive Systems (CAS) theory (Holland, 2006), firms continuously engage in interactive behaviors to adjust to their environments. Accordingly, we analyze how EDT enables firms to adapt to internal operational dynamics, thereby strengthening SCR. Second, following the self-organization principle of CAS theory, supply chain participants autonomously adjust their activities based on real-time information, allowing them to respond swiftly to market fluctuations. In this regard, we explore how firms leverage data sharing, technological infrastructure, and managerial expertise to strengthen supply chain collaboration. Finally, consistent with the emergence principle of CAS theory (Palmberg, 2009), interactions among supply chain participants contribute to supply chain learning, enabling firms to identify inefficiencies and enhance collective problem-solving. This continuous learning process helps maintain the stability and functionality of the overall system. By integrating these three dimensions, this study seeks to develop a comprehensive theoretical framework that clarifies the mechanisms through which EDT influences SCR.

This study conducts an exploratory case study based on the SCR practices of four Chinese companies. The findings reveal that EDT influences SCR through two distinct pathways. First, through the pathway of “the depth of EDT - empowerment capability - SCR”, firms strengthen their internal capabilities, such as resource integration and process optimization, which in turn enhance SCR. Notably, the effectiveness of this relationship is contingent upon environmental adaptability, suggesting that firms with greater adaptability can better leverage the depth of EDT to reinforce resilience. Second, through the pathway of “the breadth of EDT - supply chain collaboration - SCR,” EDT facilitates collaboration among supply chain members, enabling a collective response to external disruptions and enhancing overall resilience. Importantly, this relationship is moderated by supply chain learning, indicating that firms with higher levels of learning capability can more effectively translate EDT breadth into strengthened collaboration. Furthermore, empowerment capability not only has a direct positive impact on SCR but also indirectly enhances SCR by fostering supply chain collaboration.

The theoretical contributions of this study are threefold. First, this study advances the understanding of EDT by moving beyond the conventional one-dimensional perspective that primarily focuses on the application of digital technologies (Cenamor et al. 2017; Liu et al. 2023; Dubey et al. 2024; Liu et al. 2025). Instead, drawing on the concepts of EDT depth and breadth (Lu et al. 2024), we propose a more nuanced framework that delineates its multifaceted impact on SCR, while also identifying the boundary conditions that shape this relationship. Second, unlike conventional studies that categorize SCR into predictive, responsive, and recovery capabilities (Katsaliaki et al. 2022; Ivanov, 2023), this research adopts a more integrative perspective by examining how EDT actively shapes SCR dynamics. Our findings reveal that the depth of EDT fosters internal empowerment by enhancing resource integration and process optimization, thereby strengthening a firm’s capacity to respond to risks. Meanwhile, the breadth of EDT facilitates cross-organizational collaboration and supply chain adaptability, enabling more agile and coordinated responses to external disruptions. Finally, by grounding our analysis in CAS theory, this study underscores the pivotal role of adaptability, self-organization, and emergence as key mechanisms through which EDT enhances SCR. It extends CAS theory by demonstrating how EDT not only enables firms to navigate complexity but also fosters an evolving supply chain ecosystem capable of continuous learning and resilience-building.

The paper is organized as follows: Section 2 reviews key constructs like SCR, EDT, and CAS theory. Section 3 outlines the methodology. Section 4 presents case descriptions and within-case analysis. Section 5 covers cross-case analysis and proposition development. Section 6 introduces the theoretical framework and its implications. Section 7 summarizes findings, discusses limitations, and suggests future research directions.

**2. Literature Review**

**2.1 SCR**

The concept of SCR was initially defined as the ability of a supply chain to return to its original state or an even better state after disruption (Christopher et al. 2004). The currently used definition for SCR is “the adaptive capacity to anticipate unforeseen events, respond to disruptions, and recover from them, ensuring the continuity of operations at the desired level of connectivity and control over structure and function” (Ponomarov and Holcomb, 2009).

Existing studies have explored SCR from multiple perspectives, focusing on its antecedents, mechanisms, and outcomes (Shi et al. 2024). Some scholars examine how firms utilize exploitative and explorative information technology to enhance SCR through collaboration with supply chain partners (Gu et al. 2021). Others investigate the impact of information technology capability and supply chain collaboration on different types of SCR (Zhou et al. 2024). Additionally, research has explored the role of governance mechanisms in shaping SCR based on information processing theory (Lu et al. 2024). Beyond theoretical discussions, empirical studies have analyzed real-world SCR practices. For instance, Tukamuhabwa et al. (2017) identify key threats to SCR in developing countries, demonstrating how disruption risks, resilience strategies, and outcomes interact in complex and nonlinear ways. Similarly, Butt (2021) investigates how purchasing and distribution firms mitigated supply chain disruptions during COVID-19, while Shen and Sun (2023) use JD.com’s operational data to examine the challenges faced by retail supply chains in China.

Despite these advancements, research on the relationship between enterprise digital transformation (EDT) and SCR remains fragmented. While some studies have explored specific technological interventions, they often fail to capture the multidimensional nature of EDT and its varying effects on SCR. Moreover, there is limited understanding of the mechanisms through which EDT influences SCR and the boundary conditions that shape this relationship. Addressing this gap, our study seeks to provide a more nuanced perspective by distinguishing between different dimensions of EDT and investigating their respective roles in enhancing SCR.

**2.2 EDT and SCR**

EDT refers to a fundamental change process facilitated by the innovative utilization of digital technologies alongside the strategic deployment of essential resources and capabilities, aiming to significantly enhance an entity and redefine its value proposition for its stakeholders (Gong and Ribiere, 2021). Existing studies present mixed views on the impact of EDT on SCR. Some scholars argue that EDT may not always enhance resilience. For example, Faruquee et al. (2021) suggest that EDT can undermine joint problem-solving, ultimately weakening SCR. Similarly, Yang et al. (2021) caution that digital technologies may exacerbate supplier opportunism through information integration, leading to a decline in collaborative capabilities between supply chain partners. Dubey et al. (2023) further argue that EDT’s effectiveness in enhancing SCR depends on firms’ adaptability—without the ability to realign organizational structures with changing environments, EDT could fail to improve resilience. Conversely, other studies identify a positive relationship between EDT and SCR. For instance, Zhao et al. (2023) suggest that EDT enhances SCR by strengthening absorptive capacity and recovery capabilities. Yin (2023) argues that effective resource allocation is key to ensuring EDT contributes to resilience. Similarly, Shi et al. (2024) find that EDT improves the stability of manufacturing supply chains through high-quality information disclosure and robust internal governance mechanisms.

While these studies provide valuable insights, they tend to conceptualize EDT primarily as a technological investment. However, recent literature suggests that EDT is not merely about adopting individual technologies but rather the interplay between technological innovation and organizational transformation (Li et al. 2022). An oversimplified view of EDT may obscure the potential synergies among different technologies and their varied effects on SCR. In reality, firms may pursue different EDT strategies, prioritizing either deep investments in specific digital capabilities or a broad application of multiple technologies across the supply chain.

To address this complexity, scholars have proposed distinguishing between EDT depth and breadth (Lu et al. 2024). EDT depth refers to the extent of digital technology integration within an enterprise, reflecting intensive investments in technological infrastructure and organizational restructuring (Yang et al. 2023). In contrast, EDT breadth captures the scope of digital technology applications across the supply chain, highlighting the role of inter-organizational digital connectivity (Yin et al. 2023). As such, this study seeks to bridge this gap by adopting a two-dimensional perspective on EDT, offering a more comprehensive understanding of how different aspects of digital transformation influence SCR at multiple levels.

**2.3 Empowerment capability and supply chain collaboration**

Empowerment capability refers to a firm’s ability to enhance supply chain decision-making and customer experience by providing technical support and resource integration to other supply chain members (Liu et al. 2022). Prior research suggests that digital technologies contribute to empowerment capability. For example, Liu et al. (2022) find that emerging technologies facilitate information accuracy and decision-making, while Alvarenga et al. (2023) highlight the role of supply chain memory—the accumulation of knowledge on how Industry 4.0 technologies affect disruption management—in strengthening empowerment. Dubey et al. (2024) further argue that integrating digital transformation within alliance management frameworks enhances supply chain capabilities by promoting coordinated decision-making.

On the other hand, supply chain collaboration involves the exchange of information, resources, and knowledge among supply chain entities to achieve mutual goals and enhance overall efficiency (Aarikka-Stenroos et al. 2022). Scholars have extensively studied different methods, pathways, and effects of collaboration on supply chain performance. Some research also explores the interplay between empowerment capability and collaboration. For instance, Liu et al. (2021) confirm a positive correlation between empowerment capability and collaboration within logistics ecosystems. Glenn Richey and Autry (2009) argue that firms should move beyond isolated technological investments and instead leverage empowerment as a means of fostering collaborative advancements.

Moreover, empowerment facilitates optimal resource allocation, ensuring supply-demand alignment and enhancing supply chain efficiency (Pessot et al. 2023). It also builds confidence among supply chain members by equipping them with essential skills and tools. Firms can strengthen their partners’ expertise through training, technical assistance, and digital resource sharing (Gu et al. 2021). However, the extent to which empowerment and collaboration mediate the EDT-SCR relationship remains underexplored, particularly in the context of varying EDT depth and breadth.

**3. Research methodology**

**3.1 Research philosophy**

We adopt an interpretivist approach for our research due to the complex nature of constructing SCR through EDT, which is difficult to analyze through measurement alone. Interpretivism enables a nuanced exploration of theoretical dimensions while accounting for the diverse ways companies implement EDT based on their unique environments and resources (Liu et al. 2024). By conducting in-depth interviews and observations, we gain a richer understanding of each case (Voss et al. 2002). Furthermore, given the ongoing debate in the literature regarding EDT’s impact on SCR, a multiple-case study approach allows us to uncover previously unexplored factors and develop new theories grounded in real-world evidence (Eisenhardt, 1989; Yin, 2013).

CAS theory provides a valuable framework for understanding how EDT enhances SCR by fostering adaptability, self-organization, and emergence in response to environmental uncertainties (Holland, 2006). Adaptability reflects an enterprise’s ability to adjust to dynamic environments. EDT strengthens adaptability by enabling firms to process real-time data, anticipate risks, and implement proactive adjustments, enhancing resilience amid disruptions. Self-organization refers to decentralized coordination among supply chain entities (Surana et al. 2005). EDT facilitates this by improving information sharing, synchronizing decision-making, and fostering dynamic collaboration, allowing supply chain partners to respond collectively to disruptions and optimize resources. Emergence describes how complex system behaviors develop from local interactions (Palmberg, 2009). EDT promotes emergence through supply chain learning, where firms accumulate knowledge, refine best practices, and iteratively improve SCR. Digital tools enable real-time analytics and feedback loops, helping firms detect patterns, predict risks, and enhance long-term resilience.

By viewing EDT through the lens of CAS theory, we identify two key mechanisms through which it strengthens SCR: enhancing internal adaptability to mitigate operational risks and fostering supply chain coordination to counter external disruptions. This perspective highlights the role of digital transformation in shaping adaptive, self-organizing, and learning-driven supply chain systems.

**3.2 Case selection**

To ensure that this multi-case study covers different industries, we selected companies from China’s manufacturing and logistics services sectors. On the one hand, in the context of the Sino-US trade conflict and the Russia-Ukraine war, China’s supply chains, particularly those in manufacturing, confront numerous resilience challenges (Zhang et al. 2023). To this end, our sample cases include manufacturing companies. On the other hand, under the impact of the epidemic, China’s service industry has also been severely impacted and faces severe challenges of building SCR (Ge et al. 2020). As the main carrier of business flow, the logistics service industry faces urgent needs in improving the SCR based on EDT. Therefore, our sample cases also include logistics service companies. Furthermore, Sanders (1982) suggested that the optimal number of cases should be 3-6. Considering that the topic of SCR is related to some subdivisions with high division of labor, we selected the most representative home appliance and new energy vehicle manufacturers in the manufacturing sector, as well as e-commerce logistics and international maritime logistics companies in the logistics services sector. Following Liu et al. (2021), the screening criteria for selecting sample cases are as follows:

(1) Typicality: The selected companies are well-established, each with over five years of operational experience, and hold a leading market share within their industry segments.

(2) Accessibility: The selected companies had senior executives who were available for interviews, ensuring access to firsthand insights on EDT and SCR initiatives. Furthermore, we ensured that relevant data from supply chain partners could be obtained, allowing for a more comprehensive understanding of inter-firm collaboration.

(3) The selected companies differ across multiple dimensions, including industry segments, EDT implementation models, and stages of SCR development.

[Insert Figure 1 here]

Our study employs a theoretical sampling approach to identify typical cases of SCR construction through EDT (Gong et al. 2018), as depicted in Figure 1. Referring to the 2022 revenue rankings, we initially shortlisted the top three most influential companies in each sector and secured interview permissions from seven companies through telephone contact. Following preliminary discussions and adhering to the principle of differentiation, we ultimately selected one company from each of the four sectors. Detailed information on these companies is presented in Table 1.

[Insert Table 1 here]

**3.3 Data collection**

To ensure comprehensive insights, we employed a purposeful sampling strategy, selecting interviewees based on their expertise, roles, and direct involvement in EDT and SCR initiatives. Each company provided senior executives overseeing digital transformation, supply chain management, or resilience strategies. Additionally, we included key project team members who played a central role in implementing EDT. This approach ensured a balanced perspective from both strategic decision-makers and operational managers. Data collection included three aspects: (1) initial interviews with senior management; (2) semi-structured interviews with members of the senior management team; and (3) secondary data sources. Specifically, first, initial interviews with senior managers provided an overview of the companies’ development, EDT practices, and cases illustrating the impact of EDT on SCR. Key factors influencing SCR were identified through these discussions. Second, semi-structured interviews were conducted using a detailed protocol, lasting 30 to 60 minutes on average, with some extending up to 2 hours. Following the “24-hour rule”, interview details were recorded promptly, and ambiguous responses were clarified. Finally, secondary data, including industry reports and publicly available company information, were analyzed to supplement the findings and offer a comprehensive perspective on EDT and SCR.

In summary, two rounds of interviews were conducted from March 2023 to August 2024. The first round, held between March and October 2023, focused on understanding the EDT initiatives implemented by senior executives or project teams and their impact on SCR. The interview protocol and questions were designed to explore various constructs in depth. The second round, conducted in August 2024, aimed to collect any missing data from the first round and validate the proposed framework with senior executives. Additional interview details are provided in Appendix D.

**3.4 Data analysis**

Based on the CAS theory, a research framework is established to systematically study our cases. First, in alignment with the adaptation concept of CAS theory (Holland, 2006), enterprises engage in interactive behaviors to adapt to their environments. Consequently, in the process of building SCR, we examine the role of EDT from the perspective of the firm's adaptation to its internal environment. Second, according to the self-organization concept of CAS theory, participants within the supply chain spontaneously adjust their activities based on real-time information to quickly respond to market demands. Thus, in examining the relationship between EDT and SCR, we focus on how enterprises utilize data sharing, technological support, and management experience to enable autonomous decision-making among the supply chain. Finally, following the emergence concept of CAS theory (Palmberg, 2009), participants within the supply chain interact to correct inconsistencies or adverse outcomes between the system and its environment, thereby maintaining orderly system operation. As such, we investigate how the supply chain system improves coordinated processes through implementing EDT. Through these three aspects, we aim to develop a systematic theoretical framework for the relationship between EDT and SCR.

For data analysis, we employed both deductive and inductive approaches for coding. On one hand, we developed a research framework based on the CAS theory and used its three key dimensions to define the scope of the study. This framework also guided our data collection and initial categorization of the collected data, which is considered a deductive process. On the other hand, we processed the interview transcripts using a combination of open coding and axial coding to generate the evidence text. This process is regarded as inductive, specifically referring to the methods for theme identification from case evidence as outlined by Barratt et al. (2011). Open coding involves defining and naming key words or segments in the raw data. During this process, we summarized and distilled all the core concepts mentioned in the interviews. Axial coding was then conducted to refocus the content of open coding by refining the main categories through examining the relationships between subcategories. The coding structure are presented in Tables 2 and more details can be founded in Appendix B.

[Insert Table 2 here]

**3.5 Trustworthiness of research design**

We follow Lincoln and Guba’s (1985) criteria of credibility, transferability, dependability, and confirmability to ensure the rigor of our case study design, as shown in Table 3.

[Insert Table 3 here]

**4. Case description and within-case analysis**

**4.1 Company A**

Company A is committed to a full-process digital transformation and has maintained the largest market share in the global large home appliance market since 2009. Currently, Company A has 35 industrial parks and 138 manufacturing centers worldwide.

*Building SCR by increasing the depth of EDT*: Company A invested heavily in digital technology, beginning with smart home digital management in 2012. By 2017, despite these efforts, the value chain remained fragmented, leading to high sales and management costs. However, continuous optimization and strategic planning led to significant improvements. By 2024, the company reduced sales and management expenses from 25% to 18% of total revenue, improving efficiency, product quality, and market adaptability, especially during the pandemic and trade wars.

*Building SCR by increasing the breadth of EDT*: implemented a big data and IoT-driven customization platform for real-time customer feedback, and a supply chain platform for seamless information flow across suppliers and logistics partners. This integration, coupled with real-time data analysis, enabled quick market demand response and production adjustments. Despite a global market downturn in 2023, Company A's coordinated operations resulted in a 7.2% year-on-year turnover growth.

**4.2 Company B**

Company B is a global smart electric vehicle company committed to providing high-performance smart electric vehicles and an ultimate user experience. Currently, Company B has established design, R&D, and production centers in 12 locations including San Jose, Munich, London, Beijing, and Shanghai.

*Building SCR by increasing the depth of EDT*: Company B has made significant investments in digital technology, reshaping Product Lifecycle Management (PLM) to create a digital closed-loop, shortening development cycles and improving product quality through continuous Over-The-Air (OTA) updates. Ranked second globally in R&D investment among automotive manufacturers (Gartner, 2024), Company B’s focus on EDT enhances its supply chain’s predictive and responsive abilities. However, despite these advancements, the financial benefits have not yet materialized, as evidenced by a net loss of 10.384 billion yuan in the first half of 2024, a 4.95% year-on-year increase.

*Building SCR by increasing the breadth of EDT*: Company B prioritizes a digitalized user experience, managing the entire lifecycle from initial interest to after-sales service through digital platforms. However, on the production side, Company B relies on outsourcing to a Chinese automotive manufacturer, lacking digital control over capacity and processes. This dependency introduces significant uncertainty in product quality.

**4.3 Company C**

Company C is a leading technology-driven logistics service provider in China, committed to becoming a trusted supply chain infrastructure service provider for users.

*Building SCR by increasing the depth of EDT*: Company C has developed a diversified, digitally managed logistics network, including warehousing, transportation, last-mile delivery, oversized cargo, cold chain, and cross-border logistics. Initially, its self-operated service capabilities were underutilized, leading to losses. Recognizing the importance of a proprietary system, Company C increased investments to enhance its self-operated services. By 2022, leveraging digital transformation, the company saw significant performance growth. In 2023, despite pandemic challenges, Company C's revenue reached 166.6 billion yuan, marking a 21.3% year-on-year increase, demonstrating its enhanced SCR.

*Building SCR by increasing the breadth of EDT*: Company C operates its own logistics network and integrates external capacity through a platform to manage fluctuations. Additionally, Company C has shifted its business model, establishing an open platform to offer its products and services via APIs and software. For example, it aggregates idle storage resources on a cloud platform to create a digital national storage map, providing logistics cloud storage services.

**4.4 Company D**

Company D is a comprehensive provider of container shipping services, including shipping, container leasing, and freight forwarding.

*Building SCR by increasing the depth of EDT*: Company D has deepened its EDT efforts by launching an integrated service supply chain platform to address shipping market fluctuations. Utilizing advanced digital technology, it offers real-time cargo tracking and provides customers with visualized logistics updates, enhancing transparency and efficiency. Company D has also joined the Global Shipping Business Network (GSBN) to explore blockchain-based electronic documentation, improving trade financing and reducing verification costs. Its rapid order response and processing capabilities have solidified its industry leadership.

*Building SCR by increasing the breadth of EDT*: Company D is building a maritime service ecosystem through digital technology, enhancing engagement with stakeholders like port terminals, freight forwarders, banks, and customs to improve customs clearance efficiency. To strengthen SCR, the company coordinates digital transformation with upstream and downstream partners. By integrating its services into customers’ operational platforms and workflows, Company D aims to foster greater user retention and resilience against disruptions.

Table 4 summarizes the typical practices of the four companies in terms of EDT depth and breadth, along with the SCR status.

[Insert Table 4 here]

**5. Cross-case analysis**

**5.1 Relationship between the depth of EDT and SCR**

In the interviews, the manager of Company C stated that the company has deeply integrated big data and artificial intelligence technologies in its digital transformation, enabling real-time analysis of consumer behavior and rapid adjustments to operational strategies. The manager of Company D emphasized that the globalization of the shipping industry and the complexity of supply chains require companies to possess high levels of flexibility and adaptability. After implementing a comprehensive digital transformation, they integrated a global supply chain management system, which significantly enhanced company's empowerment capabilities.

In contrast, Company A had initiated its smart factory project early on, but due to considerations such as cost, corporate social responsibility, and operational risks, the plan was not fully implemented, which to some extent hindered the broader empowerment of its partners. The manager of Company B noted that the automotive industry is undergoing rapid transformations in electrification and intelligence. Through in-depth transformation, the company has strengthened its manufacturing capabilities, while also highlighting the importance of adaptability. As Company B’s manager said:

*“In markets where the infrastructure is not yet mature, excessively advancing smart connectivity technologies can lead to resource waste and even a poor consumer experience. Therefore, in our digital transformation strategy, we always consider market conditions and policy directions to ensure that technology complements the environment, thereby truly enhancing the company's operational efficiency and market competitiveness.”*

In summary, the executives of the four companies unanimously agreed that the impact of the depth of EDT on company’s empowerment capability is influenced by the environmental adaptability. The cases of Companies A and B indicate that if the alignment between EDT and the environment is low, the depth of EDT may hinder the company’s empowerment. Conversely, the cases of Companies C and D demonstrate that in highly aligned environments, the depth of EDT can significantly enhance empowerment capabilities. This is consistent with the CAS theory, where adaptability means continuous interaction between the enterprise and the environment, revealing that changes in the environment place the company in an unstable and chaotic state (Palmberg, 2009). As Enrique et al. (2022) and Vanpoucke et al. (2017) argue, digital technologies should address the adaptation to uncertain environments to enhance supply chain flexibility. Therefore, it is necessary for enterprises to maintain a depth of EDT that is in line with the environment, in order for complex systems to achieve efficient operation.

Therefore, based on existing research and interview content, we propose Proposition 1.

**Proposition 1:** *The positive relationship between the depth of EDT and empowerment capability is moderated by environmental adaptability. If the alignment between EDT and the environment is low, then the depth of EDT will hinder the empowerment capability. Conversely, if the alignment between EDT and the environment is high, then the depth of EDT will facilitate the empowerment capability.*

Additionally, the managers of the four companies discussed the impact of the digital empowerment capability on SCR from different perspectives. First, the manager of Company A mentioned that they have achieved full-process digital management from raw material procurement to product manufacturing. This digital empowerment enables the company to quickly adjust production plans and optimize inventory management in response to external fluctuations in the supply chain, thus significantly enhancing SCR. The manager of Company B further highlighted that in the context of a complex global supply chain with a high dependence on external suppliers for components, they can use big data analytics to identify potential risks in advance. This form of digital empowerment ensures the stability and flexibility of the supply chain. The manager of Company C emphasized that during order surges or sudden market changes, they can leverage digital platforms to quickly coordinate resources, optimize delivery routes, and adjust inventory allocation, ensuring the smooth operation of logistics. As stated by Company C’s manager:

*“The digital empowerment capability allows us to rapidly adjust operational strategies in the face of drastic changes in market demand, ensuring the stable operation of the supply chain.”*

Similarly, the manager of Company D pointed out that digital empowerment enables the company to quickly adjust shipping routes or plans in the event of port congestion or transport delays, reducing the risk of supply chain disruptions. In interviews, managers unanimously agreed that empowerment can strengthen enterprise capabilities at different levels, thereby expanding markets and reducing internal risks and conflicts. According to the CAS theory, the adaptive process of enterprises involves the integration and utilization of various resources, technologies, and collaborative relationships, and diversity in resources and partners can increase the SCR (Inigo and Albareda, 2016). Through the empowerment, companies can respond more agilely to uncertainties within the supply chain, which ensures business continuity and stability. Therefore, we propose Proposition 2.

**Proposition 2:** *Empowerment capability has a positive impact on SCR.*

**5.2 Relationship between the breadth of EDT and SCR**

The interviews revealed a positive impact of the breadth of EDT on supply chain collaboration across various companies. For example, Company A's broad digital transformation across R&D, production, and sales enables real-time monitoring of suppliers' inventory and production capacity, optimizing production plans through data sharing. However, challenges arose as some partners struggled to adapt to the new digital systems, limiting collaboration efficiency. Similarly, Company B's collaboration with another automaker in an “Internet + Manufacturing” mode allowed for effective joint development, but pandemic-related coordination issues caused significant production disruptions. In contrast, Company C's digital systems across warehousing, logistics, and order processing facilitated efficient collaboration between upstream suppliers and downstream distributors. Companies with partners possessing strong learning capabilities experienced faster adaptation to digital tools, improving response speed and optimizing supply chain operations. These insights highlight the critical role of adaptability and digital readiness in fostering effective supply chain collaboration. As Company C’s manager stated:

*“Enhancing the learning capabilities of supply chain partners is a core element of our strategic implementation to ensure that digital transformation maximizes its benefits.”*

The interview findings suggest that for partners with weaker learning capabilities, a broad EDT may not lead to the expected improvements in collaboration, and could even create communication and execution barriers. According to the emergent characteristics of CAS theory, interactions among supply chain members can generate complex behaviors, shared knowledge, and unexpected outcomes through continuous feedback (Palmberg, 2009). When expanding the breadth of EDT, companies should prioritize enhancing the learning capabilities of their supply chain partners to maximize collaboration outcomes. Hence, we propose Proposition 3.

**Proposition 3:** *The positive relation of the breadth of EDT on supply chain collaboration is moderated by supply chain learning. The stronger the supply chain learning ability, the greater the positive impact of the breadth of EDT on the supply chain collaboration.*

Interviews with managers from four companies revealed a strong consensus on the positive impact of supply chain collaboration on SCR. Company A's manager highlighted that close collaboration with upstream and downstream partners allowed for quick production resumption during external shocks, such as the pandemic. Sharing demand forecasts and inventory information enabled suppliers to adjust production plans, boosting SCR. The manager of Company B emphasized the complexity of the automotive supply chain, noting that while some risks can be mitigated through digital platform collaboration, limited current collaboration affects recovery speed. Company C’s manager pointed out that its self-operated ecosystem, built through heavy asset investments, facilitates high levels of internal collaboration, enabling rapid responses to demand surges and logistical challenges. Finally, Company D’s manager stressed the importance of collaboration with ports, customs, and logistics partners to receive real-time updates on freight movements and proactively develop contingency plans.

In summary, the interviews with executives from the four companies indicate that supply chain collaboration has a significant positive impact on SCR. According to CAS theory, complex systems have the ability to self-organize and self-regulate, and through collaboration, supply chain members can generate ordered structures and behaviors, thereby enhancing the system’s adaptability (Surana et al. 2005). Through close collaboration, companies can react quickly and adjust flexibly when disruptions or fluctuations occur, ensuring the continuity and recovery capability of the supply chain. In conclusion, we propose Proposition 4.

**Proposition 4:** *Supply chain collaboration has a positive impact on SCR.*

**5.3 Relationship between empowerment capability and supply chain collaboration**

Liu et al. (2021) corroborate the positive correlation between empowerment capability and supply chain collaboration within the logistics ecosystem. In the interviews, the executives of the four companies consistently emphasized the positive relationship between the empowerment capability on supply chain collaboration. The manager of Company A mentioned that empowerment allows for real-time data sharing and transparency across all stages of the supply chain. In contrast, the manager of Company B highlighted that empowering users makes it easier to identify needs and pain points, enabling the company to quickly adjust in response to changes in customer demands. As a result, digital empowerment not only enhances supply chain collaboration efficiency but also improves the customer experience. The manager of Company C pointed out that the introduction of digital technologies has significantly increased the management efficiency of complex supply chains. Empowerment ensures more precise collaboration across all stages of the supply chain, allowing companies to maintain efficient operations during major promotions or special events. Lastly, through digital platforms, Company D can seamlessly connect with logistics partners, monitor the transportation status of goods in real time, and optimize shipping routes, thereby collaborating to provide high-quality service. As the manager of Company D stated:

“*Empowerment has made collaboration in the shipping industry more flexible and efficient, greatly improving the response speed of the service supply chain.”*

Overall, managers from the four companies underscored the pivotal role of empowerment capability in strengthening supply chain collaboration. Leveraging digital tools and platforms enables more seamless communication, streamlined management, and proactive problem-solving with supply chain partners, ultimately enhancing the efficiency, responsiveness, and adaptability of collaboration. This reinforces the notion that both the depth and breadth of EDT contribute to SCR by fostering a more integrated and resilient supply chain network. Therefore, we propose Proposition 5.

**Proposition 5:** *Empowerment capability strengthens supply chain collaboration, serving as a crucial mechanism through which both the depth and breadth of EDT collectively enhance SCR.*

**6. Discussion of results**

Based on the above case analysis, EDT influences the construction of SCR through two dimensions: depth and breadth. Specifically, the depth of EDT represents the investment intensity of EDT or digital-based mode innovation, while the breadth of EDT is defined as the range of implemented EDT within the supply chain, such as the number of nodes involved in EDT (Yang et al. 2023). The mainstream view holds that EDT always has a positive impact on SCR. This study breaks down EDT into depth and breadth, and clarifies the roles of environmental adaptability and supply chain learning, respectively. The proposed theoretical framework is illustrated in Figure 2.

[Insert Figure 2 here]

The construction of SCR involves two key dimensions: managing internal operational risks and withstanding external disruptions. Internally, the depth of EDT is crucial, as its alignment with environmental factors influences the enterprise's empowerment capability (P1). Proper alignment enhances empowerment, enabling the provision of critical resources to supply chain stakeholders, thereby strengthening SCR (P2). Externally, the breadth of EDT plays a key role in enhancing supply chain collaboration, which is moderated by supply chain learning. Strong learning capabilities help firms absorb knowledge from EDT, fostering improved collaboration (P3). Collaborative networks improve SCR by enabling effective information sharing and resource coordination to manage uncertainties (P4). Additionally, empowerment positively influences collaboration (P5), with higher empowerment levels facilitating cooperation and boosting SCR. Thus, effective EDT implementation enhances both internal operational efficiency and external SCR, supporting the firm’s overall competitiveness and adaptability.

**6.1 Improve SCR by resolving internal risks**

The pathway of “depth of EDT → empowerment capability → SCR” highlights how enterprises can mitigate internal risks. Prior research has emphasized that digital technologies enhance transparency in information, goods, and financial flows, facilitating early warning mechanisms for risk assessment and prediction (Vanpoucke et al. 2017). Our findings support this view but extend it by demonstrating that the effectiveness of EDT in risk mitigation depends not only on its implementation depth but also on its coordination with environmental adaptability. This aligns with Chae et al. (2014), who argue that early warning signals enable proactive risk management, yet our study goes further by emphasizing that EDT must be embedded within business processes to maximize its impact.

CAS theory suggests that organizations must continuously adapt to environmental changes (Liu et al. 2024). Prior studies often regard EDT as a static capability that directly enhances resilience (e.g., Ivanov, 2021), but our research reveals its dynamic interaction with environmental adaptability. We find that enterprises leveraging EDT for risk mitigation must remain flexible, adjusting their digital strategies to evolving conditions. The case study of Haribo illustrates that a misalignment between EDT implementation and business operations can lead to inefficiencies, ultimately weakening SCR. This expands on Surana et al. (2005), who emphasize that enterprises function as adaptive agents in a complex system.

Moreover, empowerment capability acts as a crucial link between EDT depth and SCR. Beyond risk identification, digital technologies enable firms to take swift corrective actions by integrating real-time insights into decision-making processes. This capability strengthens internal coordination, allowing firms to reallocate resources and adjust production dynamically in response to disruptions. Thus, our study underscores that EDT-driven empowerment is not only about risk detection but also about fostering an organization’s capacity for self-adjustment and resilience-building.

**6.2 Improve SCR by resisting external disruptions**

The pathway of “the breadth of EDT → supply chain collaboration → SCR” enables supply chain members to collectively respond to external disruptions. Prior research has highlighted the role of digital platforms in enhancing supply chain connectivity and collaboration (Yin et al. 2023), which aligns with our findings. However, our study further refines this understanding by linking EDT breadth to self-organization, a key concept in CAS theory. We find that broader digitalization fosters decentralized coordination, allowing supply chain members to dynamically self-organize through real-time communication, resource integration, and joint decision-making. This adaptive coordination enhances the system’s ability to respond autonomously to disruptions without central control (Surana et al. 2005).

Additionally, we emphasize supply chain learning as an emergent property of EDT-driven collaboration. Prior research has acknowledged iterative learning as crucial for multi-tier supply chain management (Gong et al. 2018), but our findings highlight its role in transforming EDT investments into resilience. Through continuous learning cycles, enterprises collectively process feedback, refine strategies, and develop emergent intelligence that strengthens SCR. This emergence is particularly evident in crisis scenarios, where interconnected firms leverage shared data and experience to co-develop adaptive solutions.

However, as illustrated by Company C, insufficient EDT breadth can weaken self-organization and hinder emergence. Unlike previous studies that focus on technology adoption as a resilience booster, our research reveals that failing to integrate digitalization with external collaboration—such as neglecting coordination with upstream manufacturers—can create vulnerabilities like supply shortages and production bottlenecks. This underscores the need for firms to not only invest in digital infrastructure but also cultivate collaborative ecosystems that foster self-organized resilience and emergent learning capabilities.

**6.3 The positive impact of empowerment capability on supply chain collaboration**

Empowerment capability acts as a bridge between mitigating internal risks and enhancing external collaboration, strengthening SCR. Internally, digital empowerment improves operational transparency and decision-making agility, enabling firms to detect and address risks early (Vanpoucke et al. 2017). However, our findings show that internal risk management alone is insufficient—firms must extend empowerment to external partners to build collective resilience. Externally, empowerment fosters trust, knowledge sharing, and resource integration, reinforcing supply chain collaboration (Liu et al. 2021). Unlike traditional SCR models that focus on reactive responses (Zhao et al. 2023), our study highlights that firms proactively strengthen supply chain collaboration by supporting partners with digital tools and financial resources. This aligns with CAS theory’s emphasis on self-organization and emergence (Surana et al. 2005; Gong et al. 2018), where interconnected agents collectively enhance resilience.

**7. Concluding remarks**

The impact of EDT on SCR remains a debated topic in both practice and academia. Using CAS theory, we conducted a multi-case study to explore this relationship. Our findings reveal three key insights: First, deepening EDT enhances empowerment capability, which strengthens SCR, though this effect is influenced by environmental adaptability, a critical CAS characteristic. Second, the breadth of EDT promotes supply chain collaboration, enhancing SCR. This relationship is moderated by supply chain learning, where iterative interactions among members foster emergent properties like collective intelligence and adaptive collaboration, reinforcing resilience. Finally, empowerment capability not only directly impacts SCR but also indirectly enhances it by improving collaboration within the supply chain.

**7.1 Theoretical contributions**

The theoretical contributions of this study are multifaceted and make significant advances in the literature on EDT and SCR. First, this study significantly advances our understanding of the relationship between the depth of EDT and SCR by proposing a nuanced perspective on how internal technological capabilities can enhance SCR. While existing literature has generally linked digital technologies to improved operational efficiencies, our study goes beyond this by emphasizing the pivotal role of empowerment capability in strengthening SCR. Specifically, we show that the depth of EDT—encompassing technologies that integrate internal processes, resources, and decision-making systems—directly contributes to the firm’s internal adaptability. However, our findings indicate that the positive effects of this depth are not automatic; instead, they are highly contingent on the alignment between digital transformation efforts and the external environment. This dynamic relationship implies that firms must continuously assess and adapt their digital strategies to the changing external context to ensure that the depth of EDT does not become a hindrance. The study thus introduces a more sophisticated understanding of the depth of EDT, suggesting that its potential to mitigate internal risks and enhance SCR is maximized only when aligned with broader environmental factors. This contribution challenges previous views that treat digital transformation as a fixed capability, offering a more dynamic and context-sensitive framework that emphasizes adaptability.

Second, the research contributes to the literature on the breadth of EDT and its effect on supply chain collaboration and SCR by introducing the critical role of supply chain learning in this process. While prior studies have explored the relationship between digital technologies and supply chain collaboration, they often focus on technological adoption as a static factor. Our research reveals that the breadth of EDT, which includes the expansion of digital connectivity across the supply chain, is essential for fostering self-organization and dynamic collaboration. This collaborative behavior, however, does not automatically lead to resilience. Rather, it is through iterative supply chain learning—in which partners collectively refine their strategies, share knowledge, and adapt to disruptions—that the full potential of EDT breadth is realized. Our study shows that learning capability is the key enabler that determines whether the breadth of EDT can drive the positive effects of collaboration and resilience. When supply chain members possess strong learning abilities, they can effectively utilize digital tools to share real-time information, coordinate efforts, and jointly respond to disruptions. This insight expands our understanding of the breadth of EDT, suggesting that its impact is not solely driven by the adoption of digital tools, but also by the continuous development of collaborative learning processes. In doing so, our study provides a more dynamic and process-oriented view of SCR, which integrates the importance of both digital infrastructure and collective learning capabilities in adapting to disruptions.

Finally, this study makes a significant contribution by applying CAS theory to the relationship between EDT and SCR. CAS theory highlights the importance of adaptability, self-organization, and emergence in complex systems, and this study demonstrates how these principles can help explain how EDT contributes to SCR. The depth of EDT enhances an organization’s adaptability by improving internal processes and decision-making, allowing firms to respond effectively to environmental changes. On the other hand, the breadth of EDT facilitates self-organization within supply chains, where individual supply chain members autonomously adjust their behaviors, share resources, and coordinate efforts. Over time, these interactions lead to the emergence of new patterns of collaboration and resilience, where the collective intelligence of the supply chain emerges in response to disruptions. This contribution expands CAS theory by illustrating how EDT serves as a catalyst for these dynamic, adaptive processes, leading to a more resilient and adaptable supply chain system.

**7.2 Managerial implications**

The managerial insights of this study are as follows. First, aligning the depth of EDT with business strategy is paramount. Managers must carefully assess the scale of digital transformation in relation to the company’s strategic objectives, organizational size, and market positioning. For firms undertaking an aggressive digital transformation, it is critical to ensure that technological adoption is strategically aligned with core business processes and resources, thereby avoiding the risk of overwhelming the organization. Regular evaluations of digital initiatives should be conducted to verify that technological advancements contribute to long-term value creation and do not introduce unnecessary operational risks. Conversely, for companies adopting a more conservative approach, managers should monitor industry trends and competitor actions to ensure the company remains sufficiently agile to capitalize on emerging opportunities while safeguarding against technological lag.

Second, managing the breadth of EDT to foster SCR is essential. Rather than indiscriminately expanding digital capabilities, managers should focus on developing a shared vision for digital transformation with key supply chain partners. This requires leveraging historical performance data and market intelligence to identify the most impactful digital tools and platforms. Collaborative platforms that facilitate real-time communication, data sharing, and joint decision-making can significantly enhance collective resilience in the face of external disruptions. Moreover, managers should invest in training programs to upskill supply chain partners, thereby ensuring that digital tools are effectively utilized and that collaboration is optimized. By establishing clear operational guidelines and fostering a culture of knowledge-sharing, firms can drive greater value from collaborative digital initiatives.

Lastly, adopting a dual focus on internal risk management and external collaboration is crucial for strengthening SCR. Managers should adopt an integrated approach that combines internal digital empowerment with a focus on external network dynamics. Internally, it is essential to leverage digital technologies to enhance transparency, improve risk monitoring, and facilitate swift decision-making, thus ensuring agility in response to internal risks. Externally, managers must cultivate robust, long-term relationships with critical supply chain partners, promoting trust, knowledge-sharing, and joint development of strategies to address potential disruptions. This can be achieved through regular joint reviews, collaborative scenario planning, and the establishment of contingency frameworks. By embedding collaborative practices into the digital transformation strategy, managers can ensure that SCR is built through a combination of internal operational efficiency and external partnership strength.

**7.3 Limitations and future directions**

This study has limitations but also provides directions for future research. First, the analysis of factors influencing SCR did not consider the developmental stages of different enterprises. In future research, scholars could explore the impact of different developmental stages on SCR. Second, this study did not provide indicators and methods for evaluating the depth and breadth of EDT. Future research could explore how to characterize depth and breadth from perspectives of models and empirical studies. Additionally, this study only proposed an exploratory conceptual framework. It is necessary to conduct questionnaire survey to verify the theoretical framework proposed.

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Table 1 Basic information of the four sample companies

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Company** | **Year founded** | **Headquarters location** | **Registered capital** | **Description** |
| Company A | 1984 | Qingdao | More than 3 billion RMB | Leading brand of household appliances in China. Company A has continued to carry out digital R&D, digital lean manufacturing and digital business transformation, achieving growth despite a decline in overall industry sales. |
| Company B | 2014 | Hefei | More than 60 billion RMB | The top two brands of new energy vehicles in China. In recent years, Company B has been committed to providing users with full life cycle services through digital innovation. |
| Company C | 2017 | Beijing | More than 6 billion RMB | China’s largest integrated supply chain service provider. Company C is dedicated to furnishing users with supply chain solutions propelled by digital technology. |
| Company D | 2016 | Shanghai | More than 11 billion RMB | The largest shipping company in mainland China. Company D has implemented EDT across its facilities, equipment, and business processes, aiming to establish a holistic shipping logistics supply chain service ecosystem. |

(Source: table created by authors)

Table 2 Coding structure

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Dimensions based on CAS theory** | **Major Category** | **Connotation** | **Subcategory** | **Core concepts** |
| Adaptation | The depth of EDT | The degree of adoption of digital technology and its impact on organizational structure and business modes (Yang et al. 2023). | Digital technology investment | Algorithm design, equipment iteration, technology introduction |
| Digital innovation of products and services | Large scale customization, full process solution |
| Empowerment capability | The core company’s ability to improve supply chain decision-making and customer experience by providing resource integration and technical support to other supply chain members (Liu et al. 2022). | Capability building | Supplier training, process reengineering |
| Ecosystem | Ecological niche, symbiotic relationship |
| Environmental adaptability | Adaptability between environment and organization (Phadnis, 2024). | Technical environment adaptation | Software and hardware compatibility, technical agility |
| Market environment adaptation | Demand matching, digital marketing |
| Self-organization | The breadth of EDT | The range of business areas, departments, and functions involved in EDT (Yin, 2023). | Digitalization of supply chain organization | Digital supplier management, organizational collaboration |
| Digitization of business processes | Digital procurement, electronic signing |
| Supply chain collaboration | Establishing common goals based on mutual benefit and creating value through in-depth cooperation, risk sharing, information sharing, and process interoperability (Aarikka-Stenroos et al. 2022). | Resource sharing | Technology sharing, logistics resource sharing |
| Digital collaboration | Collaborative production, information traceability |
| Emergence | Supply chain learning | The ability to sustain the uninterrupted functioning of the supply chain through the exchange and internalization of knowledge/experience (Liu et al. 2023). | Internalization of knowledge | Knowledge transformation, knowledge absorption |
| Experience integration | Experience summary, experience sharing |

(Source: table created by authors)

Table 3 Measures to ensure trustworthiness

|  |  |
| --- | --- |
| **Tests** | **Application in this study** |
| Credibility | We conducted two rounds of interviews with senior executives and project teams, used triangulation by cross-referencing multiple data sources, and employed member checking to validate findings. |
| Transferability | We selected companies from different industry segments with varying EDT models and SCR practices, providing rich contextual details to enhance the applicability of our findings to similar contexts. |
| Dependability | We maintained a detailed audit trail documenting the research process, including interview protocols, coding procedures, and data analysis methods, ensuring consistency and replicability. |
| Confirmability | We minimized researcher bias by using multiple data sources, peer debriefing, and reflexive journaling, ensuring that findings were derived from the data rather than subjective interpretations. |

(Source: table created by authors)

Table 4 Summary of typical practices

|  |  |  |  |
| --- | --- | --- | --- |
| **Company** | **The depth of EDT** | **The breadth of EDT** | **SCR status** |
| Company A | Implemented an operational system distinguished by intelligent manufacturing, networked collaboration, personalized customization, and digital management. | (1) Developed a large-scale customization platform with user engagement.  (2) Established a supply chain platform, promoting integration and openness among suppliers’ and logistics companies’ information systems. | Although Company A faced issues with insufficient value chain integration in the early stages, it significantly improved production efficiency and product quality through platform design, intelligent manufacturing, and network collaboration, effectively coping with the pressures brought about by the pandemic and trade wars. |
| Company B | Established and deployed a comprehensive digital closed-loop management system spanning the entirety product lifecycle. | (1) At the user end, a fully integrated digital service system has been developed.  (2) Production have been outsourced and digitized, enabling streamlined management at the production end. | Company B has achieved a digital closed-loop for the entire product lifecycle. It has made significant investments in EDT, but has not seen substantial financial returns in the short term. Additionally, Company B relies on outsourcing for production, which increases the uncertainty in product quality. |
| Company C | Developed and implemented a sophisticated logistics service network featuring operational automation, digitized management processes, and intelligent decision-making capabilities. | (1) Platform integrated social transportation and warehousing capabilities.  (2) Platform opened up related product services and technical resources to third parties. | Although Company C faced challenges in the early stages of EDT, it has become an industry leader in responsiveness and collaboration through continuous investment. Meanwhile, by building an open platform, Company C further enhanced the resilience and scalability. |
| Company D | (1) Launched an integrated service platform and offered one-stop maritime services.  (2) Explored blockchain-based electronic documentation services. | (1) Strengthened information sharing with stakeholders such as port terminals, freight forwarders, banks, and customs.  (2) Deeply embedded services into customers’ operational platforms. | By launching an integrated service platform, Company D effectively addressed market fluctuations and transportation uncertainties. Additionally, through enhanced digital collaboration, it optimized customs clearance efficiency, strengthening the supply chain's coordination and adaptability. |

(Source: table created by authors)



Figure 1 The screening procedures of the sample companies

(Source: figure created by authors)



Figure 2 The proposed theoretical framework

(Note: The “P” and numbers correspond to this paper’s propositions)

(Source: figure created by authors)