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The impact of industry 4.0 on supply chain capability and supply chain resilience: A dynamic resource-based view

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ABSTRACT

Industry 4.0, a collection of emerging intelligent and digital technologies, has been the main interest of both researchers and practitioners in operations management (OM) in recent years. Despite its proclaimed effectiveness in supply chain (SC) management, empirical studies examining the effects of Industry 4.0 adoption on SC resilience have been underrepresented in the current OM literature. In our study, we explore the effects of 16 Industry 4.0 technologies and IT advancement concerning SC resilience through the mediating roles of SC capabilities with respect to SC collaboration and SC visibility. Following the dynamic resource-based view (RBV), we regard Industry 4.0 adoption and IT advancement as two important IT resources with heterogeneity, SC collaboration and SC visibility as essential SC dynamic capabilities, and SC resilience as competitive advantages. We suggest the combination and evolution of IT resources and dynamic SC capabilities helps firms obtain the competitive advantage regarding SC resilience. Using data from a survey of 408 Chinese manufacturing firms, we reveal Industry 4.0 adoption is positively related to IT advancement and that Industry 4.0 has a nonsignificant impact on SC capabilities, whereas IT advancement has a positive impact on SC capabilities. Additionally, both SC collaboration and visibility positively influence SC resilience and significantly mediate the impacts of Industry 4.0 and IT advancement on SC resilience. Our study offers an enhanced understanding of the specific flows between Industry 4.0 and SC resilience and provides nuanced insights for both literature and practice.

1. Introduction

The COVID-19 pandemic has caused severe global disruptions. Most companies face tremendous challenges in every stage of their supply chain (SC; (Spieske and Birkel, 2021). Many suppliers cannot meet their delivery obligations, and customer demand is highly unpredictable (Ivanov, 2020). The increasing complexities of global geopolitics, cybersecurity challenges, natural disasters, and trade disputes during recent years also highlighted the great importance of SC resilience (Brandon-Jones et al., 2014; Gu et al., 2021; Spieske and Birkel, 2021). Therefore, the literature badly needs insights concerning investments, practices, or capabilities conducive to building SC resilience.

Recent technological progress, especially Industry 4.0, indicates promising possibilities to build up SC resilience (Barata, 2021; Hägele et al., 2023; Lemstra and de Mesquita, 2023). Industry 4.0 refers to the collection and paradigm of various intelligent and digital technologies that can provide more profitable business models, higher efficiency, and improved workplace conditions for manufacturing firms (Bai et al., 2020; Frank et al., 2019; Li et al., 2020b). Governments around the world have invested in Industry 4.0 to enhance resilience. For instance, the Chinese government has planned to allocate RMB1.4 trillion for 5G networks, smart cities, and smart manufacturing development, the goal of which is to build up fifth-generation towers to achieve manufacturing resilience on the mainland (Choi et al., 2022). Industry 4.0 has been one of the most focused-upon topics for researchers and practitioners since the German government introduced it in 2011 (Veile et al., 2019).

Despite the often-proclaimed effectiveness of Industry 4.0 technologies in improving SC resilience, empirical studies examining those effects have still been underrepresented in the literature of operations management (OM). Most scholars elaborated on that topic via

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qualitative methods such as literature reviews and case studies (Barata, 2021; Hägele et al., 2023; Lemstra and de Mesquita, 2023), and the majority of the existent research has been conceptual in nature (Ardolino et al., 2022). Scholars stressed more empirical studies are needed to provide a better understanding of the application of Industry 4.0 (Ardolino et al., 2022). Although some empirical studies have examined the effects of Industry 4.0 on SC resilience, the specific influence paths regarding how Industry 4.0 influences SC resilience have still not been explicitly revealed. For instance, Zouari et al. (2021) pioneered the investigation of 15 digital technologies on SC resilience. However, such an approach does not reveal the internal mechanisms within the Industry 4.0–SC resilience link. Scholars have argued specific factors are required to play instrumental roles in the "black box" and called for in-depth research (Ivanov and Dolgui, 2020; Ivanov et al., 2019). Thus, we aim to empirically examine the impact of Industry 4.0 technologies on SC resilience and reveal their internal mechanisms.

We employ a dynamic resource-based view (RBV) as our theoretical foundation, which combines concepts pertinent to RBV and dynamic capability view (DCV; (Helfat and Peteraf, 2003). Dynamic RBV proposes a dynamic influence path covering the framework of resources-capability-competitive advantage (Barney, 1991; Helfat and Peteraf, 2003; Li et al., 2022; Teece et al., 1997). A fundamental assumption of dynamic RBV is resources and capabilities are heterogeneous across firms (Barney, 1991). Resource heterogeneity derives from two sources: size advantages and first-mover advantages (Peteraf, 1993). We regard Industry 4.0 and IT advancement as two typical types of resource heterogeneity. Specifically, The adoption of Industry 4.0 technologies represent size advantages derived from the scale bases of resources (Ghemawat, 1986). IT advancement corresponds to first-mover advantages of resources, which reflects a firm's strategic focus on adopting and being the first mover of advanced technology (Tigga et al., 2021; Wu et al., 2006; Yeniyurt et al., 2019). Additionally, dynamic RBV maintains there exist unique evolution paths within different types of resources in firms (Helfat and Peteraf, 2003). We thus argue the adoption of Industry 4.0 technologies can be evolved to support IT advancement so as to be further ahead of competitors.

In addition, the implementation of IT resources never stands alone but needs to be transformed into capabilities so as to exert resources efficiently and effectively (Ardolino et al., 2022). However, many studies focused only on the roles of technologies in achieving resilience while neglecting the fundamental aspect: dynamic capabilities (Ardolino et al., 2022). Dynamic RBV stresses two essential dynamic capabilities that enable firms to obtain competitive advantage: relational capability and informational capability (Salisu and Bakar, 2019; Wang et al., 2013; Yang et al., 2018). SC collaboration, as one of the representative types of relational capability, refers to the ability to align and unite SC partners to mitigate distortions and form beneficial relationships (Scholten and Schilder, 2015). SC visibility, considered an important type of informational capability, indicates the SCs have access to accurate, timely, and complete information to make rapid decisions and take responsive actions (Swift et al., 2019). Therefore, following dynamic RBV, we focus on examining the mediating role of these two SC capabilities, i.e., SC collaboration and SC visibility, in the relationship between IT resources and SC resilience.

Generally, our paper aims to answer the fundamental research question: How firms' IT resources consisting of Industry 4.0 adoption and IT advancement can evolve into dynamic capabilities in SCs and further achieve sustained competitive advantage in terms of SC resilience? More specifically, our study aims to address the four following specific research questions.

- *RQ1:* How does Industry 4.0 influence IT advancement?
- *RQ2:* How do Industry 4.0 and IT advancement influence SC collaboration and visibility?
- *RQ3:* How do SC collaboration and SC visibility influence SC resilience?
- *RQ4:* How do SC collaboration and SC visibility mediate the relationship between Industry 4.0/IT advancement and SC resilience?

We empirically address these research questions using survey data from 408 Chinese manufacturing firms. By answering these questions, our study contributes to the literature in several ways. First, we contribute to the dynamic RBV by investigating the internal mechanisms and evolution paths from Industry 4.0 adoption to IT advancement. We reveal that the adoption of Industry 4.0 has positive effects on IT advancement, confirming the theoretical logic of the dynamic RBV that different types of resource heterogeneity can be evolved and developed internally. Second, our results reveal while IT advancement has a significantly positive effect on both SC collaboration and SC visibility, Industry 4.0 adoption has nonsignificant effects on SC capabilities. Those surprising results contributed to Industry 4.0 literature by implying firms with different types of resource heterogeneity show distinct influences on SCs. Third, we confirm the mediating effect of SC collaboration and SC visibility concerning the relationships between Industry 4.0 adoption and SC resilience, suggesting the essential roles of SC capabilities in the Industry 4.0 context. Fourth, we empirically employ the theoretical perspective of dynamic RBV to explain the relationship among Industry 4.0 adoption, IT advancement, SC capabilities, and SC resilience, providing novel insights into the application of the dynamic RBV for further studies. Our results indicate Industry 4.0 adoption can achieve SC resilience through enhancing IT advancement and building up SC capabilities. In that way, we scrutinize the influence paths from Industry 4.0 technologies to SC resilience, thus revealing the black box regarding the relationship between the two.

2. Theoretical background

2.1. Industry 4.0 technologies

Industry 4.0 indicates the revolution of production modes marked by intelligent manufacturing (Ghobakhloo, 2018). The core concept of Industry 4.0 is to deeply use information and communication technology to promote the integration of the physical and virtual network world and form a system of resources, information, and people (Barata, 2021; Lemstra and de Mesquita, 2023). Industry 4.0 aims to promote the intelligent transformation of the traditional manufacturing industry through advanced technologies (Ghobakhloo, 2018; Liao et al., 2017b).

Based on a thorough literature review and practitioner interviews, we proposed 16 representative Industry 4.0 technologies (details in Section 4.1). Those 16 Industry 4.0 technologies are artificial intelligence (AI), augmented reality (AR), autonomous vehicles (AV), blockchain, big data analytics (BDA), business intelligence (BI), cloud computing (CC), enterprise resource planning (ERP), Internet of Things (IoT), machine to machine (M2M), radio frequency identification (RFID), robotics, simulation, sensors, virtual reality (VR), and 3D printing (3DP) (Bai et al., 2020; Ghobakhloo, 2019). Based on the literature, we summarize their definitions, application areas, advantages, and disadvantages in Table 1.

However, there have not yet been widely recognized dimensions of various technologies under the complex technology architecture of Industry 4.0. Scholars have studied and elaborated on the dimensions of various Industry 4.0 technologies from different perspectives (Frank et al., 2019; Liao et al., 2017b). For example, Frank et al. (2019) summarized a framework containing two layers for an Industry 4.0 adoption pattern: the base technology layer (i.e., CC, IoT, and BDA) and the front-end technology layer (i.e., ERP, robotics, sensors, AI). Ghobakhloo (2019) categorized Industry 4.0 technologies into five groups: human–machine interaction, sensors and data acquisition technologies, operations technologies, computing technologies, and information and communication technologies. Núñez-Merino et al. (2020) classification was based on the technology life cycle theory: obsolete, mature, emerging, and general approaches to information systems. Bai et al.

Table 1
Definition, areas, advantages, and disadvantages of industry 4.0 technologies.

Type	Definition	Area	Advantages	Disadvantages	Related Paper
Artificial intelligence (AI)	Aims to develop the nature of intelligence and generate a new intelligent machine that can react similarly to human intelligence via robot research, language and image recognition, and an expert system.	Logistics; Production management; Demand forecasting and marketing	Intelligent decision-making; Reduced forecast errors; Saved costs	Layoffs of staff; Liability issues when accidents occur for unmanned robots/ vehicles; High investment cost	Toorajipour et al. (2021)
Augmented reality (AR)	Aims to increase the user's perception of the real world through a virtual object or real scene for "enhancement of reality" via multimedia, 3D modeling, multi-sensor combination, real-time tracking, and scene synchronization.	Production and logistics systems; Service	Efficient emergencies; Enhanced customer experiences in retailing; Better services to customer; New ways of design and manufacturing process integration	Customer involvement is nontrivial; Discrepancy in the perceived fit still exists; Performance varies and highly relies on the processing speed and design of AR	(Ahmed et al., 2021; Choi et al., 2022; Masood and Egger, 2019)
Autonomous vehicle (AV)	Aims to manage operational tasks intelligently without requiring a human operator via a robot environment interaction system, human–computer interaction system, and driving system.	Production and Logistics systems; Service	Reduced vehicle crashes; More efficient travel; Decreased traffic flow	Massive job loss in the transportation sector; Hackers and cyber threats; Moral dilemma	Frank et al. (2019)
Blockchain	Aims to develop the chain structure for the time-series data of information stored on a distributed ledger, ensuring the integrity, reliability, and high traceability of information sharing.	Supply chain transparency; Smart contract; Initial coin offering and cryptocurrency	Better trust; Enhanced auditing; Facilitated transactions	Reduces the firm's bargaining power; Contracts become more inflexible	(Choi et al., 2022; Kamble et al., 2018a)
Big data analytics (BDA)	Aims to analyze the different sources and sizes of structured, semi-structured, and unstructured data for better and faster decision-making, modeling, and predicting via data mining, predictive analytics, machine learning, statistics, and natural language processing.	Logistics; Production management; Demand forecasting and marketing; Decision-making	Intelligent decision-making; Cost saving; Increased productivity; Improved customer service; Fraud detection; Faster speed to market	Moral dilemma; Data quality issue; Cybersecurity risks; High investment costs	(Li et al., 2020b; Roden et al., 2017)
Business intelligence (BI)	Aims to help firms better understand business performance, make better business decisions, and facilitate actions through data acquisition and analysis.	Decision-making; Demand forecasting and marketing	Increased productivity; Improved visibility; Simplified business processes	Costly and complex implementation; Time consuming	Lemstra and de Mesquita (2023)
Cloud computing (CC)	Aims to compute for massive data processing and send back the computing, analyzing, and processing results to users in a short period under the powerful network services via the technologies of grid computing, distributed computing, parallel computing, network storage, and load balancing.	Logistics; Production management; Demand forecasting and marketing; Decision-making	Reduced infrastructure costs; Consolidated data; Better defense against disaster; Enhanced collaboration	Losing control over the data; Data safety on the web; Service outages	(Ahmed et al., 2021; Li et al., 2020b; Subramanian and Abdulrahman, 2017)
Enterprise resource planning (ERP)	Aims to integrate the management of core business processes and operational resources from finance accounting, human resources, distribution, production, and warehouses.	Logistics; Production management	Consolidated data across departments; ensured data availability; automated functions; Enhanced savings; Better customer relationships	Costly and challenging implementation	Veile et al. (2019)
Internet of things (IoT)	Aims to integrate devices, computing, and networking to realize intelligent identification and management via connection and recognition technologies and stability of the networking infrastructure.	Production and logistics systems; Smart cities	Enhanced efficiency of machines and robotics; Reduced errors; More convenient lives	Layoffs of human staff; Liability issues when accidents occur for unmanned robots/ vehicles; High investment cost; Privacy issues	(Choi et al., 2022; Manavalan and Jayakrishna, 2019)
Machine to machine (M2M)	Aims to empower industrial networks and machine communication for collaborative automation and intelligent optimization via high-quality connectivity, ubiquitous messaging, and semantic interoperability technology.	Logistics; Production management; Decision-making	Synergy between machines; Enhanced efficiency; Boosted growth	Concerns relating to flexibility and security in systems	Meng et al. (2017)
Radio frequency identification (RFID)	Aims to identify specific targets and read and write relevant data through wireless signals without establishing mechanical or optical contact between the identification system and specific targets via radio frequency and wireless communication technology.	Logistics; Production management; Demand forecasting	Inventory shrinkage; Enhanced data and inventory accuracy; Smart shelving; Privacy and transparency	High investment cost; ethical problems; data security risk of RFID chips	Ahmed et al. (2021)
Robotics	It aims to facilitate productivity, efficiency, and cost-effective solutions by integrating industrial robotic arms, collaborative robots, and robotic sensors.	Logistics; Production management;	Intelligent decision-making; Reduced forecast errors; Saved costs	Layoffs of staff; Liability issues when accidents occur for unmanned robots/ vehicles. High investment costs	Choi et al. (2022)
Sensors	Aims to respond to a physical stimulus (i.e., heat, light, sound, pressure, magnetism, or a particular motion) and transmit a	Automotive industry; Mobile industry	Enhanced efficiency; Boosted growth; Better accuracy	Costly and challenging implementation; Sensitive to extreme environmental changes	Javaid et al. (2021)

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Table 1 (*continued*)

Type	Definition	Area	Advantages	Disadvantages	Related Paper
	resulting impulse via a device for self-identification, diagnosis, configuration, and calibration.				
Simulation	Aims to support decision-making using computer modeling to imitate a real-world process or system via numerical simulation, physical simulation, and expert systems.	Logistics; Production management; Decision-making	Riskless investigation in critical situations; Cost effectiveness; Avoided danger and loss of life	Costly and complex implementation	Barata (2021)
Virtual reality (VR)	Aims to create and integrate all kinds of virtual environments through a computer-based framework and VR platforms to redesign, retest, and refine them in a virtual application.	Industrial and architecture design; Restorative nature experience; Digital marketing	Detailed views; More informative than reality; Effective communication	High cost; Feeling of worthlessness by employees	Stylios (2019)
3D printing (3DP)	Aims to print three-dimensional objects and shapes under the control of additive manufacturing and laminated manufacturing through the technologies of FDM melt lamination, SLA three-dimensional lithography, SLS selective laser sintering, DLP laser forming, and UV molding.	Production and logistics systems	Useful for prototyping; Supported personalization and custom manufacturing; Cost saving for logistics; Enhanced environmental sustainability	High product cost; Quality issue; Slow in production for consumer products	(Choi et al., 2022; Lam et al., 2019)

(2020) categorized Industry 4.0 technologies into physical/manufacturing technologies (e.g., additive manufacturing) and digital/information and communication technologies (e.g., CC, blockchain, BDA, and simulation). Ruel et al. (2023) divided 15 digital technologies into two categories based on the decision-oriented way: operational technologies (i.e., self-driving vehicles, robotics, sensors, collaborative technologies, mobile devices, RFID, 3DP, and CC) and support technologies (i.e., AI, machine learning, BDA, blockchain, VR, and IoT). Based on the literature and firm practices, we categorize 16 technologies into three dimensions according to their applications and typical functions: computing, digitalizing, and integrating technologies (Frank et al., 2019; Ghobakhloo, 2019). First, computing technologies include CC, BDA, and AI (Ghobakhloo, 2019). The common attributes for computing technologies are their powerful computing capability to analyze modeling and predict processing in SC networks (Roden et al., 2017; Toorajipour et al., 2021). Computing technologies can provide cost-effective, smart solutions in complex global SC operations as well as upstream and downstream partnerships (Ghobakhloo, 2019; Subramanian and Abdulrahman, 2017). Second, digitalizing technologies include BI, AV, ERP, simulation, IoT, robotics, and blockchain (Frank et al., 2019; Ghobakhloo, 2019). The common attributes for digitalizing technologies are the digital capability to achieve transformation and digitalization connectivity in SC networking (Manavalan and Jayakrishna, 2019). These digitalizing technologies benefit firms by providing mobilization, real-time data analytics, decision support, high traceability, and collaborative processes. Third, integrating technologies include M2M, 3DP, sensors, RFID, VR, and AR. Common attributes for integrating technologies are related to the physical and virtual hardware and software integration in production facility and SC management (Masood and Egger, 2019). Integrating technologies are conducive to improving the efficiency, accuracy, and controllability, as well as the capability of self-diagnosis, real-time tracking, and error-reduction in production (Javaid et al., 2021; Lam et al., 2019; Meng et al., 2017; Stylios, 2019).

Our classification of Industry 4.0 dimensions depicts a holistic picture of applications of various Industry 4.0 technologies. This attempt provides useful guidance for future researchers to investigate Industry 4.0's adoption profiles in practice and better understand the potential interaction or integration of the dimensions of technologies within Industry 4.0. We also summarize the empirical studies regarding the adoption of various Industry 4.0 technologies in Table 2, which suggests several research gaps in the current literature on Industry 4.0. First, empirical studies examining the relationship between various Industry 4.0 technologies and SC resilience were still limited in the existing literature, with most of them investigating firm performance and operational performance as consequences (i.e., Chauhan et al., 2021; Eslami et al., 2021; Tortorella et al., 2020). Second, few studies scrutinized the mediation mechanisms between Industry 4.0 and its consequences. Zouari et al. (2021) were one of the first to study a total of 15 digital technologies in relation to SC resilience, and they found positive results. However, they did not offer insight concerning the mediations and evolution flow from digital resources to resilience. Despite Nakandala et al. (2023) examining the mediating roles of incremental innovation and operations resilience, they only focused on four Industry 4.0 technologies and lacked solid theoretical support in the development of the research model. Further, although dynamic RBV is a highly relevant theory for SCs in the dynamic business environment, few studies employ that theory to explain the dynamic influence paths from Industry 4.0 to SC resilience, leaving us with a wealth of research opportunities.

2.2. *IT advancement*

IT advancement is defined in this study as the extent to which a firm's adoption and implementation of the most sophisticated information and digital technologies for SC management surpass industry standards or competitors (Tigga et al., 2021; Wu et al., 2006; Yeniyurt

Table 2
The summary of empirical studies about the adoption of various Industry 4.0 technologies.

Studies	Constructs	Mediations	Consequences	Theoretical lenses	Samples	Major findings
Frank et al. (2019)	Base technologies (4 items) and front-end technologies (4 categories)	/	/	/	A survey of 92 manufacturing firms	Industry 4.0 is related to a systemic adoption of front-end technologies, in which smart manufacturing plays a central role.
Rossini et al. (2019)	Industry 4.0 base technologies (16 items)	/	/	/	A survey with 108 European manufacturers	Higher Industry 4.0 adoption levels are easier to achieve when lean production practices are widespread
Li et al. (2020b)	Digital technologies (4 items)	Digital SC platforms	Economic and environmental performance	Information processing theory	A survey of 188 Chinese manufacturing firms	Digital SC platforms mediate the effects of digital technologies on both economic and environmental performance
Tortorella et al. (2020)	Industry 4.0 adoption	Organizational learning capabilities	Operational performance	/	A survey of 135 Brazilian manufacturers	Learning capabilities at an organizational level positively mediate the impact of Industry 4.0 for achieving higher operational performance levels. However, learning capabilities at a team and individual level may not present a significant effect on such mediation.
Ali et al. (2021)	Industry 4.0 technologies (4 items)	/	Firm performance	/	A survey of 302 senior managers from Australian food industry	Industry 4.0 technologies significantly mitigate supply-demand mismatch and process risks and any resulting SC disruptions
Bag et al. (2021)	Industry 4.0 adoption (3 items)	/	Sustainable production	RBV	A survey of 270 respondents	Industry 4.0 adoption has a positive relationship with sustainable production
Chauhan et al. (2021)	Industry 4.0 adoption (10 items)	/	Operational performance and SC competency.	RBV and contingency approach	A survey of 143 manufacturing firms	Industry 4.0 adoption improves operational performance as well as SC competency.
De Giovanni and Cariola (2021)	Industry 4.0 technologies (6 items)	/	Operational performance and economic performance	/	A survey of 172 firms	A process innovation strategy based on Industry 4.0 technologies improves the effect of Leanness on operational performance, which also leads to higher economic outcomes.
Eslami et al. (2021)	Industry 4.0 technologies (5 items)	/	Financial performance	Dynamic capabilities theory	A sample of 274 Swedish manufacturing firms	Industry 4.0 digital technologies as moderators, strengthen the effect of SC agility on financial performance
Narayanamurthy and Tortorella (2021)	Industry 4.0 base technologies (4 items)	/	Employee performance	Social construction of technology	A survey of 106 employees of Indian service organizations	Industry 4.0 technologies differently moderate the relationship between work conditions during the COVID-19 outbreak and employee performance in terms of output quality and output delivery.
Soomro et al. (2021)	Industry 4.0 technologies (2 items)	/	/	Technology acceptance model	A survey of 238 Malaysian technology companies	Firm's size, age, leadership strategy and innovation exert different influences on industry 4.0 readiness and adoption
Stentoft et al. (2021)	Industry 4.0 practices (13 items)	/	/	/	A survey of 190 manufacturers	The managers' lack of perceiving Industry 4.0 drivers, not their perceptions of high Industry 4.0 barriers that obstruct small and medium-sized enterprises (SMEs)' development of Industry 4.0 readiness and their application of Industry 4.0 technologies.
Zouari et al. (2021)	Digital tools adoption (15 items)	/	SC resilience	/	A survey of 300 SC managers	The degree of digital maturity and the adoption of digital tools is positively related to SC resilience
Bai et al. (2022)	Industry 4.0 technologies investment	/	Stock prices and financial performance	RBV	A sample of 563 investment announcements of Chinese publicly listed firms	Investment announcements of Industry 4.0 technologies lead to positive stock market reactions and improved financial performance
Benitez et al. (2022)	Industry 4.0 technology provision (15 items)	/	Cost reduction, customer loyalty,	/	A survey of 77 SMEs from the automation sector	The provision of Industry 4.0 technologies increases customer loyalty and technology innovation

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Table 2 (*continued*)

Studies	Constructs	Mediations	Consequences	Theoretical lenses	Samples	Major findings
			and technology innovation			
Di Maria et al. (2022)	Industry 4.0 technologies (smart-manufacturing technologies and data-processing technologies)	SC integration	Circular economy	/	A survey of 1229 Italian manufacturing firm	Smart manufacturing technologies have a stronger impact on Circular economy outcomes than data processing technologies; the mediating effect of SC integration is verified for the former but not for the latter type
Qader et al. (2022)	Industry 4.0 (3 items)	/	SC resilience and SC performance	Information processing theory and RBV	A survey of 458 respondents working in food, beverage, and pharmaceutical companies	The adoption of Industry 4.0 enhances SC resilience and SC performance; SC visibility significantly moderates the relationship between Industry 4.0 and SC resilience.
Sharma et al. (2022b)	Industry 4.0 technologies (4 items)	/	SC performance.	/	A survey of 361 manufacturing firms	Industry 4.0 technologies positively affect SC performance.
Umar et al. (2022)	Industry 4.0	Green SC management (GSCM) practices	Economic and environmental performance	Practice-based view	A survey of 284 Pakistan firms	Industry 4.0 improve GSCM practices, which mediate the effect of Industry 4.0 on both economic and environmental performance.
Nakandala et al. (2023)	Industry 4.0 technology capabilities (4 items)	Incremental innovation and operations resilience	SC resilience	/	A survey of 117 Australian manufacturing firms	Industry 4.0 capabilities directly and positively impact SC resilience and incremental innovation acts as a complementary mediator for the Industry 4.0 technologies' relationship with SC resilience.
Ruel et al. (2023)	SC digital tools adoption level (15 items)	/	/	RBV	A survey of 311 SC managers	Firm sizes show a significant difference in SC digital tools adoption level
Our study	Industry 4.0 adoption level (16 items)	SC collaboration and SC visibility	SC resilience	Dynamic RBV	A survey of 408 Chinese manufacturing firms	The adoption of Industry 4.0 technologies enhances IT advancement and further achieves SC resilience through the mediating roles of SC collaboration and SC visibility.

et al., 2019). Dynamic RBV suggests IT advancement is an important type of resource heterogeneity. Firms having sustainable technological leadership and taking the lead in adopting advanced technologies means those firms have important first-mover advantages. Based on the literature, although firms increasingly invest resources to facilitate IT development, a higher level of IT investment does not necessarily mean a better use of IT resources (Wu et al., 2006; Yeniyurt et al., 2019). For a particular IT resource to become a firm-specific resource heterogeneity, thereby increasing its applicability in SC management, resources must continue to be advanced or adopted ahead of competitors. A firm with a high level of IT advancement possesses IT resources that are unique and valuable among firms and can thus provide exclusive benefits for the firm than that of its competitors in a certain period (Yeniyurt et al., 2019). A high level of IT advancement might provide additional benefits such as digital competitiveness and high operations efficiency that later adopters cannot obtain (Tortorella et al., 2019).

2.3. *SC capability*

For decades, dynamic RBV has demonstrated the crucial roles of capabilities in enhancing a firm's competitive advantage (Helfat and Peteraf, 2003; Teece et al., 1997). SC capability refers to firms' ability to interact with their SC partners to support productivity improvement, network visibility, and real-time feedback in all stages of the SCs (Queiroz et al., 2019). With the development of digital technologies, collaboration and end-to-end visibility have been acknowledged as major drivers of future improvements in SCs and the OM domain (Dolgui & Ivanov, 2022).

Based on dynamic RBV, we focus on two representative SC capabilities: SC collaboration and SC visibility. SC collaboration represents relational capability that can improve mutual interaction between SC partners and build SC relationships, whereas SC visibility represents technological capability that can improve SC transparency and enhance information sharing (Wang et al., 2013). Specifically, SC collaboration indicates multiple SC partners build closer relationships and make decisions together to create mutual values (Liao et al., 2017a; Scholten and Schilder, 2015). SC collaboration helps the whole SC achieve a competitive advantage through the coordination of relationships, mutual interests, and risk sharing (Benitez et al., 2021; Li et al., 2021; Zhao et al., 2011). By contrast, SC visibility refers to the ability the entire SCs can have real-time access of data to support planning, monitoring, and control decision-making (Ivanov, 2021). SC visibility significantly benefits the whole SC by enhancing SC responsiveness (Srinivasan and Swink, 2018), facilitating operational performance (Swift et al., 2019), and curbing opportunism (Yang et al., 2021).

Many studies have focused on SC capabilities concerning those two specific types. For instance, Salisu and Bakar (2019) examined the impacts of informational capability (i.e., visibility) and relational capability (i.e., collaboration) regarding the performance of small- and medium-sized firms. Pettit et al. (2013) studied SC visibility to demand and supply information, and SC collaboration with suppliers and customers played essential roles in strategic performance. Accordingly, we chose SC visibility and SC collaboration as two representatives and commonly deployed capabilities based on both dynamic RBV and SC literature.

2.4. SC resilience

In recent years, SC resilience has drawn increased attention from academics and practices. Scholars have identified three phases of SC resilience: pre-disruptions, during disruptions, and post-disruptions. These correspond to three SC resilience strategies: proactive, concurrent, and reactive, respectively (Ali et al., 2017; Mubarik et al., 2021). However, some relevant concepts such as pre-disruptions and anticipation seem to overlap with practices in a broader managerial approach called SC risk management (e.g., risk prevention and control).

In this study, we define SC resilience as the effectiveness of SC in responding to and recovering from disruptions or risk events, as well as absorbing the shock, bouncing back, and continuing to grow (Ambulkar et al., 2015; Pettit et al., 2019; Yang et al., 2021). This definition focuses on firms' effectiveness in responding to and recovering from disruptions. SC resilience is related to quick reactive thinking and is the first response to cope with disturbances in the during-disruptions phase. Meanwhile, a quick recovery is required in the post-disruption phase to bounce back from disruption and return to the original or desired status (Ali et al., 2017; Brandon-Jones et al., 2014). The literature suggested SC resilience enables firms to quickly respond to changes in an uncertain environment, thus reducing the negative impacts of SC disruptions and improving firms' operational performance. SC resilience ensures continuity of material supply and provides fast and reliable delivery, enhancing end customers' value and satisfaction (Gu et al., 2021).

Moreover, different researchers have operationalized SC resilience in different ways. Some have focused on the capability aspects of resilience (i.e., Gu et al., 2021; Pettit et al., 2019). Gu et al. (2021) regarded resilience as a kind of SC capability that can improve SC performance, whereas other scholars have focused on the competitive advantage aspects of resilience (i.e., Brandon-Jones et al., 2014; Shin and Park, 2021). Brandon-Jones et al. (2014) regarded SC resilience as a competitive advantage that can be achieved through SC visibility. Shin and Park (2021) also considered SC resilience as a performance outcome; they examined how it could be enhanced by leadership-driven SC structures.

Accordingly, both capability and competitive advantage perspectives of SC resilience are important in the literature, and SC resilience performs different roles based on distinct studies and theories. Based on dynamic RBV, we regard SC resilience as the competitive advantage of SCs rather than capability because SC resilience can represent an outcome status of risk mitigation and disruption restoration, and it can be achieved from IT resources and dynamic SC capabilities. Distinguishing SC resilience from SC capabilities also allows us to scrutinize exactly which form of SC capability can enhance SC resilience and reveal the intricacy in the relationships between them.

2.5. Dynamic RBV

We draw on dynamic RBV (Helfat and Peteraf, 2003; Peteraf, 1993; Teece et al., 1997) to theoretically investigate the relationship between Industry 4.0, IT advancement, SC capability, and SC resilience. Dynamic RBV is the combination of RBV and DCV (Helfat and Peteraf, 2003). RBV emphasizes the importance of heterogeneity of resources and capabilities, but it ignores that obtaining competitive advantage is a dynamic process involving the development, accumulation, and combination of distinct resources and capabilities (Barney et al., 2021; Li et al., 2022; Teece et al., 1997). To explain competitive advantage, RBV should be supplemented by concepts from the evolution and dynamic perspective (Helfat and Peteraf, 2003). The equilibrium viewpoint of RBV has led many scholars to criticize RBV as static and lacking a dynamic viewpoint (Barney, 2020; Barney et al., 2021). As such, DCV can address that limitation of RBV by adding a dynamic element to the static theory (Barney, 2020; Barney et al., 2021) and demonstrating how resources and capabilities can lead to competitive advantages over time (Li et al., 2022). Therefore, dynamic RBV integrates both RBV and DCV and specifically complements RBV with its focus on dynamically reconfiguring resources and capabilities to gain sustained competitive advantage (Li et al., 2022).

The core concepts of dynamic RBV suggests that an organization can achieve a competitive advantage by possessing bundles of resource heterogeneity (Barney, 1991; Brandon-Jones et al., 2014). Resource heterogeneity indicates unique and varying resources of firms that are difficult to imitate and surpass (Helfat and Peteraf, 2003; Peteraf, 1993). Firms endowed with such resources can better satisfy customer needs and compete in the market (Peteraf, 1993). Resource heterogeneity can be further classified into two types: size advantages and first-mover advantages (Ghemawat, 1986; Helfat and Peteraf, 2003). Size advantages indicate scale advantages of differential levels of resources owned by firms (Helfat and Peteraf, 2003). Adopting Industry 4.0, which involves substantial resources, is in part related to size advantages. First-mover advantages represent firms' pioneering efforts to own resources superior to their competitors' (Lieberman and Montgomery, 1988), which is consistent with the concepts of IT advancement in this study. Indeed, firms can obtain first-mover advantages through sustainable leadership in technology and by being a first-mover in specific advanced technology (Lieberman and Montgomery, 1988; Peteraf, 1993). In addition, dynamic RBV suggests there exist development and shift paths through which different kinds of resources can be coordinated and evolved, thus facilitating capabilities and maintaining sustained competitive advantages. In our study, we follow the theoretical logic of dynamic RBV and regard Industry 4.0 adoption and IT advancement as two important kinds of resource heterogeneity that can be shifted and transformed internally.

Furthermore, dynamic RBV stresses two essential dynamic capabilities that enable firms to obtain and maintain sustainable competitive advantage: relational capability and informational capability (Salisu and Bakar, 2019; Wang et al., 2013; Yang et al., 2018). Relational capability refers to firms' ability to engage in mutual adjustment activities and to develop and leverage intra-firm/inter-firm cooperation (Wang et al., 2013). On the other hand, informational capability refers to the capability to share rich information with partners and reduce information distortion within and outside of firms (Wang et al., 2013). We consider SC collaboration as relational capability and SC visibility as informational capabilities. In summary, we employ dynamic RBV to investigate the relationship between IT resources (Industry 4.0 technology and IT advancement), SC capabilities (SC collaboration and SC visibility), and SC resilience as a competitive advantage, which coincides with the theoretical framework of dynamic RBV.

3. Hypothesis development

3.1. Effect of industry 4.0 adoption on IT advancement

According to dynamic RBV, there are unique evolution and development paths of a firm's different types of resources with heterogeneity (Helfat and Peteraf, 2003; Teece et al., 1997). Industry 4.0 and IT advancement, as two representative IT resources, can be evolved internally. As an intangible technological resource, IT advancement depends on adapting and implementing tangible information and digital technologies (Wu et al., 2006). The intangible nature of IT advancement relies on the implementation of tangible and preexisting technologies such as Industry 4.0 technologies.

To achieve IT advancement, firms should fully integrate diverse advanced technologies in their operational processes and adopt them ahead of competitors. Therefore, firms taking the lead in adopting or orchestrating diverse advanced technologies of Industry 4.0 can generate first-mover advantage among industry competitors (Dalenogare et al., 2018), thus improving their IT advancement. Based on dynamic RBV, when the size advantage of Industry 4.0 technologies accumulates to a certain extent, the adoption of Industry 4.0 technologies can be transformed and developed into firms' IT advancement ahead of the industry. Accordingly, we argue the adoption of Industry 4.0 leads to the development of IT advancement and propose the following hypothesis.

H1. The adoption of Industry 4.0 is positively related to IT advancement.

3.2. *Effects of industry 4.0 adoption on SC capability*

Digital and advanced technologies play an increasingly important role in SC capabilities (Dolgui & Ivanov, 2022). The literature suggested Industry 4.0 technologies as unique technological resources might affect firms' SC capability, particularly regarding collaboration and visibility (Ahmed et al., 2021; Núñez-Merino et al., 2020). Specifically, in the digital age, Industry 4.0 can maintain and enhance collaboration across SCs (Fatorachian and Kazemi, 2021; Queiroz et al., 2019). For instance, the application of CC and BDA allow for a web-based management dashboard and enhance cloud-based collaboration both within and outside an SC (Ghobakhloo, 2018). The IoT combines intelligent and autonomous machines that allow collaboration among SC partners (Ahmed et al., 2021; Eslami et al., 2021; Manavalan and Jayakrishna, 2019). M2M is conducive to gathering and exchanging data both remotely and automatically (Frank et al., 2019) to improve interfirm coordination. As a kind of electronic contract, blockchain offers a new way to enforce agreements and suppress opportunism in exchanges, thereby improving SC coordination (Queiroz et al., 2019; Tortorella et al., 2021).

Further, Industry 4.0 enables SCs to obtain accurate, timely, and useful information, promoting and maybe improving SC visibility (Li et al., 2021; Yang et al., 2021). Specifically, CC and BDA provide the service of remote storage of real-time, operational data, and on-demand access to data displayed in a cloud (Li et al., 2020b). That facilitates the fully sharing, free circulation, and optimized configuration of information needed in the entire SCs. ERP and RFID enhance data collection and help achieve transparency and information visibility, along with the SC. IoT enhances quality control, and production efficiency enables manufacturing firms to monitor and evaluate both upstream and downstream operations. That leads to increased information sharing within SCs (Ahmed et al., 2021; Eslami et al., 2021; Manavalan and Jayakrishna, 2019). AR and VR provide pick-by-vision application and interactive robot trajectory planning in warehouse operations, enhancing SC visual perception and efficiency (Masood and Egger, 2019; Woltering et al., 2020). Therefore, digital technologies jointly enable manufacturers to obtain accurate and timely information from major suppliers and customers, promoting SC visibility (Fatorachian and Kazemi, 2021; Yang et al., 2021). In summary, we believe Industry 4.0 can effectively improve both SC collaboration and SC visibility and propose the following hypotheses.

H2a. The adoption of Industry 4.0 is positively related to SC collaboration.

H2b. The adoption of Industry 4.0 is positively related to SC visibility.

3.3. *Effects of IT advancement on SC capability*

According to dynamic RBV, IT advancement, as first-mover advantage of firms, can also help build SC capabilities concerning SC collaboration and visibility. A high level of IT advancement indicates the firm is equipped with advanced IT resources that help it achieve more instant communication and lower transaction costs with SC partners than its competitors (Li et al., 2020a; Wu et al., 2006). For instance, Dell is known for its advanced SC system, which can coordinate different parties efficiently for the just-in-time assembly of customized computer orders. That allows Dell to enjoy a more beneficial collaboration with its suppliers and customers than its competitors (Erhun et al., 2021). Advanced IT resources also assist in promoting SC coordination by reducing coordination costs or increasing the efficacy and quality of coordination activities such as inventory planning, demand forecasting, and order scheduling thus improving interfirm collaboration among SC partners (Tigga et al., 2021; Yeniyurt et al., 2019).

IT advancement might also benefit SC visibility. Specifically, advanced IT resource equipment can enhance the speed, trust, and efficiency of information transferred in an SC (Barratt and Oke, 2007; Fatorachian and Kazemi, 2021; Tortorella et al., 2021). By increasing the speed and reliability of information acquisition and exchange, IT advancement ensures the availability and timeliness of important information for each SC party (Tigga et al., 2021). Firms with advanced IT resources can provide a visual platform where SC partners can share information with a low leakage threat and high reliability, thus enhancing SC visibility (Fatorachian and Kazemi, 2021; Yeniyurt et al., 2019). In summary, IT advancement will support and stimulate SC collaboration and SC visibility. We propose the following hypotheses.

H3a. IT advancement is positively related to SC collaboration.

H3b. IT advancement is positively related to SC visibility.

3.4. *Effects of SC capability on SC resilience*

The capability of SC partners to anticipate and respond to disruptions significantly affects SC resilience (Brandon-Jones et al., 2014; Tukamuhabwa et al., 2015). In line with dynamic RBV, firms attempting to achieve the competitive advantage of SC resilience must integrate and orchestrate capabilities in their SCs. The literature concerning SC resilience also suggested, to achieve resilience, it is vital for firms to build certain capabilities that are aligned with their SC partners to manage both expected and unexpected disruptions (Ivanov, 2021; Ivanov and Dolgui, 2021; Queiroz et al., 2019). SC collaboration and visibility are important SC capabilities that can enhance SC resilience effectively.

Specifically, we argue SC collaboration can improve SC resilience through goal congruence and operations synchronization. A high level of SC collaboration is about jointly developing strategic plans, sharing risks, and having mutual interests within an SC (Scholten and Schilder, 2015). The characteristics of goal congruence derived from SC collaboration indicate the whole SC will act in concert for mutual interests when risks and disruptions occur, which is essential for achieving effective communication and SC resilience. Moreover, increasing SC collaboration is often associated with aligning and adjusting operations routines in a synchronized manner within the SC. The operations synchronization formulated in SC collaboration benefits system-level responses and recovery when disruption occurs, thus achieving SC resilience (Tukamuhabwa et al., 2015). Therefore, SC collaboration helps SCs respond to disruptions through collaborative planning and sharing of intelligence to coordinate immediate responses (Ali et al., 2017; Eslami et al., 2021; Scholten and Schilder, 2015).

Additionally, SC visibility might positively affect SC resilience concerning two mechanisms: ex-ante monitoring and ex-post response. On the one hand, SC visibility enables a firm to generate awareness of the current status of SC operating assets and the environment by monitoring performance (Ali et al., 2017; Ambulkar et al., 2015; Swift et al., 2019). This also allows the firm to work jointly with SC partners to correct operating deviations and develop contingency plans for unseen risks (Mubarik et al., 2021). On the other hand, SC visibility serves as a warning strategy that provides valuable time for firms to align their SC partners to minimize disruptive impact (Ali et al., 2017). SC visibility supports the development of real-time information transparency in the entire SC, assisting firms in coping with SC disruption risks and events (Mubarik et al., 2021). The subsequent timely exchange of information improves risk event readiness of SC members, thus making the SC more resilient and responsive to disruptions (Jüttner and Maklan, 2011). Therefore, SC visibility can help an SC quickly recover and return to a better performance state. In summary, a high level of SC collaboration and SC visibility might positively influence SC resilience, so we propose the following hypotheses.

H4a. SC collaboration is positively related to SC resilience.

H4b. SC visibility is positively related to SC resilience.

Through hypotheses 2a–b, 3a–b, and 4a–b, we propose Industry 4.0 and IT advancement might indirectly affect SC resilience through SC capabilities, namely SC collaboration and visibility. The indirect effect of Industry 4.0 technologies and IT advancement on SC resilience can be understood based on the resources-capability-performance framework proposed in dynamic RBV (Barney, 1991; Grant, 1991). According to dynamic RBV, when IT resources (i.e., Industry 4.0 and IT advancement) are combined and used, advanced resources create capabilities (i.e., SC collaboration and SC visibility). An SC equipped with SC collaboration and SC visibility is more capable of responding to and recovering from SC disruptions and risks, resulting in stronger SC resilience (Fatorachian and Kazemi, 2021; Queiroz et al., 2019). Industry 4.0 and IT advancement might positively and indirectly affect SC resilience through SC collaboration and visibility. We propose the following hypotheses.

H5a. The adoption of Industry 4.0 positively and indirectly affects SC resilience through SC collaboration.

H5b. The adoption of Industry 4.0 positively and indirectly affects SC resilience through SC visibility.

H6a. IT advancement positively and indirectly affects SC resilience through SC collaboration.

H6b. IT advancement positively and indirectly affects SC resilience through SC visibility.

Fig. 1 represents our study's overall conceptual model, which illustrates the interrelationships of the five key research constructs: Industry 4.0 adoption, IT advancement, SC collaboration, SC visibility, and SC resilience.

4. Research methodology

4.1. Questionnaire development

We used the survey method to test our hypotheses. Survey designs with questionnaires are the most commonly used methodology in empirical OM research (Zhao et al., 2011). The results of a survey can explain and predict phenomena or relationships and thus contribute to theory development (Malhotra and Grover, 1998). We designed our questionnaire based on the adaptation of several existing effective instruments. We reviewed the literature extensively to identify valid survey items to measure our constructs. To ensure conceptual equivalence, we used the following translation/back-translation procedures. First, we developed an English questionnaire and translated it into Chinese. Then two researchers independently translated the Chinese version back into English. We compared the translated version with the original and made minor changes to the Chinese version when we found discrepancies. A third researcher was involved when necessary.

The proposed 16 representative Industry 4.0 technologies were based on both literature and practice. First, we conducted a systematic literature review by searching keywords (e.g., Industry 4.0 technologies, digital technologies, front-end technologies) in journal publications for the past 10 years. That process enabled us to prepare a list of 18 representative Industry 4.0 technologies that were widely studied in the literature. Then we developed a construct to measure Industry 4.0 using those 18 technologies. We pretested that construct through four practitioner interviews. Specifically, we targeted managers or executives who were knowledgeable of Industry 4.0 and in charge of IT and digital technologies in firms. The four selected interviewees were working in various industries and firms of different sizes and ages. All interviews were conducted using online meetings (e.g., VooV Meeting). Each lasted around 30 min and was recorded. We incorporated a semi-structured interview protocol to guide the interviews. We asked interviewees questions about the particular Industry 4.0 technologies being implemented in their firms.

Based on the interview results, we removed two Industry 4.0 technologies that are less common in practice from our construct: digital twins and cyber–physical system (CPS). For instance, several managers stated, "I do not think that digital twins/CPS is a common practice in manufacturing firms like ours." That process allowed us to confirm that the 16 Industry 4.0 technologies covered by our construct widely exist in firms (Li et al., 2021). Finally, we put forward 16 representative Industry 4.0 technologies that were supported by both the literature and real-world practices to form the construct in our major survey (Choi et al., 2022).

We measured the 16 Industry 4.0 technologies based on firms' different adoption levels. Specifically, we asked the respondents to indicate the different stages during which their firms adopted and implemented the 16 types of Industry 4.0 technologies from (1) None,

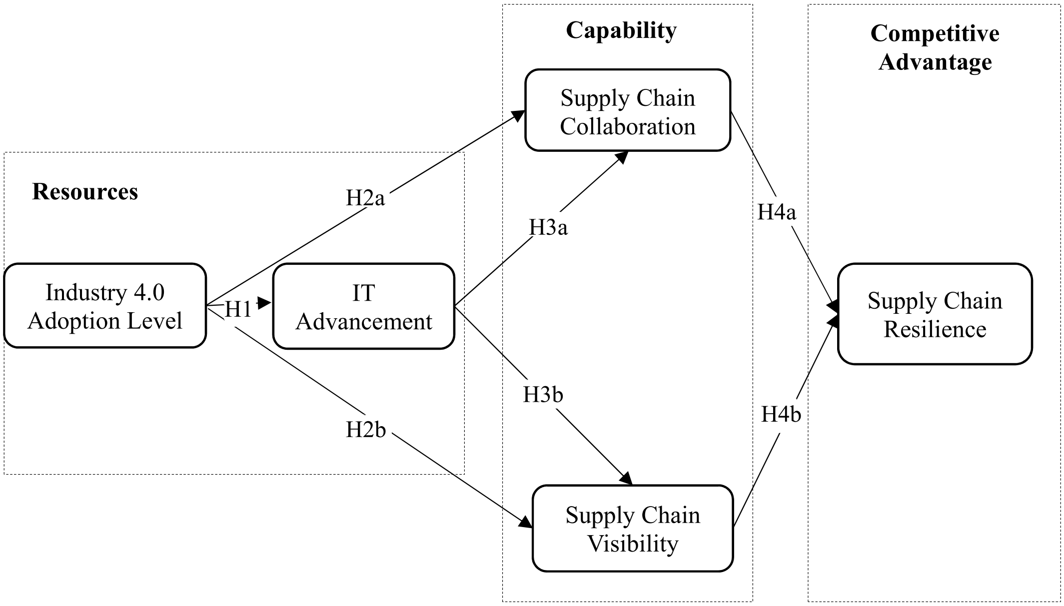


Fig. 1. Research model.

(2) Initiation, (3) Adoption, (4) Adaptation, (5) Acceptance, (6) and Routinization to (7) Infusion (Cooper and Zmud, 1990). We provided definitions for all 16 technologies of Industry 4.0 in the survey so respondents could better comprehend the measures. We considered Industry 4.0 adoption as a second-order construct.

We adapted the measures for IT advancement from Wu et al. (2006). IT advancement measures the degree of proactive adoption and implementation of advanced IT to find SC management solutions ahead of competitors. We asked respondents to evaluate how much they agreed with the advancement of their firm's information and digital technology compared with the industry standards and their competitors. We used a 7-point Likert scale with "1" for "strongly disagree" and "7" for "strongly agree." We adopted measures for SC collaboration from Mandal et al. (2016) and Jüttner and Maklan (2011).

We asked the respondents to evaluate how much they agreed that their firms collaborate with SC partners. We used a 7-point Likert scale with "1" for "strongly disagree" and "7" for "strongly agree." We adopted measures for SC visibility from Mandal et al. (2016) and Jüttner and Maklan (2011). We then asked respondents to indicate how much they agreed that the whole SC has access to monitoring, forecasting, and tracking information. We used a 7-point Likert scale with "1" for "strongly disagree" and "7" for "strongly agree." We adopted the measures for SC resilience from Brandon-Jones et al. (2014). We asked respondents to evaluate whether they agreed that their firm can speedily recover after SC disruption. We used a 7-point Likert scale with "1" for "strongly disagree" and "7" for "strongly agree." We also added the respondent's character as the marker variable (Li et al., 2021). We evaluated it based on the respondents' years of working in their firms, with "1" for "less than 1 year" and "5" for "more than 12 years."

We added firm size (measured by the number of employees and fixed assets) and firm age as control variables. Because larger and older companies tend to have more resources, they might achieve a higher level of SC capability and resilience than smaller and younger competitors (Gu et al., 2021). Moreover, we controlled for the impact of industry heterogeneity. Despite our sample's being focused on manufacturing firms, each manufacturer in different industry might have had its own SC capabilities to cope with disruption and crisis and show different levels of resilience. Industry heterogeneity might influence firms' SC capability and resilience differently. Therefore, we followed previous studies to control industry heterogeneity by creating two dummy variables: industry 1 (coded as 1 if the firm was in the semiconductor industry; 0 otherwise) and industry 2 (coded as 1 if the firm was in the computer and electronic products industry; 0 otherwise), with other industry types as the baseline group (Huo et al., 2022; Yang et al., 2021; Zhou et al., 2014).

Further, we controlled for the types of resource intensity concerning the industries of the sample firms (e.g., labor-intensive, capital-intensive, and technology-intensive industries) because firms with different levels of resource intensity can have distinct SC capabilities and perform distinctively during SC disruptions. Therefore, we created two dummy variables: intensive 1 (coded as 1 if the firm were in the labor-intensive industry; 0 otherwise) and intensive 2 (coded as 1 if the firm were in the capital-intensive industry; 0 otherwise), with technology-intensive industry as the baseline group.

Prior to the final data collection procedures, we arranged a 30-sample pilot study to assess the clarity of the whole questionnaire (Huo et al., 2016; Li et al., 2021). We then interviewed pilot participants after they completed the questionnaire. Based on their valuable feedback, we modified and refined the questionnaire to ensure all the items were easy to understand. All the measures are shown in Appendix A.

4.2. Sampling and data collection

We conducted the survey in China for two main reasons. First, Chinese manufacturing firms play important roles worldwide and are widely considered global manufacturing powerhouses (Zhao et al., 2011), thus providing a large population for the sampling design. Second, the Chinese government was implementing the national strategic plan, "Made-in-China 2025," which aims to enhance industry capability through innovation-driven manufacturing and industrial transformation (Choi et al., 2022). That national strategic plan motivates manufacturing firms to invest heavily in innovation and implement advanced manufacturing technology, which is consistent with our study's theme of Industry 4.0.

Given the uneven economic development in China, we collected data from manufacturing companies located in both economically developed regions, including Bohai Bay Economic Rim, Pearl River Delta, and Yangzi River Delta, and other regions that are less economically developed, which included areas in Northeastern, Central, and Western China (Zhao et al., 2011). Our sample firms also covered all 34 provinces in China, ensuring generalizability. Our sampling frame was developed based on information and services provided by a leading professional market research consulting firm in China. The company is a member of the Chinese Information Industry Association and possesses comprehensive business directories and information such as names and contact information of senior managers.

With our sampling frame in hand, we first contacted companies we randomly selected to inform them about the aim and relevance of our study, invite their participation, and identify a qualified informant. We explained the research objective to enhance their willingness to participate in the survey. Qualified informants needed to have a minimum of 3 years of SC-management-related work experience and to understand the firm's information and digital technology implementation status and future plans.

With that communication approach, the final version of the survey was sent to 976 manufacturing firms through email, along with a cover letter detailing the study's objectives and instructions for the questionnaire. Email and online survey methods offer benefits such as the ability to save time and money by overcoming geographical distance (Kamble et al., 2018a). After screening out the unqualified samples (i.e., incomplete questionnaires, respondents lacking SC experience, and firms without Industry 4.0 investment or planning in the past 3 years), we obtained a total of 408 qualified and useable samples, resulting in a response rate of 41.8%.

Table 3
Summary of descriptive statistics.

Title	Frequency	%	Title	Frequency	%
Main Administrative Regions in China			Firm History		
Northeastern region	42	10.3	Under 5 years	25	6.1
Central region	77	18.9	6–10 years	116	28.4
Eastern region	270	66.2	11–15 years	120	29.4
Western region	19	4.7	16–20 years	90	22.1
Industry			21–25 years	32	7.8
Food industry	24	5.9	Over 25 years	25	6.2
Textiles mills and clothing	18	4.4	**Sales Revenue (RMB)**		
Wood and bamboo products	7	1.7	Under 10 million	63	15.4
Paper and printing	23	5.6	11–50 million	77	18.9
Chemical and material	33	8.1	51–100 million	66	16.2
Plastic and rubber materials	17	4.2	101–1000 million	104	25.5
Electronic parts	40	9.8	1–5 billion	81	19.9
Semiconductors	39	9.6	Over 5 billion	17	4.1
Computers and electronics	102	25.0	**Respondents**		
Machinery and equipment	41	10.0	CEO/President	31	7.6
Precision instrument	40	9.8	VP/Director	91	22.3
Motor vehicles and transport	24	5.9	Functional manager	189	46.3
			Professionals	97	23.8

Table 3 shows the companies' profiles and informants' essential information. We categorized the demographic data analysis of 408 valid samples by their main economic, administrative region, industry, firm history, firm sales, and informants' positions. As a result, firms of various sizes and ages from different regions and industries were present in our sample, indicating the representative generalizability of our study (Flynn et al., 2010). More than 75% of informants were in a managerial or higher position, suggesting they were knowledgeable about the subject matter of the questionnaire.

4.3. Nonresponse bias and common method bias

Nonresponse bias is a survey result that varies between the respondent and nonrespondent that might cause a bias in the results of the survey (Dillman, 2007). In line with Wagner and Kemmerling (2010), we conducted an independent sample test to compare early respondent-responses received within the first 2 weeks and late respondent-responses received within the 3rd week or later. We found no statistically significant differences between the early and late waves of respondents ($p > 0.05$; (Handfield et al., 2015), indicating nonresponse bias did not significantly affect this study.

We also took several steps to mitigate and check potential common method bias (CMB). First, we conducted Harman's one-factor test with confirmatory factor analysis (CFA; (Sanchez and Brock, 1996). The model fit indices were $\chi2$ (511) = 1501.85, NNFI = 0.88, CFI = 0.89, RMSEA = 0.093, and SRMR = 0.086. These were much worse than those of the measurement model, indicating a single factor was not acceptable. Second, we used the informants' years of working in their firms as the marker variable to assess the potential CMB (Lindell and Whitney, 2001). The difference between $\chi2$ (454) = 515.89 and Chi-$\chi2$ (475) = 530.64 was $\chi2$ (21) = 14.75, which was not significant ($p > 0.05$). We also used the value of the smallest positive correlation ($r = 0.12$) between the marker variable and other latent variables to adjust the correlations among the variables. All the originally significant correlations remained significant after the adjustment. These results indicated that CMB was unlikely to be a serious concern in our study.

4.4. Reliability and validity

We employed the two-step method to test reliability (Narasimhan and Jayaram, 1998). First, we performed two EFAs to ensure the one-dimensionality of the constructs. The first EFA was performed with Industry 4.0 adoption. The KMO measure of sampling adequacy was 0.851, indicating sufficient intercorrelation, whereas Bartlett's test of sphericity was significant ($\chi^2/\text{df} = 1198.192/120$, $p < 0.001$) (Narayanamurthy and Tortorella, 2021; Zailani et al., 2012). In that step, we removed two Industry 4.0 technologies items, blockchain and M2M, because their factor loadings were lower than the 0.5 minimum criterion (Hair, 2006; Hair et al., 2017). As Table 4 shows, three factors were extracted, and the factor loadings of the remaining 14 Industry 4.0 technologies were found to be higher than the 0.5 minimum criteria (Hair, 2006; Hair et al., 2017) and to have low cross-loadings on other factors, ensuring one-dimensionality. Table 5 shows factor analysis for IT advancement, two SC capabilities, and SC resilience. We used Varimax rotation to validate there were four constructs with eigenvalues greater than 1.0. The KMO measure of sampling adequacy was 0.934, indicating sufficient intercorrelation whereas Bartlett's test of sphericity was significant ($\chi^2/\text{df} = 2183.32/78$, $p < 0.001$) (Narayanamurthy and Tortorella, 2021; Zailani et al., 2012). Second, we calculated Cronbach's alpha and composite reliability for each construct, and Table 6 shows all values were higher than the threshold of 0.70, confirming the constructs had good reliability (Lance et al., 2006).

To assess convergent validity, we conducted a CFA in which all items were linked to corresponding constructs, with the covariance freely estimated. The model fit indices were $\chi2$ (475) = 537.90, NNFI = 0.99, CFI = 0.99, RMSEA = 0.017, and SRMR = 0.038, indicating it was acceptable (Hu and Bentler, 1999). In addition, the CFA results showed all factor loadings were higher than 0.50 and were significant at the 0.01 level, indicating convergent validity was satisfied. We also calculated the average variance extracted (AVE) for all constructs. Results showed AVE for all constructs was greater than 0.50, indicating convergent validity (Flynn et al., 2010). Regarding assessing discriminant validity,

Table 4
EFA results for industry 4.0 adoption level (computing, digitalizing, and integrating technologies).

	Factor Loadings		
	Digitalizing Technologies	Integrating Technologies	Computing Technologies
AV	**.662**	.256	−.106
BI	**.646**	.033	.190
Simulation	**.572**	.105	.296
IoT	**.558**	.128	.212
ERP	**.557**	−.013	.296
Robotics	**.539**	.204	.106
AR	.006	**.668**	.286
3DP	.043	**.626**	.127
VR	.226	**.609**	−.028
RFID	.297	**.604**	−.059
Sensors	.076	**.577**	.276
BDA	.224	.127	**.730**
CC	.191	.164	**.721**
AI	.180	.115	**.629**
Eigenvalue	2.361	2.099	1.905
Total Variance Explained		45.468%	

Table 5
EFA results in IT advancement, supply chain collaboration, supply chain visibility, and supply chain resilience.

	Factor Loadings			
	Supply Chain Resilience (RES)	Supply Chain Visibility (VIS)	IT Advancement (ADV)	Supply Chain Collaboration (COL)
RES3	**.784**	.104	.249	.145
RES2	**.714**	.145	.109	.276
RES4	**.703**	.224	.153	.201
RES1	**.654**	.353	.226	.114
VIS3	.157	**.807**	.221	.156
VIS2	.226	**.697**	.176	.301
VIS1	.326	**.634**	.157	.317
ADV3	.264	.061	**.752**	.248
ADV1	.254	.280	**.752**	.048
ADV2	.097	.219	**.740**	.274
COL3	.205	.344	.149	**.730**
COL2	.252	.170	.354	**.725**
COL1	.338	.343	.201	**.560**
Eigenvalue	2.590	2.139	2.119	1.876
Total Variance Explained		67.109%		

Table 6
Means, standard deviations, and correlation.

	Mean	S.D.	1	2	3	4	5
1. Industry 4.0 Adoption Level	3.39	0.935	**.82**				
2. IT Advancement	5.01	1.107	.22**	**.72**			
3. Supply Chain Collaboration	5.26	1.054	.24**	.60**	**.72**		
4. Supply Chain Visibility	5.41	1.047	.28**	.54**	.69**	**.85**	
5. Supply Chain Resilience	5.28	1.003	.22**	.55**	.63**	.60**	**.71**

Note. Numbers on the diagonal are the square root of the AVE values.
**$p < 0.01$.

the square roots of AVE (the bold diagonal of the matrix in Table 7) of every construct were higher than other correlation coefficients, thus ensuring discriminant validity (Fornell and Larcker, 1981).

4.5. Hypotheses testing

We used structural equation modeling (SEM) with LISREL 8.54 software to test the direct hypotheses. The model fit indices were $\chi 2$ (480) = 572.47, NNFI = 0.99, CFI = 0.99, RMSEA = 0.022, and SRMR = 0.041, indicating the model was acceptable (Hu and Bentler, 1999). To test whether there was any multicollinearity problem, we computed variance inflation factors (VIF). The maximum VIF of our models was 2.00, substantially lower than the threshold of 10 (Dubey et al., 2017; Hair, 2006; O'brien, 2007). Therefore, it was impossible for multicollinearity to be a significant issue.

Fig. 2 shows SEM results with significant paths and standard coefficients. The impact of the adoption of Industry 4.0 technologies on IT advancement was positive and significant, supporting H1. The results showed implementing Industry 4.0 technologies had a nonsignificant effect on SC collaboration and SC visibility, rejecting H2a and H2b, whereas IT advancement is significantly and positively related to SC collaboration and visibility, supporting H3a and H3b. Both SC collaboration and visibility have significant and positive effects on SC resilience, thus supporting H4a and H4b.

To test the mediation hypotheses, we used the bootstrapping method with SPSS 25 software to obtain confidence intervals (CIs) following the approach Preacher and Hayes (2008) proposed. We used bootstrapping with 5000 resamples to test the significance of the indirect effects of Industry 4.0 on SC resilience through SC collaboration and visibility.

Table 8 showed Industry 4.0 technologies had a positive, indirect effect on SC resilience (total effect = 0.24; $t = 4.58$, p < 0.001) through SC collaboration (indirect effect = 0.11; $t = 4.40$, p < 0.001) with a 95% CI not containing zero (95% CI [0.059, 0.157]) and through SC visibility (indirect effect = 0.09; $t = 3.75$, $p < 0.001$) with a 95% CI not containing zero (95% CI [0.051, 0.143]). Therefore, H5a and H5b were supported. Similarly, bootstrapping with 5000 resamples was used to test the significance of the indirect effects of IT advancement on SC resilience through SC collaboration and SC visibility. Results showed IT advancement had a positive indirect effect on SC resilience (total effect = 0.50, $t = 13.29$, $p < 0.001$) through SC collaboration (indirect effect = 0.18, $t = 4.62$, $p < 0.001$) with a 95% CI not containing zero (95% CI [0.100, 0.252]) and through SC visibility (indirect effect = 0.13; $t = 3.94$, $p < 0.001$) with a 95% CI not containing zero (95% CI [0.068, 0.199]). Therefore, H6a and H6b were supported.

Table 7
Reliability and validity analysis.

Construct	Items	Factor Loading	Cronbach's α	CR	AVE
Industry 4.0 Adoption Level	COM	0.95	0.686	0.841	0.644
	DIG	0.77			
	INT	0.66			
IT Advancement	ADV1	0.72	0.761	0.760	0.514
	ADV2	0.71			
	ADV3	0.72			
Supply Chain Collaboration	COL1	0.71	0.761	0.764	0.519
	COL2	0.74			
	COL3	0.71			
Supply Chain Visibility	VIS1	0.75	0.769	0.767	0.524
	VIS2	0.72			
	VIS3	0.70			
Supply Chain Resilience	RES1	0.72	0.799	0.803	0.504
	RES2	0.69			
	RES3	0.73			
	RES4	0.70			

4.6. Robustness and endogeneity tests

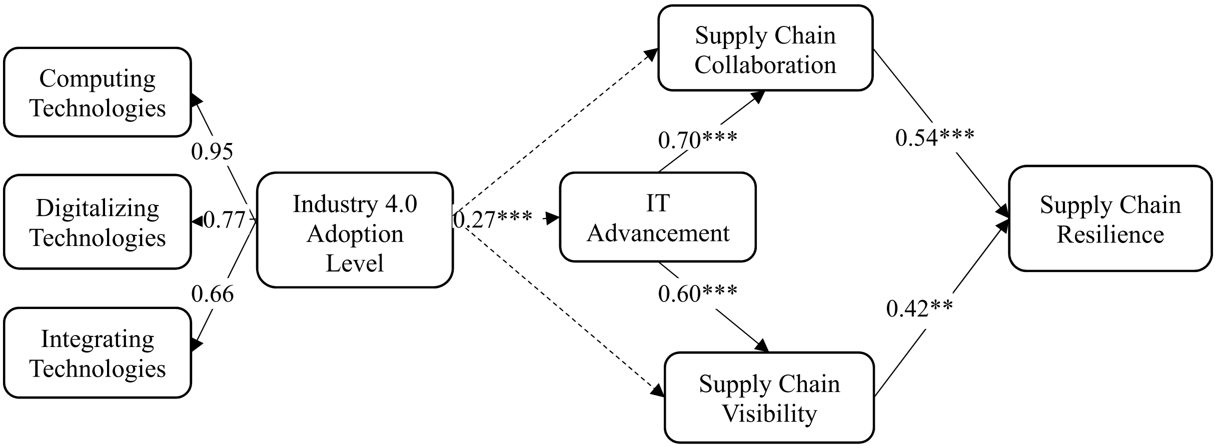
We also conducted robustness checks to ensure the credibility of the results. First, we used an alternative measure of SC resilience. The literature suggested SC flexibility and SC velocity are key components and dimensions of SC resilience (Pettit et al., 2019; Scholten et al., 2014). Therefore, we used SC flexibility and SC velocity as two suborder constructs to capture SC resilience. SC flexibility refers to the ease with which an SC can change its range number and range heterogeneity to cope with market changes or events (Pettit et al., 2019; Stevenson and Spring 2007). We adopted the items of SC flexibility from Mandal et al. (2016). SC velocity refers to the speed with which an SC can react to market changes or events (Sharma et al., 2022a). We adopted the items of SC velocity from Mandal et al. (2016). Appendix A shows measures of SC flexibility and SC velocity. We estimated a direct model without specifying the indirect effect to test H1, H2a-b, H3a-b, and H4a-b. The model fit indices were $\chi 2$ (583) = 752.54, NNFI = 0.99, CFI = 0.99, RMSEA = 0.027, and SRMR = 0.041 (Hu and Bentler, 1999).

All the results shown in Appendix B demonstrated consistency with our previous model. To test H5a-b and H6a-b, we used the bootstrapping method with 5000 resamples and tested the significance of the indirect effects. Results showed Industry 4.0 had a positive indirect effect on SC resilience (total effect = 0.30; $t = 6.12$, $p < 0.001$) through SC collaboration (indirect effect = 0.10; $t = 4.53$, $p < 0.001$) with a 95% CI not containing zero (95% CI [0.057, 0.143]) and through SC visibility (indirect effect = 0.14; $t = 5.12$, $p < 0.001$) with a 95% CI not containing zero (95% CI [0.087, 0.191]), thus supporting H5a and H5b. Results also showed IT advancement still had a positive indirect effect on SC resilience (total effect = 0.53; $t = 15.46$, $p < 0.001$) through SC collaboration (indirect effect = 0.17; $t = 6.46$, $p < 0.001$) with a 95% CI not containing zero (95% CI [0.124, 0.230]) and through SC visibility (indirect effect = 0.21; $t = 7.47$, $p < 0.001$) with a 95% CI not containing zero (95% CI [0.155, 0.261]), thus supporting H6a and H6b. In summary, the results of the alternative measurement of the SC resilience approach were consistent with those of the original model, ensuring the robustness of our findings.

Second, we used the Sobel test as an alternate mediating analysis (Zhang et al., 2022). Appendix C shows a mediation effect as a result of those alternate analyses. Therefore, our research findings were robust.

Third, considering multicollinearity might be a concern for formative second-order constructs (in our study, Industry 4.0 adoption), we further computed both bivariate correlations between any three first-order Industry 4.0 dimensions and VIFs for each Industry 4.0 dimensions to test whether there was any multicollinearity problem (Benlian et al., 2011; Hartono et al., 2014). The results shown in Appendix D suggest none of the bivariate correlations between the three dimensions was above 0.90 (Tabachnick et al., 2013). Moreover, the maximum VIF was 1.08, substantially below the tolerance criteria of 3 (Benlian et al., 2011). Therefore, these results suggest multicollinearity is not a problem in our data and our formative second-order construct of Industry 4.0 adoption is reliable.

Fourth, because this study employed cross-sectional survey research, the threat of endogeneity might be a concern (Wang et al., 2016). Endogeneity refers to the problem where an explanatory variable is correlated with the error term or disturbance term (Lu et al., 2018). The endogeneity issues can seriously bias empirical results and lead to unreliable conclusions. We attempted to address potential issues of endogeneity by employing the instrumental variable (IV) approach (Dong et al., 2020; Lu et al., 2018). Specifically, we conducted a two-stage least squares (2SLS) regression analysis. IVs are correlated with endogenous independent variables but have no correlation with the error term (Wooldridge, 2010). In our model, the independent variable, IT advancement, was not assigned randomly and might have been endogenous. To address that concern, we instrumented IT advancement using high-tech industry type. According to the literature (Tigga et al., 2021), manufacturing firms in high-tech industry might have superior IT



Note. Dashed line indicates nonsignificant relationships.
$^{**}p < 0.05$, $^{***}p < 0.01$.

Fig. 2. Sem results.

Table 8
Mediation results.

Relationship	Total Effect				Indirect Effect			
	Effect	SE	t-student	95% CIs	Effect	SE	t-student	95% CIs
I4.0-COL-RES	0.24***	0.052	4.58	[0.136, 0.340]	0.11***	0.025	4.40	[0.059, 0.157]
I4.0-VIS-RES	0.24***	0.052	4.58	[0.136, 0.340]	0.09***	0.024	3.75	[0.051, 0.143]
ADV-COL-RES	0.50***	0.038	13.29	[0.425, 0.572]	0.18***	0.039	4.62	[0.100, 0.252]
ADV-VIS-RES	0.50***	0.038	13.29	[0.425, 0.572]	0.13***	0.033	3.94	[0.068, 0.199]

Note. $^{***}p < 0.001$; I4.0 refers to Industry 4.0 adoption level.

advancement but do not directly influence the error terms SC collaboration ($t = 1.38, p > 0.1$) and SC visibility ($t = 1.20, p > 0.1$). We created a dummy variable *type* (coded as 1 if the firm was in the high-tech industry; 0 otherwise). Model 1 in Appendix E reports first-stage results, in which we regressed IT advancement from high-tech industry type, and Model 2 reports second-stage results. We used the predicted values from the first stage in the second-stage regressions.

Our IVs passed the under-identification and weak identification tests. The Cragg-Donald Wald F statistic (18.37) exceeded the 10% maximal threshold of the Stock-Yogo weak ID test's critical values (16.38 (Lu et al., 2018); The Kleibergen–Paap rk LM statistic of the under-identification test was 14.56 ($p < 0.001$). That test result rejected the null hypothesis the model was under-identified. Further, the Wald F statistic for the Cragg–Donald weak-identification test was 18.37 ($p < 0.001$). The Wald F statistic of the Kleibergen–Paap rk weak-identification test was 15.49 ($p < 0.001$). Thus, the null hypothesis the instruments were weak was also rejected, indicating our IVs did not suffer from the weak IV problem. The results from the 2SLS estimation were qualitatively consistent with those from the main analysis. Results showed the predicted values (IT advancement) had a significantly positive relationship with SC collaboration ($\beta = 0.59$, $p < 0.01$) and SC visibility ($\beta = 0.34$, $p < 0.1$). That suggests our results are robust after coping with potential omitted variables issues.

5. Discussion

5.1. Results discussion

5.1.1. The impact of industry 4.0 adoption on IT advancement

Our results showed the adoption of Industry 4.0 technologies positively affects IT advancement, which are partially supported by previous studies (i.e., Ghobakhloo, 2019; Tortorella et al., 2019; Veile et al., 2019). The results indicated a firm consistently takes the lead in adopting or orchestrating diverse advanced Industry 4.0 technologies can generate superior IT advancement in their SC management. The results also corresponded with dynamic RBV, indicating there are patterns and paths through which different kinds of resource heterogeneity can be transformed internally (Peteraf, 1993). Firms' first-mover advantage (e.g., IT advancement) ahead of industry and competitors can be achieved in case of the size advantage of Industry 4.0 adoption is accumulated to a considerable degree.

5.1.2. The impact of industry 4.0 adoption and IT advancement on SC capabilities

Surprisingly, we found the adoption of Industry 4.0 had nonsignificant effects on SC collaboration and visibility whereas IT advancement had positive and significant effects on those two SC capabilities. This somewhat contradicted the findings of previous studies (Ahmed et al., 2021; Benitez et al., 2021; Ghobakhloo, 2018; Kamble et al., 2018b). A possible explanation might be the level of Industry 4.0 technology adoption in China might not have reached an advanced enough stage to affect the whole SC (Xu et al., 2018). Industry 4.0 technologies might be implemented internally within firms with limited mobilization and interaction with SC partners.

The results indicated the effectiveness of Industry 4.0 adoption might depend on several factors such as each technology's varying maturity levels and application levels in firms (Ardolino et al., 2022). When digital processes are not robustly designed and continuous implementation practices are not established, the effectiveness of firms' Industry 4.0 adoption might be limited (Rossini et al., 2019). The interesting results, to some extent, further support the theoretical view that dynamic RBV resources with first-mover advantage can exert more effective effect than resource with size advantage (Helfat and Peteraf, 2003; Peteraf, 1993). Specifically, size advantage or scale advantage (i.

e., the adoption of Industry 4.0 technologies) might only help firms achieve internal capability, whereas having superior resources such as first-mover advantage (i.e., IT advancement) enables firms to exert their advantages beyond an organization by influencing SC partners (Peteraf, 1993). In other words, a firm with superior IT advancement can more directly exert its influence on its SC partners and affect the development of leading-edge capabilities along the SC.

Our findings imply investments in Industry 4.0 technologies might not directly result in the anticipated benefits (Wu et al., 2006; Yeniyurt et al., 2019). A scale advantage in the form of front-end technologies needs to be coordinated and transformed to superior resources concerning IT advancement, explaining the pathway with which firms can effectively obtain benefits from the adoption of Industry 4.0 technologies (Tortorella et al., 2019).

5.1.3. *Impact of SC capabilities on SC resilience*

Our study confirmed SC collaboration and SC visibility. Relational and informational SC capabilities, respectively, can effectively facilitate SC resilience, which are in line with the literature (i.e., Brandon-Jones et al., 2014; Jüttner and Maklan, 2011; Scholten and Schilder, 2015). Because our research focused on both the during- and post-disruption phrases of resilience, our findings indicate SC collaboration and SC visibility can effectively improve SC resilience during the last two phrases of resilience complement previous research findings substantially. Specifically, some studies merely regarded SC visibility as a warning strategy that can be effective in the pre-disruption phase (Ali et al., 2017; Ambulkar et al., 2015) and regarded SC collaboration as the ability to respond to SC disruptions in the during-disruption phase (Ali et al., 2017; Pettit et al., 2013). Our study empirically revealed that SC collaboration and SC visibility can exert effect roles in both during- and post-disruption phrases of resilience, making a valuable complement to the literature.

Our study further illuminated and verified the mediating role of SC capabilities in the relationship between Industry 4.0 and SC resilience. Our findings revealed the effect of Industry 4.0 and IT advancement in achieving SC resilience can be realized through the development of SC capabilities. Although researchers have generally discussed the important mediating role of SC capabilities concerning the relationship between traditional technologies and performance (i.e., Wu et al., 2006; Yang et al., 2021), our research further confirmed SC capabilities can play a valid mediating role in the Industry 4.0 era.

To the best of our knowledge, previous studies have not explored the transformation path from Industry 4.0 adoption to SC resilience. Our results reveal both SC collaboration and SC visibility mediate the effect of Industry 4.0 adoption and IT advancement on SC resilience. This finding is important because it answers the question of the influence path from firms' Industry 4.0 adoption to resilience achievement in SCs (Li et al., 2022). From this perspective, by investigating the roles of SC collaboration and SC visibility in the wake of Industry 4.0, we provided a stronger explanation and evidence for their effects on SC resilience, in addition to highlighting their significant mediating roles in the relationship between Industry 4.0 and SC resilience.

5.2. *Theoretical implications*

This study involves several theoretical implications to the literature. First, it adds to the development of dynamic RBV by empirically revealing the development and evolution path of different types of resources heterogeneity. Like the evolution paths from resources to capabilities, there is also a dynamic transformation process inside resources (Helfat and Peteraf, 2003; Peteraf, 1993; Teece et al., 1997). Size advantage can be evolved to first-mover advantage. Specifically, we regard Industry 4.0 as size advantage and IT advancement as first-mover advantage and empirically find the size advantage of Industry 4.0 adoption accumulated to a certain degree can be transformed to IT advancement ahead of industry. To the best of our knowledge, our study is the first to reveal the internal evolution path of resources between industry 4.0 technologies and IT advancement based on dynamic RBV. Our approach also echoes the call of Helfat and Peteraf (2003) for a more in-depth understanding of the evolution of resources.

Second, our study contributes to dynamic RBV by empirically showing different types of resources heterogeneity exert distinct influence on value creation. Our results demonstrate Industry 4.0 has a nonsignificant effect on SC capabilities, whereas the relevant effect from IT advancement is direct and positive. These interesting results add to our understanding of dynamic RBV as relying solely on size and scale advantage brings limited benefits. Meanwhile, superior resources, such as maintaining the lead in technology adoption, enable firms to fully exert their advantages beyond an organization by influencing their SC partners (Peteraf, 1993). Our results should inspire future studies to further examine the distinct influence of various heterogeneous resources as to deepen our understanding of dynamic RBV.

Third, our study enriches the literature by empirically examining the roles of SC capabilities in influencing SC resilience. Our results suggest SC collaboration and SC visibility can effectively improve SC resilience at both the during- and post-disruption phrases of resilience, substantially complementing previous research which limited their application to only one of the phrases of resilience (Ali et al., 2017; Brandon-Jones et al., 2014; Pettit et al., 2013). Our results also echo previous research calls for empirical testing to confirm propositions of SC capabilities and SC resilience (Pettit et al., 2013). Our study regards SC capabilities and SC resilience as two categories of variables rather than considering SC capabilities as the dimensions of SC resilience (e.g., Zouari et al. (2021). This conceptual classification enables us to identify exactly the difference between SC capabilities and resilience as well as scrutinize which specific SC capabilities contribute to SC resilience. Our research also contributes to the literature by investigating the mediating roles of SC capabilities in the Industry 4.0–SC resilience relationship, echoing the call from Ardolino et al. (2022) to more thoroughly examine the various conceptual and practical aspects of digital capabilities. We must emphasize the need for future studies to examine the role of different SC capabilities for firms operating in the Industry 4.0 context.

Fourth, our study contributes to the literature by employing dynamic RBV to empirically examine the influence paths from Industry 4.0 adoption, IT advancement, SC capability to SC resilience. Based on dynamic RBV, we regard Industry 4.0 adoption and IT advancement as resource heterogeneity; SC collaboration and SC visibility as relational and informational capabilities, respectively; and SC resilience as a sustained competitive advantage. We empirically reveal the evolution paths firms adopted Industry 4.0 technologies can take to enhance their IT advancement, which in turn helps building dynamic capabilities of collaboration and visibility in SCs, thereby leading to the achievement of sustained SC resilience.

Therefore, our results are consistent with the mobilization of dynamic RBV and ascertains the resource-capability-competitive advantage model (Helfat and Peteraf, 2003; Peteraf, 1993; Teece et al., 1997). We also complement research that focused on the relationship between Industry 4.0 technologies and resilience (i.e., Nakandala et al., 2023; Zouari et al., 2021). Based on the dynamic RBV, we provide more details about and novel insights into the specific flow of the relationship. Particularly, in the era of digital transformation, firms consistently face challenges to obtain competitive advantages through endless new digital technologies (Dolgui & Ivanov, 2022; Ivanov, 2022); our suggested future work provides rich opportunities concerning the application of dynamic RBV in such a context for researchers.

5.3. *Managerial implications*

Our conclusions also provide implications for firms in practice. First, our study shows the synergy among various Industry 4.0 technologies benefits firms in building IT advancement. Based on that result, firms should attach importance to the coherent effects among software, hardware, and cyber-physical platforms for long-term Industry 4.0 infrastructure development rather than only considering single technologies. Furthermore, our results show the adoption of Industry 4.0 has nonsignificant effects, whereas IT advancement has significant and positive effects on SC capabilities. Our work has implications for demonstrating the importance of IT advancement to formulate a first-mover advantage and ahead of competitors and the industry. Our findings reveal technology alone does not bring SC capabilities; only when firms fully integrate these front-end technologies into the SC process and operations to achieve IT advancement ahead of industries and competitors can they fully benefit from implementing Industry 4.0.

Given the increasing dominance of technological competition, IT advancement will continue to be vital for success. Our results reveal although some firms have not seen the expected benefits or returns on their investment in Industry 4.0 adoption in the initial stage (Dalenogare et al., 2018), they need to be aware of the long-term benefits and advantages of Industry 4.0 implementation. We suggest firms absorb and internalize these front-end technologies in their processes and operations, constantly update their technological bases, and place them at the forefront to gain competitive advantage (Tortorella et al., 2019).

Second, our findings show SC collaboration and SC visibility have positive effects on SC resilience and play mediating roles in the relationship among Industry 4.0, IT advancement, and SC resilience. The findings indicate by embedding IT resources into a firm's SC system, the firm can enhance SC resilience through effective visibility and better coordination with SC partners (Wu et al., 2006; Yeniyurt et al., 2019). SC managers need to realize SC collaboration and SC visibility have the capability to absorb the shock and bounce back. It is beneficial for firms to build up responsiveness and formulate recovery strategies at the during-disruption and post-disruption phases of SC resilience (Ali et al., 2017; Mubarik et al., 2021). SC managers should also realize investments in IT resources can achieve SC resilience when they are transferred to SC capabilities. Therefore, our results have provided constructive guidance that might encourage firms to orchestrate their IT resources fully and build up their SC capabilities to achieve SC resilience in the currently turbulent SC environment.

6. Conclusion and limitations

The primary purpose of our study was to understand the impact of Industry 4.0 and IT advancement on SC capability and SC resilience based on dynamic RBV. Although many researchers are interested in Industry 4.0-related topics, there has been a lack of empirical studies investigating the influence paths from Industry 4.0 adoption to SC resilience through SC capabilities. Following the logic of dynamic RBV and based on a survey sample of 408 Chinese manufacturing firms, we empirically examined the impact of Industry 4.0 and IT advancement on SC capabilities and SC resilience. Our results show Industry 4.0 has a positive impact on IT advancement, empirically revealing the positive evolution path within different resources between Industry 4.0 and IT advancement. Additionally, our results show IT advancement is positively related to SC capabilities, whereas Industry 4.0 has nonsignificant effects on SC capabilities. The contrastive results suggest the distinct effects between types of resource heterogeneity. Moreover, we observed SC capabilities have positive effects on SC resilience and exert mediating effects on the relationship between Industry 4.0/IT advancement and SC resilience. This paper contributes to both the literature and practices.

As with all studies, our study still has some limitations that afford opportunities for future research. First, because of limited time and resources, our sample frame only focused on the manufacturing firms. Future research can include service firms in their scope to compare the differences. Second, although we conducted a wide scope of Industry 4.0 technologies, we did not include blockchain or M2M in our analysis because of the EFA results, so our study may lack a comprehensive perspective of Industry 4.0 technologies. Because blockchain and M2M are becoming increasingly popular and important in practice, further studies could consider involving them to arrive at nuanced conclusions. Third, firms are going through a stage of technological explosion, with many new technologies continually emerging. Future research can also add more advanced technology to the research scope such as digital twins (Wamba et al., 2021) and interoperability (Koh et al., 2019) to assess the effect of Industry 4.0. Fourth, although our conceptualization of SC collaboration and SC visibility as two representative capabilities are based on the theoretical background of dynamic RBV. There are other SC capabilities (e.g., SC adaptability, SC agility, SC innovation capabilities) (Nakandala et al., 2023) that might also exert effective influence on SC resilience. We encourage further scholars to involve broader SC capabilities and investigate the roles of other SC capabilities in the context of Industry 4.0. Finally, our study investigated the impact of Industry 4.0 technologies on SC resilience based on the survey method, and the data were cross-sectional. We could not account for the causation effect, so our conclusion lacks an objective assessment of Industry 4.0 adoption. Future research can go a step further by considering objective data (i.e., secondary data) to investigate the causalities between Industry 4.0 adoption and SC resilience.

Data availability

Data will be made available on request.

Appendices

Appendix A

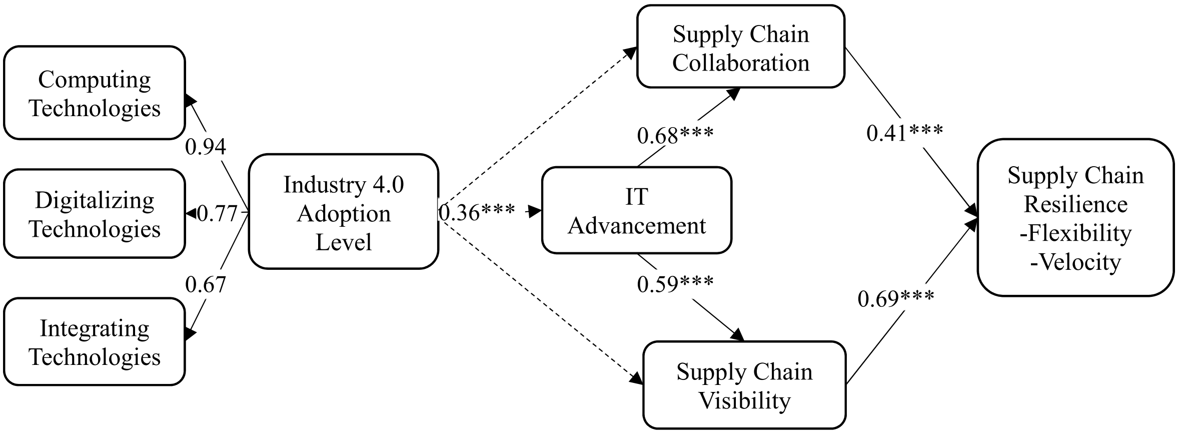
Measurement Items in Detail

Construct	Code	Measurement Items	Source
Industry 4.0 Adoption Level	COM1	The stage of cloud computing (CC) implementation in the supply chain	(Lemstra and de Mesquita, 2023), (Barata, 2021)
	COM2	The stage of big data analytics (BDA) implementation in the supply chain	
	COM3	The stage of artificial intelligence (AI) implementation in the supply chain	
	DIG1	The stage of simulation technology (ST) implementation in the supply chain	
	DIG2	The stage of enterprise resource planning (ERP) implementation in the supply chain	
	DIG3	The stage of business intelligence (BI) implementation in the supply chain	
	DIG4	The stage of blockchain technology (BCT) implementation in the supply chain	
	DIG5	The stage of internet of things (IoT) implementation in the supply chain	
	DIG6	The stage of autonomous vehicle (AV) implementation in the supply chain	
	DIG7	The stage of robotics technology (RT) implementation in the supply chain	
	INT1	The stage of machine-to-machine (M2M) implementation in the supply chain	
	INT2	The stage of 3D printing (3DP) implementation in the supply chain	
	INT3	The stage of smart sensor (SS) implementation in the supply chain	
	INT4	The stage of radio frequency identification (RFID) implementation in the supply chain	
	INT5	The stage of virtual reality (VR) implementation in the supply chain	

(continued on next page)

Appendix A (*continued*)

Construct	Code	Measurement Items	Source
	INT6	The stage of augmented reality (AR) implementation in the supply chain	
IT Advancement	ADV1	Our information and digital technologies for supply chain management are always state-of-the-art.	Wu et al. (2006)
	ADV2	Our digital supply chain technologies are more advanced than our competitors'.	
	ADV3	Our firm is always the first to use new information and digital technologies for supply-chain management in our industry.	
Supply Chain Visibility	VIS1	Our supply chain members have the information for monitoring and changing operations strategies	(Mandal et al., 2016), (Jüttner and Maklan, 2011)
	VIS2	Our supply chain members have access to inventory and order status information for forecasting	
	VIS3	Our supply chain members have the necessary information system for tracking goods	
Supply Chain Collaboration	COL1	Our firm works jointly with its key suppliers to achieve mutual goals	(Mandal et al., 2016), (Jüttner and Maklan, 2011)
	COL2	Our firm shares rewards and risks evenly with our supply chain partners	
	COL3	Our firm works jointly with its key supply chain members for mutual benefits	
Supply Chain Resilience	RES1	The material flow in the supply chain would be quickly restored under an unexpected disruption event	Brandon-Jones et al. (2014)
	RES2	It would not take long for our supply chain to recover normal operating performance under an unexpected disruption event	
	RES3	The supply chain would easily recover its original state under an unexpected disruption event	
	RES4	Disruptions in our supply chain could be dealt with quickly under an unexpected disruption event	
Supply Chain Flexibility	FLX1	Our firm can adjust suppliers' order quantity to mitigate a disruption	Mandal et al. (2016)
	FLX2	Our firm can adjust the delivery time of suppliers' order for mitigating a disruption	
	FLX3	Our supply chain can adjust production volume capacity in response to a disruption	
	FLX4	Our supply chain can adjust its delivery schedules for coping with disruptions	
Supply Chain Velocity	VEL1	Our supply chain can quickly respond to disruption risk	Mandal et al. (2016)
	VEL2	Our supply chain can rapidly deal with threats in the business environment	
	VEL3	Our supply chain can quickly respond to changes in the business environment	



Note. Dashed line indicates nonsignificant relationships. $^{**}p < 0.05$, $^{***}p < 0.01$.

Appendix B. *Robustness Results With Alternative Measures of SC Resilience*

Note. Dashed line indicates nonsignificant relationships. $^{**}p < 0.05$, $^{***}p < 0.01$.

Appendix C

Robustness Checks for Mediating Effect Using Sobel Test

Relationship	Effect	SE	Z	P
I4.0-COL-RES	0.16***	0.033	4.73	0.000
I4.0-VIS-RES	0.16***	0.032	5.06	0.000
ADV-COL-RES	0.26***	0.030	8.49	0.000
ADV-VIS-RES	0.21***	0.027	7.75	0.000

Notes: $^{***}p < 0.001$; I4.0 refers to Industry 4.0 adoption level.

Appendix D

Multicollinearity tests for second-order construct

Dimensions	VIFs	Correlations		
		1	2	3
1. Computing Technologies	1.08	1		
2. Digitalizing Technologies	1.02	.48**	1	
3. Integrating Technologies	1.02	.37**	.42**	1

Notes: $^{**}p < 0.01$ (two-tailed).

Appendix E

2SLS Results

Panel A: First Stage	IT Advancement	Panel B: Second Stage	SC Collaboration	SC Visibility
	(1)		(1)	(2)
Type	0.58***	IT Advancement	0.59***	0.34*
	(0.207)		(0.160)	(0.204)
Firm age	0.11**	Firm age	0.02	0.09**
	(0.042)		(0.035)	(0.039)
Firm size	−0.012	Firm size	−0.02	−0.01
	(0.166)		(0.020)	(0.021)
Industry 1	0.32	Industry 1	−0.28*	0.21
	(0.122)		(0.146)	(0.133)
Industry 2	0.01	Industry 2	−0.09	0.04
	(0.123)		(0.103)	(0.108)
Intensive 1	0.32**	Intensive 1	−0.07	−0.03
	(0.141)		(0.111)	(0.117)
Intensive 2	−0.134	Intensive 2	−0.34***	−0.38***
	(0.148)		(0.101)	(0.109)
constant	4.23***	constant	2.55***	3.60***
	(0.207)		(0.751)	(0.968)
N	408	*N*	408	408
R2	0.076	Centered R2	0.389	0.302
F	4.58	F	7.38	6.77
p	0.000	p	0.000	0.000
Adjust r2	0.060	Wald $\chi2$	52.70	48.35

Notes: $*p < 0.1$, $**p < 0.05$, $***p < 0.01$ (two-tailed). Robust standard errors are in parentheses.

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