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The impact of digital technologies on economic and environmental performance in the context of industry 4.0: A moderated mediation model

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ABSTRACT

Digital technologies for Industry 4.0, such as the Internet of Things, cloud computing, big data and analytics, have attracted much attention from both researchers and practitioners. Based on information processing theory, this study intends to explore how digital technologies influence economic and environmental performance in the new era of Industry 4.0. The mediating effect of digital supply chain platforms and the moderating effect of environmental dynamism are proposed and evaluated using a survey of Chinese manufacturing firms. The results indicate that digital supply chain platforms mediate the effects of digital technologies on both economic and environmental performance and that the mediating effects are enhanced under a high degree of environmental dynamism. This study offers an enhanced understanding of the performance implications of digital technologies and provides managerial insights into how to promote economic and environmental sustainability in the era of Industry 4.0.

1. Introduction

In the new era of Industry 4.0, the development and adoption of digital technologies has become one of the most frequently trending topics in both academic and professional areas. The term "digital technologies" refers to a collection and a paradigm of various intelligent and innovative technologies in the era of Industry 4.0, such as big data analytics, the Internet of Things and cloud computing, which realize connectivity, communication and automation (Ardolino et al., 2018; Frank et al., 2019; Ivanov et al., 2019). In a digitally driven manufacturing system, these emerging advanced technologies empower companies to adopt data-driven strategies for collecting data across the product life cycle ranging from material properties and process parameters (Tao et al., 2018) and to improve the vertically and horizontally integrated manufacturing system (Frank et al., 2019).

Digital technologies bring both opportunities and challenges for the sustainable development of manufacturing companies. With the deep integration of intelligent technologies in the manufacturing industry, there has been a digital transformation that has changed the traditional production and operations management methods and offers the potential for the improvement of product development, production efficiency and customer service (Neuhofer et al., 2015). Moreover, these advanced technologies can enable the efficient allocation of resources and therefore unlock the full potential of environmental sustainability (Gobbo et al., 2018; Jabbour et al., 2018; Dubey et al., 2019). However, emerging technologies may further increase the competitive dynamics in business environments and impose financial and environmental burdens on manufacturing firms (Kiel et al., 2017). In this case, digital technologies may lead to unintended negative consequences on sustainable development. It should be noted that how digital technologies influence sustainability performance in terms of economic and environmental performance is still under-investigated.

This study argues that the effect of digital technologies on sustainability performance needs to be realized through a well-established supply chain platform. Prior studies have recognized the role of advanced digital technologies for Industry 4.0 in supply chain relationships (Zhou et al., 2015; Govindan et al., 2018; Ben-Daya et al., 2019). Further, the establishment of digital supply chain platforms enables massive information gathering and disposal and excellent cooperation and integration (Büyüközkan and Göçer, 2018). To achieve sustainable development, manufacturing firms are encouraged to extend the application of digital technologies into supply chains and to connect with their supply chain partners (Camara et al., 2015). However, while scholars aim to integrate digital technologies with supply chains, few

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studies have empirically explored how digital technologies influence economic and environmental sustainability through the establishment of digital supply chain platforms.

The theoretical foundation for our research study is drawn from the information processing theory (IPT) (Galbraith, 1973; Premkumar et al., 2005). Operations and environmental management are identified as information-intensive processes (Lai et al., 2015; Addo-Tenkorang and Helo, 2016). IPT indicates that an organization as an open social-economical system can achieve superior performance by improving its informational processing capabilities and information quality (Galbraith, 1973; Premkumar et al., 2005). Digital technologies form the internal information architecture, which represents a firm's information processing capabilities. Moreover, supply chain platforms serve as the channel for the information exchange between supply chain partners, which is regarded as a major source of external information. The enhanced information processing capabilities complementing the external supply chain information lead to the sustainable development of manufacturing firms. Therefore, based on IPT, this study examines how digital technologies are applied in supply chain relationships and the resulting impact on economic and environmental performance.

In addition, we investigate how the impacts of digital technologies would be varied by contingency factors such as environmental dynamism. IPT highlights that the organization's information processing capabilities and information requirements should be matched with the business environment. It is suggested that the performance of implementing advanced digital technologies and supply chain platforms may be affected by environmental conditions (Raymond, 2005; Cegielski et al., 2012; Mithas et al., 2013). This study focuses on environmental dynamism, which refers to the instability or volatility of a firm's environment (Azadegan et al., 2013; Chan et al., 2016), and argues that the impact of digital technologies and supply chain platforms on economic and environmental performance is contingent upon environmental dynamism.

This study will contribute to relevant research from three aspects. First, we intend to establish the links between digital technologies and two dimensions of sustainability performance (i.e., economic and environmental performance), which can help enhance the understanding of the performance implications of digital technologies in Industry 4.0. Second, we propose the mediating effect of digital supply chain platforms on the relationships between digital technologies and economic and environmental performance, thus establishing a mechanism explaining how digital technologies relate to economic and environmental performance. Third, we identify a contextual factor (i.e., environmental dynamism) to determine the effectiveness of digital technologies and supply chain platforms. The remainder of this paper is arranged as follows. Section 2 reviews the relevant literature and Section 3 proposes the hypotheses. We show the research methodology in Section 4 and present the results in Section 5. Finally, the paper ends with our discussion and conclusions in Section 6.

2. Literature review

2.1. Digital technologies in industry 4.0

Industry 4.0, which originally initiated in Germany, is the fourth industrial revolution in manufacturing. The concept of Industry 4.0 and its other synonyms, such as smart manufacturing, smart production or smart factories, refer to "the horizontal and vertical integration of production systems driven by real-time data interchange and flexible manufacturing to enable customized production" (Jabbour et al., 2018, p. 19). In the era of Industry 4.0, advanced digital technologies, which are mostly mentioned by practitioners and researchers, include the Internet of Things, cloud computing, big data and analytics (Jabbour et al., 2018). Ivanov et al. (2019) particularly note that firms are integrating and interconnecting these local solutions to enhance their data-processing capabilities. In other words, digital technologies are expected to covary or interact with each other in the new era of Industry 4.0, which represents the organization's information processing capabilities in the new era of Industry 4.0.

The Internet of Things, as one of the latest information technology breakthroughs, refers to an information technology infrastructure that establishes the interconnectivity of physical objects and enables data collection and transmission between devices (Lee and Lee, 2015). The four main essential layers of the Internet of Things are a sensing layer to integrate radio frequency identification (RFID) tags, sensors and actuators; a networking layer to support information transfers through wireless sensor networks; a service layer to integrate services and applications through middleware technology; and an interface layer to display information, identify problems and suggest solutions to the user (Xu et al., 2014). Scholars have discussed the application of the Internet of Things in operations and supply chain management, such as manufacturing systems (Tao et al., 2014), innovative product delivery (YU et al., 2015), mass customization (Ng et al., 2015) and end-of-life product recovery (Joshi and Gupta, 2019).

Cloud computing is applied to realize the aggregation, management, optimal allocation and on-demand use of information and data in the form of remote service (Tao et al., 2014; Liu and Xu, 2017). Camara et al. (2015) define cloud computing as a bundle of virtualized and distributed resources that can be accessed on an on-demand basis through software as a service, infrastructure as a service and platform as a service. Scholars summarize four types of deployment models, i.e., public clouds, private clouds, community clouds and hybrid clouds (Singh et al., 2015; Kochan et al., 2018). With cloud computing, manufacturing firms can access substantial and customized information from the cloud service provider via the Internet with no investment in complex and on-premise systems. Schniederjans and Hales (2016) summarize that cloud computing is characterized by massively scalable and virtualized resources, reduced support infrastructure needs, the rapid deployment of information and green computing potential. It is expected that cloud computing will promote the future development of manufacturing firms in the manufacturing community.

The application of big data and analytics is closely interlinked to enable manufacturing firms to make better decisions. Hence, prior literature has always discussed the two digital technologies together. Scholars define big data in terms of the 5 V's (Wamba et al., 2015): (1) volume, indicating the large amount of data; (2) variety, implying a large variety of sources and multidimensional data fields; (3) veracity, to ensure the quality of the data and reliable prediction through big data analytics; (4) velocity, indicating the frequency of data generation and delivery; and (5) value, stressing the economic benefits from data extraction and transformation. Analytics refers to "the ability to gain insights from data by applying statistics, mathematics, econometrics, simulations, optimizations or other techniques" (Wang et al., 2016, p. 99). Big data and predictive analytics allow the use of advanced information technology tools and architectures to collect, store, extract and analyse a large amount of data for decision-making processes (Wamba et al., 2015). In the context of Industry 4.0, there are many areas in operations and supply chain management that benefit from big data and analytics technologies, such as investigations of supply chain risks (Wu et al., 2017), social and environmental sustainability (Dubey et al., 2019), supply chain and organizational performance (Gunasekaran et al., 2017), and servitization (Opresnik and Taisch, 2015).

2.2. Digital supply chain platforms

Digital supply chain platforms have been proposed since traditional information and communication technologies are developed and applied (Pettit and Wang, 2016), and are defined as the digitally driven infrastructure a focal firm has established "for the consistent and high-velocity transfer of supply chain-related information within and across its boundaries" (Rai et al., 2006, p. 229). Reuver et al. (2018) note that a digital platform can "be characterized as a sociotechnical assemblage encompassing the technical elements (of software and hardware) and associated organizational processes and standards" (p. 126). Compared with the focus on technical elements of the concept, Büyüközkan and Göçer (2018) highlight that digital supply chain platforms are related to how supply chain processes are managed in a digital form. Following the view of Rai et al. (2006) and Büyüközkan and Göçer (2018), our study mainly emphasizes the establishment of cross-organizational platforms that realize digital connectivity, system integration and information exchange within the supply chains.

In the era of Industry 4.0, scholars have begun to explore the application of advanced digital technologies in supply chains through narrative literature reviews or exploratory case studies (Addo-Tenkorang and Helo, 2016; Wang et al., 2016; Govindan et al., 2018; Nguyen et al., 2018; Tiwari et al., 2018; Ben-Daya et al., 2019). In addition, Waller and Fawcett (2013) note that data science, predictive analytics and big data will contribute to the transformation in supply chain design and management. Gunasekaran et al. (2017) indicate that big data and predictive analytics can improve supply chain performance through visibility and decision making. Ben-Daya et al. (2019) advocate that the Internet of Things enables the remote coordination and management of supply chain operations. Kochan et al. (2018) identify cloud computing as an enabler of electronic supply chain management systems. Advanced and interconnected technologies are dynamically reconfigurable to establish a digitally driven network within the supply chain and to support communication within and across organizational boundaries (Zhou et al., 2015; Govindan et al., 2018).

Scholars have also indicated that digital supply chain platforms contribute to coordinating external suppliers, customers and other partners, providing on-demand access to external information, and promoting real-time communication and integration of the supply chain (Frank et al., 2019). Yu et al. (2018) confirm that a data-driven supply chain has a significantly positive effect on supply chain capabilities, including information exchange, coordination, activity integration and responsiveness, which leads to financial performance. However, Büyüközkan and Göçer (2018) note that although digital supply chain platforms are the key for organizations' competitive advantages, many specific benefits are untapped. Studies that address the establishment and benefits of digital supply chain platforms are still in their early stages. It is necessary to empirically investigate the impact of digital technologies for Industry 4.0 on the establishment of supply chain platforms and the role of digital supply chain platforms for modern manufacturing firms.

2.3. Information processing theory

IPT was proposed to support the design of organizational structures (Galbraith, 1973). Based on IPT, information-processing needs and information processing capabilities should be matched to obtain the optimal performance (Premkumar et al., 2005). Information-processing needs are determined by various environmental contexts in which the organization is located, while information processing capabilities refer to the configurations of resources, technology architecture and other work units that facilitate information collection, processing and distribution (Galbraith, 1973; Tushman and Nadler, 1978). To cope with environmental dynamism or the frequency of changes in environmental factors, organizations can adopt two strategies to support decision making and improve performance: (1) acquire a greater amount of high-quality information to reduce the effect of dynamism and (2) devote more efforts to improving information processing capabilities for effective decision making (Fan et al., 2017). Recently, IPT has been extensively applied in information systems (Wong et al., 2015), technology integration (Stock and Tatikonda, 2008), production control systems (Gong et al., 2014), maintenance management (Swanson, 2003) and supply chain management (Cegielski et al., 2012; Fan et al., 2017).

Previous studies have tended to identify digital technologies as the key aspect of the organization's information processing capabilities. Based on IPT, Premkumar et al. (2005) suggest access to information processing capabilities through information technology support. Melville and Ramirez (2008) highlight that information processing capabilities can be enhanced through investments in technology-based process improvement (e.g., the adoption of information technology). Cegielski et al. (2012) define information processing capabilities as the organization's capability "to utilize and structure information in a meaningful fashion that supports decision making" (p. 189) and regard cloud-based infrastructure as a proxy for organizational information processing capabilities. In this study, the Internet of Things, cloud computing, big data and analytics are structured and linked to handle needed quantities of information and therefore represent the organization's information processing capabilities. Moreover, digital supply chain platforms provide information exchange channels to access external information. That is, digital technologies drive supply chain platforms to satisfy information requirements caused by environmental dynamism.

3. Hypotheses development

3.1. Digital technologies and economic and environmental performance

Operations and environmental management are both identified as information-intensive activities (Lai et al., 2015; Addo-Tenkorang and Helo, 2016). From the perspective of IPT, digital technologies represent the firm's information processing capabilities to support decision-making processes related to operations and environmental management. It can be foreseen that digital technologies in Industry 4.0 will contribute to the improvement of manufacturing firms' economic and environmental performance through information gathering and processing.

Digital technologies support the decisions of production planning and control through efficient information processing (Nguyen et al., 2018), which can enhance operational efficiency, reduce the cost and increase profits. In an advanced manufacturing system, firms configure the Internet of Things, cloud computing, big data and analytics to more efficiently and effectively collect and process production- and operations-related information. The Internet of Things establishes a global network in which tags, sensors, actuators and other physical devices are heterogeneously interconnected within plants to exchange data and communicate with each other (Ardolino et al., 2018). Machine-to-machine communication (M2M), as a classic example of the application of the Internet of Things, can realize data gathering and exchange remotely and automatically (Frank et al., 2019). Cloud computing provides the service of the remote storing of real-time operational data and on-demand access to data displayed in a cloud (Camara et al., 2015). In this case, the Internet of Things and cloud computing can realize the full sharing, free circulation, on-demand use and optimal allocation of information required by manufacturing (Tao et al., 2014), resulting in high operational efficiency. While a tremendous amount of data are generated, collected and integrated in the manufacturing system, big data and analytics can further help to identify and extract valuable information for manufacturing firms to make effective and correct decisions (Gunasekaran et al., 2017; Wamba et al., 2017). Overall, the enhanced information processing capability is the key enabler to improve production efficiency and hence obtain a competitive advantage (Cao et al., 2019).

Additionally, digital technologies support the decisions of demand forecasting, price optimization and product development (YU et al., 2015; Joshi and Gupta, 2019), which can better satisfy customers' demands and increase market share and sales. Wong et al. (2015) support this idea and indicate that information technology infrastructure can lead to customer service performance. Manufacturing firms are encouraged to embed the Internet of Things, cloud computing, big data and analytics into the whole value chain of a product from design to after-sales (Curran et al., 2007). These advanced digital technologies can provide sufficient product and market information, thus enabling product optimization and demand forecasting to rapidly respond to customers' requests. Moreover, with digital technologies for information processing, firms can reconfigure production lines and resources for the production of customized products in a more flexible and efficient way (Dalenogare et al., 2018). Wamba et al. (2015) highlight a digitally enabled infrastructure, and multiple data sources allow the firm to tailor customer demands and seek new market opportunities. Furthermore, customized products can create a differentiated competitive advantage and increase their perceived values. Therefore, it is hypothesized that the application of digital technologies will lead to the improvement of economic performance:

H1a. Digital technologies have a positive impact on economic performance.

This study also suggests a positive relationship between digital technologies and environmental performance. The achievement of environmental performance requires the integration of environmental concerns into traditional product development and manufacturing processes (Schniederjans and Hales, 2016), which makes the decisions and operations more complex. Digital technologies can provide efficient solutions for green product design, production and service processes, which lead to less hazardous pollutants and minimize natural resource consumption in the entire product life cycle. The Internet of Things, cloud-based design and big data analytics allow for enhanced information flow management and facilitate green product development and eco-design innovation (Wu et al., 2015; Dubey et al., 2019). Jabbour et al. (2018) indicate that manufacturing firms use digital technologies to collect and process accurate consumption information, thus enabling product development with the 5 R's strategy (i.e., reduce, repair, reuse, recycle, and remanufacture). The RFID tags and sensors embedded in products collect all the data about a product's life cycle and monitor components' conditions for reuse, recycling and remanufacturing (Tao et al., 2016; Joshi and Gupta, 2019). As a result, digital technologies support eco-product design and promote product optimization to minimize the environmental impact.

Moreover, the use of digital technologies can help improve information gathering and processing to better control energy efficiency, water quality, air pollution and heavy metals through automatically optimizing production processes (Gobbo et al., 2018). In the digitally enabled manufacturing system, firms embed sensors and RFID technology in the production equipment or production line connected to the Internet, which can efficiently collect production information and control environmental conditions in real time. This approach is echoed by Bai and Sarkis (2017), who find that advanced manufacturing technologies have the potential to support green manufacturing processes. Peukert et al. (2015) indicate that digital technologies such as data-centred carbon footprint analyses contribute to the reduction of greenhouse gas emissions. Jabbour et al. (2018) propose that digital technologies in Industry 4.0 can unlock the potential of environmentally sustainable manufacturing. Therefore, digital technologies tend to promote environmental performance through developing eco-friendly products and enabling green manufacturing processes (Kiel et al., 2017; Stock et al., 2018). The following hypothesis is then proposed:

H1b. Digital technologies have a positive impact on environmental performance.

3.2. *The mediating role of digital supply chain platforms*

This study proposes that digital supply chain platforms mediate the impact of digital technologies on economic and environmental performance in the Industry 4.0 era. Digital technologies, including the Internet of Things, cloud computing, big data and analytics, facilitate the technical establishment of digital supply chain platforms. In the era of Industry 4.0, manufacturing firms increasingly invest in digital technologies to develop their internal information-processing and decision-making capabilities. We argue that organizations' internal capabilities are the premise and basis of the establishment of digital supply chain platforms. Digital supply chain platforms imply more extensive information sources and higher-order information processing capabilities. Manufacturing firms can better coordinate information exchanges and transmissions with external suppliers and customers only when they are equipped with adequate internal information processing capabilities (Shou et al., 2017). Particularly, in a highly interconnected industrial network, firms take the initiative to extend digital technologies into the whole supply chain, from raw material provision to final product delivery, or they are compelled to apply digital technologies in supply chain activities to achieve compatibility with their suppliers and customers. Otherwise, the firm can hardly survive in the intensely competitive marketplace. As Frank et al. (2019) find in a survey of 92 manufacturing companies, digital platforms for integration with supply chain partners are adopted at a relatively high level in advanced adopters of digital manufacturing technologies.

Because operations management and environmental management are both information-intensive activities (Lai et al., 2015; Addo-Tenkorang and Helo, 2016), the achievement of economic and environmental performance relies on sufficient information and adequate information processing capabilities to support product design, production and delivery. From the perspective of IPT, supply chain platforms embedded with advanced digital technologies provide a channel to exchange high-quality information with suppliers, customers and other partners, thus satisfying the increasing demand for information processing in the supply chain processes. Digital technology architectures targeted at the firm's supply chain promote real-time information transmission, data integrity, visibility and connectivity between supply chain partners (Rai et al., 2006). Supply chain related information is recognized as being more beneficial for customer demand management, material supply and inventory management, and production optimization and control (Qrunfleh and Tarafdar, 2014), which will potentially lead to economic and environmental performance.

Several studies have documented the role of supply chain oriented efforts in the improvement of economic and environmental performance. Wu et al. (2006) confirm that information flows facilitated by a digital supply chain system allow the firm to exactly match supply and demand and rapidly respond to customers' requests, which ultimately increase sales and profitability. Prajogo and Olhager (2012) indicate that information technology-enabled supply chain platforms contribute to a decrease in production costs. Qrunfleh and Tarafdar (2014) also demonstrate that a supply chain information system strategy leads to economic performance. For environmental performance, Lai et al. (2015) find that environmental management information exchange with suppliers and customers can bring environmental performance. Jadhav et al. (2018) reveal the role of supply chain orientation in terms of communication in achieving environmental sustainability. Hence, we propose that digital supply chain platforms have a positive impact on economic and environmental performance.

In sum, while the use of digital technologies enhances the organization's internal information-processing and decision-making capabilities, the establishment of digital supply chain platforms increases sources of high-quality information externally and further strengthens the capabilities by connecting suppliers and customers. Digital technologies enhance the speed, quality and quantity of information dissemination across the supply chain. Then, manufacturing firms can leverage both internal and external information to conduct operations and environmental management more efficiently and effectively. Furthermore, owing to the interconnectedness enabled by digital supply chain platforms, the once-isolated decision-making process is becoming more integrated from upstream suppliers to the downstream customers (Wu et al., 2006). In this case, digital technologies and supply chain platforms have potential synergistic benefits for the improvement of economic and environmental performance. Based on the above discussions, we propose the following hypotheses:

H2a. Digital supply chain platforms mediate the relationship between digital technologies and economic performance.

H2b. Digital supply chain platforms mediate the relationship between digital technologies and environmental performance.

3.3. The moderating role of environmental dynamism

Environmental dynamism, which refers to the instability or volatility of a firm's environment (Pagell and Krause, 2004), has been widely identified as a contextual factor in the fields of operations management (Sousa and Voss, 2008) and environmental management (Maletič et al., 2018). Literature suggests that companies should design their organizational structures based on the environment in which they compete to achieve high performance (Miller, 1987; Raymond, 2005; Sousa and Voss, 2008). Based on IPT, manufacturing firms in industrial environments with short product life cycles and frequent changes in demand, production and regulations are characterized by a high degree of dynamism (Bozarth et al., 2009; Azadegan et al., 2013; Chan et al., 2016), leading to massive information-processing requirements (Melville and Ramirez, 2008). Therefore, firms are recommended to adapt their information technology infrastructures to maintain fit with their degree of environmental dynamism.

Under a dynamic environment, manufacturing firms cannot solely rely on the data or information collected within the organizational boundary. They need to access more accurate and sufficient external information, thereby accurately predicting changes and reducing uncertainty. Childerhouse et al. (2003) suggest that information flow needs to be transparent and two-way in supply chains (i.e., both upstream and downstream) to overcome environmental dynamism. In turn, inadequate information is regarded as a significant problem (Bailey and Francis, 2008) and will affect the organization's decision-making abilities (Boyle et al., 2008). Hence, when facing high levels of environmental dynamism, the firm is more inclined to extend the application of digital technologies into supply chain processes to integrate information from upstream suppliers and downstream customers. Digital infrastructures incorporating supply chain partners can detect and monitor changes in the external environment more efficiently and effectively than those that do not. Therefore, we argue that manufacturing firms are more motivated to leverage digital technologies to establish supply chain platforms in a dynamic environment.

The establishment of digital supply chain platforms can not only provide sources of external information but also further upgrade the manufacturing firm's information processing capabilities so that manufacturing firms are able to respond to frequent and major changes in a timely manner. Competing in a dynamic environment, manufacturing firms tend to establish digital supply chain platforms to better support decision making for operations and environmental management. The enhanced information processing capabilities matched with higher information-processing requirements can ultimately realize optimal performance. Therefore, as environmental dynamism grows, the effects of digital supply chain platforms on economic and environmental performance will be much stronger. Previous studies have also found that environmental dynamism positively moderates the effect of supply chain relationships on economic performance (Wong et al., 2011; Zhang et al., 2017) and environmental performance (Wu, 2013), which supports the assertions made in this study.

Overall, manufacturing firms are more likely to leverage digital technologies to establish supply chain platforms to achieve higher economic and environmental performance in a dynamic environment. Considering the mediating role of digital supply chain platforms, this study highlights that the indirect effects of digital technologies on economic and environmental performance through digital supply chain platforms will be enhanced as environmental dynamism grows. Thus, the following hypotheses are proposed in this study. Furthermore, a moderated mediation effect exists when a mediation process is dependent on a moderating variable (Hayes, 2017; Yuan et al., 2020). Fig. 1 presents the moderated meditation model of this study.

H3a. Environment dynamism positively moderates the indirect effect of digital technologies on economic performance through digital supply chain platforms.

H3b. Environment dynamism positively moderates the indirect effect of digital technologies on environmental performance through digital supply chain platforms.

4. Research methods

4.1. Sampling and data collection

This study conducted a questionnaire survey in China. The units of analysis were individual Chinese manufacturing firms, and the targeted respondents were middle- and senior-level managers. The survey comprised target sampling areas from northern China (e.g., Beijing, Tianjin, Hebei and Shanxi), southern China (e.g., Guangdong, Guangxi and Fujian), eastern China (e.g., Shanghai, Zhejiang, Jiangsu, Shandong and Anhui) and Western China (e.g., Sichuan, Yunnan, Chongqing and Shanxi). The manufacturing firms in these rapidly developing regions tend to apply digital technologies to achieve competitive advantages. We used the Yellow Pages of China Telecom to determine the potential sample pool (Jacobs et al., 2016) and to obtain the contact information of the firms in the target sampling areas.

Following the proposed sampling procedure for questionnaire formatting, distribution, and collection (Dillman, 2007), we created an online survey, emailed the survey link to managers with high levels of experience in the selected sample firms, and promised to keep the data confidential. Follow-up telephone calls and two reminder emails were made to improve the response rate. To encourage participation in the surveys, the respondents were promised access to a summary of the research findings. In total, 5534 questionnaires were distributed, and 188 useable responses were received. The response rate (3.4%) was comparable to the relevant research in similar nature (e.g., Jin et al., 2014), considering the decreasing response level of the top managers and a large number of invalid email addresses.

Table 1 provides the profiles of the respondents, which further demonstrates the representativeness of the sample. The respondents in our study included production managers (30.3%), R&D managers (17.6%), product managers (16.0%), marketing managers (14.4%), purchasing managers (6.4), plant managers (3.2%), CEOs (2.1%) and others (10.0%). A total of 92% had more than 5 years of work experience, indicating that they were knowledgeable in the application of digital technologies in product development and production and familiar with purchasing and supply chain management. Moreover, the sample covered a variety of manufacturing industries (e.g., chemicals and petrochemicals, electronics and electrical equipment, food, beverages and alcohol) and different types of manufacturing firms (e.g.,

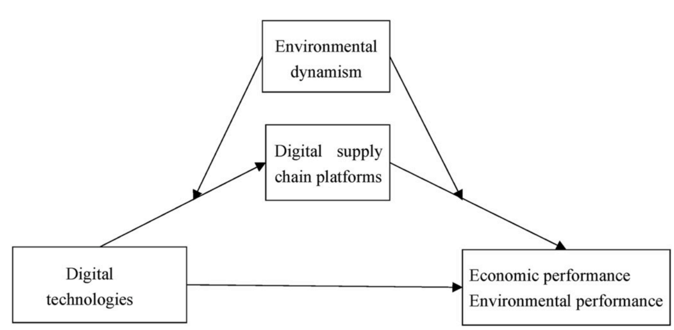

Fig. 1. Conceptual framework.

Table 1
Demographics of respondents.

Position	Frequency	Percentage
CEO	4	2.1
Production manager	57	30.3
Purchasing manager	12	6.4
Product manager	30	16.0
R&D manager	33	17.6
Marketing manager	27	14.4
Plant manager	6	3.2
Others	19	10.0
Working experience	**Frequency**	**Percentage**
1–5 years	15	8.0
6–10 years	105	55.9
>10 years	68	36.2
Firm sales (million CNY)	**Frequency**	**Percentage**
<1000	16	8.5
1001–5000	61	32.4
5001–10000	63	33.5
>10000	48	25.5
Number of employees	**Frequency**	**Percentage**
<100	25	13.3
101–500	74	39.4
501–2000	63	33.5
>2000	26	13.8
Industry	Frequency	Percentage
Building materials	7	3.7
Chemicals and petrochemicals	8	4.3
Electronics and electrical	64	34.0
Equipment	26	13.8
Food, beverage and alcohol	17	9.0
Metal, mechanical and engineering	28	14.9
Pharmaceutical and medical	13	6.9
Publishing and printing	1	0.5
Rubber and plastics	8	4.3
Textiles and apparel	13	6.9
Toys	1	0.5
Wood and furniture	2	1.1
Building materials	7	3.7
Chemicals and petrochemicals	8	4.3
Firm nature	**Frequency**	**Percentage**
Private	98	52.1
State-owned	41	21.8
Foreign-owned	21	11.2
Joint venture	28	14.9

private, state-owned, foreign-owned and joint venture). In terms of firm size, 13.3% of the respondents came from firms with less than 100 employees, 39.4% came from firms with between 101 and 500 employees, 33.5% came from firms with between 501 and 2000 employees, and 13.8% came from firms with over 2000 employees. Additionally, 40.9% of the respondents' firms had sales below CNY 5000 million, and the others had higher sales. Thus, the sample represented both large and small firms.

4.2. Common method bias and non-response bias

This study adopted both procedure and statistical methods to control the common method bias. With regard to the procedure remedies, we kept the questionnaire simple and specific, presented the measurement items for each construct in distinct sections, selected knowledgeable upper- and middle-level managers (over 90% of them with more than 5 years of work experience) as respondents, and ensured the full protection of the respondents' anonymity (Podsakoff et al., 2003). These procedures ensured that respondents could answer the questions carefully and honestly. Thus, we obtained reliable sources of information. Furthermore, we conducted Harman's single factor test using CFA and EFA. The results of EFA show four distinct factors with eigenvalues above or near 1.0, explaining 65.82% of the total variance. The first extracted factor explained only 33.69% of the total variable (less than 40 percent), which did not account for the majority of the variance. Then, CFA was also used by linking all items of the constructs to a single method factor. The fit indices (χ^2/df = 4.498, CFI = 0.616, IFI = 0.620, TLI = 0.570, RMSEA = 0.137 and SRMR = 0.116) were obviously unacceptable and considerably worse than those of the measurement model (χ^2/df = 1.597, CFI = 0.938, IFI = 0.939, TLI = 0.927, RMSEA = 0.057 and SRMR = 0.059). Based on the above statistical examination, we concluded that common method bias was not a serious threat in this study.

The non-response bias was assessed by comparing the difference between the responses from the early and late respondents (Armstrong and Overton, 1977). In this study, a *t* test on the number of employees and sales was compared between the early and late responses. The results showed no significant differences in the number of employees ($t = 0.176$, $p = 0.860$) and sales ($t = -0.288$, $p = 0.774$), confirming that non-response bias was not a serious concern.

4.3. Measures

Measures for the relevant constructs in this study were adapted from established instruments in previous literature. Because the survey was conducted with Chinese respondents, a back-translation method was employed to ensure conceptual equivalence (Chan et al., 2016). The measures were then reviewed and revised by several experts in operations management. A focus group discussion and pilot test with 20 respondents further helped to improve the measurement items to be more understandable and valid. Table 2 presents the constructs and measurement items adopted in this study. We used 7-point Likert scales to measure all these items, with "1" representing "strongly disagree" to "7" representing "strongly agree".

The measures for digital technologies were adapted from Dalenogare et al. (2018), Mittal et al. (2018) and Frank et al. (2019), which include the Internet of Things, cloud computing, big data and analytics. In the era of Industry 4.0, these innovative technologies have been integrated and interconnected to realize a more coherent effect (Ivanov et al., 2019). This implies that the items for digital technologies are highly correlated. Hence, our study applied a reflective model to measure digital technologies. The participants were asked to indicate the extent to which their firm has implemented digital technologies in their operations. Digital supply chain platforms refer to the platforms that promote interactions among supply chain partners (Rai et al., 2006; Reuver et al., 2018). We adopted the scale of Frank et al. (2019) to measure digital supply chain platforms, as shown in Table 2. The respondents were required to indicate the degree to which their firm has established digital platforms with suppliers, customers and other partners.

Economic and environmental performance were assessed by asking the respondents to indicate the extent to which their firm's performance has been achieved in the past three years. The measures for economic performance were adapted from Akter et al. (2016), Chan et al. (2016) and Schniederjans and Hales (2016), including growth in return on sales, growth in profit, growth in return on investment, growth in sales and growth in market share. Environmental performance was measured by four items adapted from Zhu et al. (2008), Schniederjans and Hales (2016) and Dubey et al. (2019). The items were reduction of air emission, reduction of wastewater, reduction of solid wastes and improvement of the firm's environmental situation. Although the self-reported perception measures of economic and environmental performance may be criticized as a limitation, Liu et al. (2016) note that these measures "have merits in soliciting the specificity for industry, time horizon, and economic (and environmental) conditions and thus facilitating comparisons across firms" (p. 18). The same measuring method has been commonly applied in the relevant research (e.g., Melnyk et al., 2003; Shashi et al., 2019).

Environmental dynamism is defined as the instability or volatility of

Table 2
Construct reliability and validity analysis.

Constructs and items		Factor loadings	S.E.	T value	Reliability and validity
Digital technologies (Dalenogare et al., 2018; Frank et al., 2019)					
DT1	Internet of Things	0.645	0.091	9.323	Cronbach's α = 0.830; CR = 0.836; AVE = 0.562
DT2	Cloud computing	0.790	0.087	12.254	
DT3	Big data	0.807	0.084	12.622	
DT4	Analytics	0.745	0.079	11.289	
Digital supply chain platforms (Rai et al., 2006; Frank et al., 2019; Ivanov et al., 2019)					
DSC1	Digital platforms with suppliers	0.743	0.08	10.838	Cronbach's α = 0.784; CR = 0.788; AVE = 0.555
DSC2	Digital platforms with customers	0.680	0.087	9.694	
DSC3	Digital platforms with other company units	0.807	0.085	12.053	
Environmental dynamism (Bozarth et al., 2009; Azadegan et al., 2013; Chan et al., 2016)					
ED1	Major changes in the modes of production and/or service provision	0.774	0.088	11.579	Cronbach's α = 0.819; CR = 0.823; AVE = 0.540
ED2	Major changes in consumer demographics	0.834	0.105	12.807	
ED3	Frequent and major changes in government regulations	0.641	0.104	9.087	
ED4	Short product life cycle	0.674	0.099	9.684	
Economic performance (Akter et al., 2016; Chan et al., 2016; Schniederjans and Hales, 2016)					
ECP1	Growth in return on sales	0.752	0.071	11.403	Cronbach's α = 0.843; CR = 0.846; AVE = 0.524
ECP2	Growth in profit	0.779	0.068	12.004	
ECP3	Growth in return on investment	0.706	0.077	10.465	
ECP4	Growth in sales	0.648	0.075	9.36	
ECP5	Growth in market share	0.729	0.08	10.935	
Environmental performance (Zhu et al., 2008; Schniederjans and Hales, 2016; Dubey et al., 2019)					
ENP1	Reduction of air emission	0.671	0.067	9.23	Cronbach's α = 0.771; CR = 0.771; AVE = 0.458
ENP2	Reduction of waste water	0.689	0.076	9.548	
ENP3	Reduction of solid wastes	0.648	0.076	8.857	
ENP4	Improvement of the firm's environmental situation	0.697	0.074	9.681	

Note: DT-digital technologies; DSC-digital supply chain platforms; ED-environmental dynamism; ECP-economic performance; ENP-environmental performance.

a firm's environment (Pagell and Krause, 2004). The scale to measure environmental dynamism was adapted from the literature of Bozarth et al. (2009), Azadegan et al. (2013), and Chan et al. (2016), including major changes in the modes of production and/or service provision, major changes in consumer demographics, frequent and major changes in government regulations, and short product life cycle.

We also controlled for ownership type and firm size in terms of the number of employees and sales. Scholars have indicated that ownership type may influence supply chain activities and performance (Liu et al., 2016; Amoako-Gyampah et al., 2019). This study used dummy variables for ownership types. Firm size has often been used as a control variable in previous studies. The larger firms are more likely to have adequate resources and capabilities to establish supply chain platforms and achieve a better performance than smaller firms (Shou et al., 2017).

4.4. Reliability and validity

This study conducted exploratory factor analysis (EFA) and confirmatory factor analysis (CFA) to evaluate the focal constructs' reliability and validity. EFA was first carried out to examine construct unidimensionality. The results indicated that all items have lower loadings on the irrelevant constructs and higher loadings on their corresponding construct. Cronbach's α for each construct was then calculated. As shown in Table 2, all the values were greater than 0.75 (Fornell and Larcker, 1981), ranging from 0.771 to 0.843. Hence, the internal consistency of the five constructs was ensured.

We assessed the convergent validity and discriminant validity of our measures by conducting CFA with the maximum likelihood method. The indices for the CFA model, $\chi^2/df = 1.597$, CFI = 0.938, IFI = 0.939, TLI = 0.927, RMSEA = 0.057 and SRMR = 0.059, indicated a reasonably high level of model fit (Hu and Bentler, 1999). Table 2 provides the values of the standardized factor loadings, composite reliability (CR) and average variance extracted (AVE). All factor loadings were greater than 0.50, ranging from 0.641 to 0.834. The estimates for CR were all higher than 0.70, ranging from 0.771 to 0.843. The AVE values were higher than 0.50 for four constructs in our study, while the AVE for environmental performance was 0.458, which is slightly below the suggested minimum (Fornell and Larcker, 1981). Considering that the values of the factor loadings, Cronbach's α and CR for environmental performance satisfied the detailed criteria (O'Leary-Kelly and Vokurka, 1998), we argue that the constructs had convergent validity.

The discriminant validity was confirmed by comparing the square root of the AVE value for each construct with the correlations between the paired constructs (Fornell and Larcker, 1981). The results presented in Table 3 show that the square root of the AVE values on the diagonal were greater than the correlations between the respective construct and the other constructs. Therefore, discriminant validity was ensured in our study.

5. Analyses and results

This study used the PROCESS proposed by (Hayes, 2017) to validate the hypotheses. Some scholars, such as Preacher and Hayes (2004) and Zhao et al. (2010), have noted the potential shortcomings of the multistep regression approach (e.g., the type I error about the mediation) in Baron and Kenny (1986). MacKinnon et al. (2002) find that the method of Baron and Kenny (1986) may lead to low statistical power. Preacher and Hayes (2004) suggest a more powerful strategy test to estimate the size and significance of the effect and develop a SPSS macro program (i.e., PROCESS) that relies on a nonparametric bootstrapping procedure. PROCESS can assess a complex model including both mediator and moderator variables and has been widely used in prior studies (e.g., Amoako-Gyampah et al., 2019; Wang et al., 2019; Wu et al., 2019; Yuan et al., 2020). Since a multiple regression analysis should be conducted based on the PROCESS program, the variance inflation factor (VIF) was calculated for each model. The results showed that the VIF values ranged from 1.211 to 1.812, which is lower than the threshold value of 10, thus confirming that multi-collinearity was not a serious issue for this study.

5.1. Hypothesis testing

We first built the mediation model using "Model 4" in PROCESS, as shown in Fig. 2, to test Hypotheses 1a, 1b, 2a and 2b. Table 4 summarizes the regression results. H1a and H1b examined the impact of digital technologies on economic and environmental performance. As shown in Table 4, controlling for the number of ownership types, employees and sales, digital technologies had a positive and significant impact on economic performance ($c_1' = 0.326$, t = 4.993) and environmental performance ($c_2' = 0.139$, t = 2.145). Thus, H1a and H1b were supported.

Table 3
Descriptive statistics, correlations and square root of AVE values.

Construct	Mean	S.D.	DT	DSC	ED	ECP	ENP
DT	5.145	1.057	**0.749**				
DSC	5.280	1.025	0.611***	**0.745**			
ED	4.053	1.177	0.403***	0.292***	**0.735**		
ECP	5.372	0.874	0.524***	0.468***	0.266***	**0.724**	
ENP	5.652	0.780	0.313***	0.328***	0.154*	0.501***	**0.677**

Note: Square root of AVE on the diagonal in bold.
***P < 0.001; **P < 0.01; *p < 0.05.

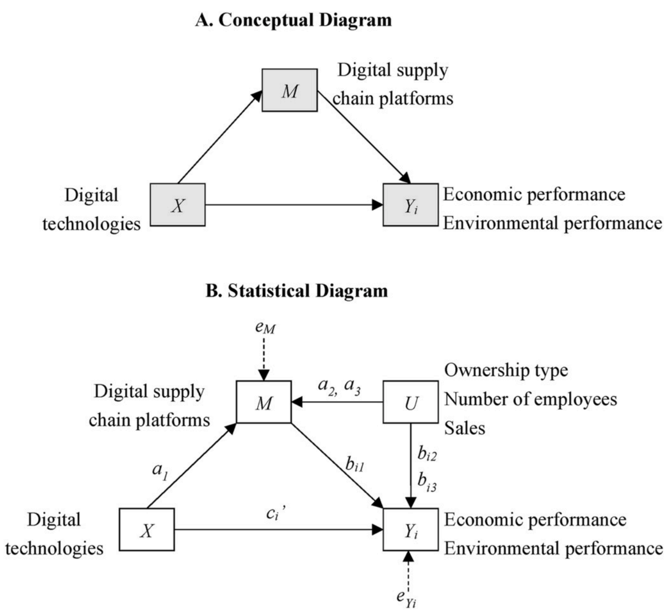

Fig. 2. The mediation model in conceptual (a) and statistical (b) diagram.

H2a and H2b examined the mediation effect of digital supply chain platforms on the relationship between economic performance and environmental performance. We tested the mediation effect using the bootstrapping application recommended by Hayes (2017). The results revealed that the path from digital technologies to digital supply chain platforms ($a_1 = 0.587$, t = 9.944) was significant and positive, while the path from supply chain platforms to economic performance (b_{11} = 0.201, t = 3.005) and environmental performance (b_{21} = 0.154, t = 2.345) was also significant and positive. The bootstrapping with 5000 resamples was executed to test the significance of the indirect effect of digital supply chain platforms. The results showed that the indirect effect of digital technologies on economic performance (indirect effect = 0.118, SE = 0.053) and environmental performance (indirect effect = 0.090, SE = 0.048) through digital supply chain performance was significant. Moreover, the bias-corrected 95th percentile confidence interval (CI) for the indirect effect on economic performance was [0.029, 0.235] and that on environmental performance was [0.002, 0.193], which did not contain zero. Thus, both the direct and indirect effect of digital technologies on economic performance and environmental performance were significant and positive, which indicated a partial mediation effect of digital supply chain platforms. Thus, H2a and H2b were supported in this study.

Regarding Hypotheses 3a and 3b, we predicted that environmental dynamism positively moderates the indirect effect of digital technologies on economic and environmental performance through digital supply chain platforms. “Model 58” in PROCESS with a bootstrap analysis on 5000 resamples was therefore established, as shown in Fig. 3. The interaction effects between environmental dynamism and digital technologies on digital supply chain platforms and that between environmental dynamism and digital supply chain platforms on economic and environmental performance were examined. Table 5 summarizes the regression results. The results indicated that the interaction term between digital technologies and environmental dynamism had a significant and positive effect on digital supply chain platforms ($a_3 = 0.124$, t = 2.694) and that the interaction term between digital supply chain platforms and environmental dynamism had a significant and positive impact on economic performance ($b_{13} = 0.118$, t = 2.545) and environmental performance ($b_{23} = 0.108$, t = 2.373).

Table 6 summarizes the conditional indirect effect of digital technologies on economic and environmental performance through digital supply chain platforms. The results indicated that the conditional indirect effect of digital technologies on economic performance was significant when environmental dynamism was high (95% CI = [0.109, 0.481]) but was insignificant when environmental dynamism was lower (95% CI = [-0.024, 0.152]). Therefore, the mediation effect of digital supply chain platforms on the relationship between digital technologies and economic performance was stronger when environmental dynamism was higher. Thus, H3a was supported. Similarly, the conditional indirect effect of digital technologies on environmental performance

Table 4
Regression results for mediation effect of digital supply chain platforms.

Dependent Variable	Digital supply chain platforms				Economic performance				Environmental performance			
	β	SE	T	p	β	SE	T	p	β	SE	T	P
Constant	2.259***	0.408	5.536	0.000	2.668***	0.397	6.712	0.000	4.287***	0.390	11.004	0.000
Ownership 1	0.198	0.181	1.191	0.274	0.046	0.163	0.281	0.779	0.120	0.160	0.752	0.453
Ownership 2	0.244	0.202	1.394	0.228	−0.088	0.183	−0.481	0.631	0.147	0.179	0.820	0.413
Ownership 3	0.072	0.239	0.715	0.764	−0.056	0.215	−0.262	0.794	−0.304	0.211	−1.438	0.152
employee	0.023	0.046	0.488	0.623	−0.020	0.042	−0.486	0.628	−0.046	0.041	−1.123	0.263
sales	−0.058	0.058	−0.848	0.323	0.012	0.052	0.229	0.819	−0.005	0.051	−0.098	0.922
DT	0.587***	0.059	9.944	0.000	0.326***	0.066	4.993	0.000	0.139*	0.065	2.145	0.033
DSC					0.201**	0.067	3.005	0.003	0.154*	0.066	2.345	0.020
R^2	0.382				0.315				0.173			
F	18.684***				11.824***				5.370***			
					Indirect effect	SE	95% CI		Indirect effect	SE	95% CI	
					0.118	0.053	[0.029, 0.235]		0.090	0.048	[0.002, 0.193]	

***P < 0.001; **P < 0.01; *p < 0.05.

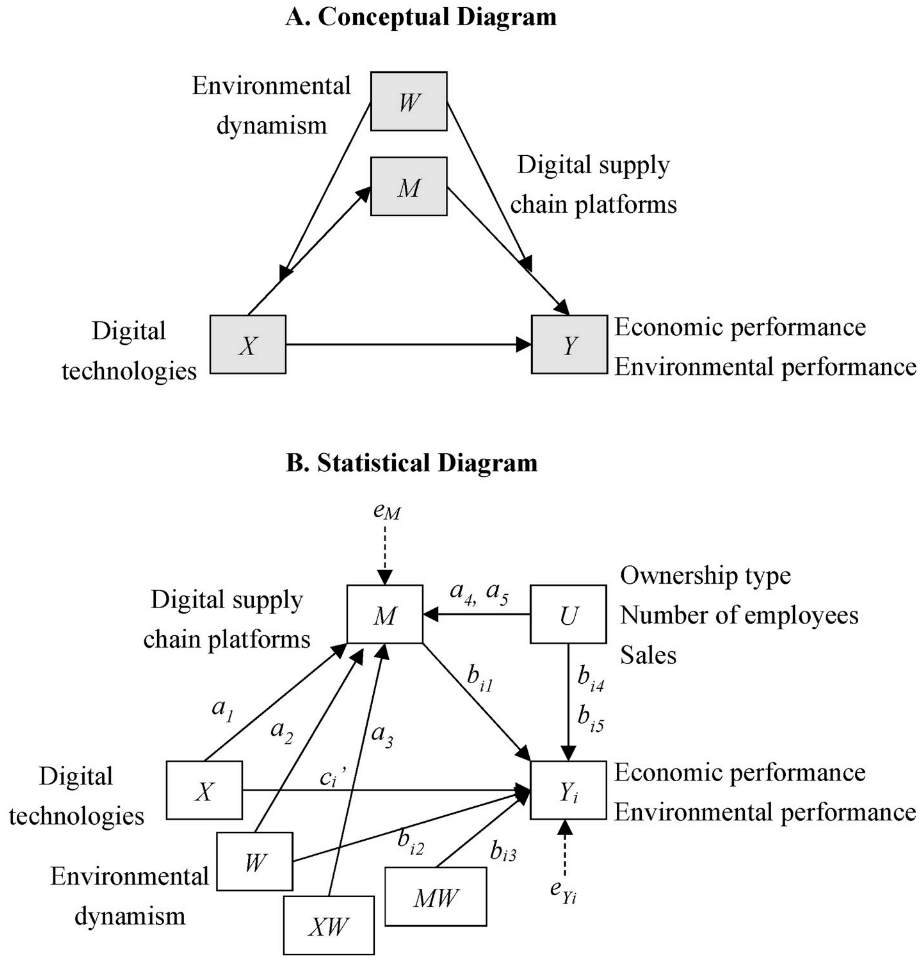

Fig. 3. The moderated mediation model in conceptual (a) and statistical (b) diagram.

Table 5
Regression results for moderation effect of environmental dynamism.

Dependent Variable	Digital supply chain platforms				Economic performance				Environmental performance			
	β	SE	T	p	β	SE	T	p	β	SE	T	p
Constant	−0.140	0.290	−0.482	0.630	5.320***	0.261	20.371	0.000	5.739***	0.257	22.347	0.000
ownership 1	0.249	0.178	1.395	0.165	0.071	0.162	0.441	0.660	0.139	0.159	0.877	0.382
ownership 2	0.276	0.200	1.378	0.170	−0.083	0.182	−0.454	0.650	0.145	0179	0.813	0.417
ownership 3	0.074	0.235	0.314	0.754	−0.029	0.213	−0.135	0.892	−0.280	0.209	−1.336	0.183
employee	0.040	0.046	0.877	0.382	−0.008	0.041	−0.194	0.846	−0.036	0.041	−0.885	0.377
sales	−0.065	0.057	−1.141	0.255	0.007	0.052	0.131	0.896	−0.009	0.051	−0.170	0.865
DT	0.592***	0.065	9.098	0.000	0.295***	0.069	4.280	0.000	0.117†	0.068	1.725	0.086
ED	0.044	0.056	0.799	0.426	0.017	0.051	0.332	0.740	−0.001	0.050	−0.003	0.998
DSC					0.231***	0.068	3.418	0.001	0.183**	0.066	2.750	0.007
ED*DT	0.124**	0.046	2.694	0.008								
ED*DSC					0.118*	0.046	2.545	0.012	0.108*	0.045	2.373	0.019
R^2	0.410				0.341				0.199			
F	15.557***				10.223***				4.901***			

***P < 0.001; **P < 0.01; *p < 0.05; †p < 0.1.

was significant when environmental dynamism was high (95% CI = [0.079, 0.403]) but was insignificant when environmental dynamism was lower (95% CI = [-0.058, 0.113]). Hence, the mediation effect of digital supply chain platforms on the relationship between digital technologies and environmental performance was stronger when environmental dynamism was higher. Thus, H3b was also supported in this study.

5.2. Endogeneity

Digital technologies may be endogenously influenced by the firm's performance. To address the potential endogeneity bias, this study adopted the Hausman test, as suggested by Davidson and MacKinnon (1993). We first identified firm size in terms of the number of employees and sales as potential instrumental variables because these two variables were not significantly related to economic and environmental performance (see Table 4) (Liu et al., 2016). Frank et al. (2019) note that large firms are more prepared for the adoption of advanced digital

Table 6
Conditional indirect effect of digital technologies on economic and environmental performance at different levels of environmental dynamism.

Dependent variable	Condition of environmental dynamism	Conditional indirect effect through digital supply chain platforms		
		Indirect effect	SE	95% CI
Economic performance	Lower (−1 SD)	0.041	0.046	[-0.024, 0.152]
	Middle (0)	0.137	0.055	[0.042, 0.258]
	High (+1 SD)	0.272	0.094	[0.109, 0.481]
Environmental performance	Lower (−1 SD)	0.025	0.044	[-0.058, 0.113]
	Middle (0)	0.108	0.045	[0.021, 0.198]
	High (+1 SD)	0.228	0.084	[0.079, 0.403]

technologies, which indicates that firm size influences digital technologies. Then, digital technologies were regressed on the assumed instrumental variables and control variables. The results indicated a significant relationship between the number of employees and digital technologies ($\beta = 0.199$, $t = 2.227$, $p = 0.027$). Further, economic and environmental performance were regressed on the error term of digital technologies obtained from the first stage of regression, digital technologies and control variables. The error term was insignificantly related to economic performance ($\beta = 0.154$, $t = 0.414$, $p = 0.679$) and environmental performance ($\beta = 0.504$, $t = 1.240$, $p = 0.216$). Hence, we concluded that endogeneity was not an issue that impacted the findings of our study.

6. Discussion and conclusions

6.1. Theoretical implications

This study empirically investigates how digital technologies in the context of Industry 4.0 influence economic and environmental performance from the perspective of IPT. Based on a survey of Chinese manufacturing firms, the mediating effect of digital supply chain platforms and the moderating effect of environmental dynamism are proposed and investigated. The results contribute to relevant research on operations management and environmental management from four aspects.

First, this study finds that digital technologies positively influence economic and environmental performance. In the context of Industry 4.0, advanced digital technologies, including the Internet of Things, cloud computing, big data, and analytics, emerge and develop rapidly in a meaningful fashion. Although scholars have discussed the impact of a specific emerging digital technology on firms' performance, such as the Internet of things (YU et al., 2015), big data analytics (Akter et al., 2016; Wamba et al., 2017; Dubey et al., 2019), cloud computing (Schniederjans and Hales, 2016), and others (Dalenogare et al., 2018), manufacturing firms tend to integrate and configure these front-end technologies to establish a digitally enabled infrastructure, thus supporting their operations and environmental management (Ivanov et al., 2019). This study identifies the emerging advanced technologies as a unified construct that indicates the firm's information processing capabilities and empirically investigates the coherent impact of advanced digital technologies on economic and environmental performance. The findings can help to better understand the integration of innovative and emerging digital technologies in the new era of Industry 4.0 and their coherent effect on firms' sustainable development.

In particular, previous studies have drawn inconsistent conclusions about the relationship between digital technologies and sustainability. On the one hand, scholars have recognized that digital technologies have the potential to facilitate product and operational performance (Dalenogare et al., 2018), environmental control and protection (Gobbo et al., 2018; Kamble et al., 2018), and environmentally sustainable manufacturing (Jabbour et al., 2018), which may lead to sustainability performance (Schniederjans and Hales, 2016; Dubey et al., 2019). However, these studies, especially those on environmental sustainability, have been mostly based on qualitative reasoning. On the other hand, some previous studies have found that some digital technologies have a potential negative impact on product performance (Dalenogare et al., 2018) and bring financial and environmental burdens (Kiel et al., 2017). We highlight that the relationships between digital technologies and sustainability performance have not been fully investigated. Jabbour et al. (2018) strongly recommend that future research develop the relationships between digital technologies and sustainability and test the relationships through quantitative methods. Our study provides empirical evidence for the relationship between the use of digital technologies and sustainability performance in the context of Industry 4.0, responding to the call of Jabbour et al. (2018).

Second, our study confirms that the adoption of digital technologies facilitates the establishment of supply chain platforms in the era of Industry 4.0. This assertion is consistent with those Jacobs et al. (2016) and Shou et al. (2017), who indicate that the firm's internal communication and integration capabilities entail the exchange of real-time data and information across supply chains. Scholars have been attempting to establish the links between digital technologies and supply chain processes through narrative literature review or exploratory case studies (Zhou et al., 2015; Addo-Tenkorang and Helo, 2016; Govindan et al., 2018; Nguyen et al., 2018; Ben-Daya et al., 2019; Ivanov et al., 2019). The findings in this study provide empirical evidence for the links between digital technologies and supply chain platforms.

Moreover, this study proposes and validates the mediating role of digital supply chain platforms, which serves as the underlying mechanism to explain the relationship between digital technologies and sustainability performance. The findings reveal that the effectiveness of digital technologies should be realized through the establishment of digital supply chain platforms. Some studies have discussed the mediating role of supply chain activities in the relationship between traditional information technology and performance (e.g., Wu et al., 2006). However, in the context of Industry 4.0, few studies have empirically explored how supply chain platforms mediate the effect of advanced digital technologies on sustainability performance. The study of Camara et al. (2015) is rare in that it indicates that the impact of cloud computing on operational performance requires the mediating support of supply chain integration. In this study, the mediation effect of digital supply chain platforms implies that incorporating proper mediators can help better explain the impact of digital technologies on economic and environmental performance.

Third, our study reveals that environmental dynamism moderates the indirect effect of digital technologies for Industry 4.0 on economic and environmental performance through digital supply chain platforms. To the best of our knowledge, there is limited empirical research examining the moderating factors in the field of digital technologies for Industry 4.0. Our study indicates that, particularly in a dynamic environment, manufacturing firms should not only rely on internal information processing capabilities by use of digital technologies but also need to make the utmost digital supply chain platforms access more sufficient information externally, thereby realizing higher economic and environmental performance. In other words, digital technologies and supply chain platforms play a more crucial role in the dynamic environment. These findings can further contribute to the understanding of the contextual conditions to develop and apply digital technologies and supply chain platforms.

Last but not least, based on the IPT (Galbraith, 1973; Tushman and Nadler, 1978), this study identifies the application of digital platforms as the organization's information processing capabilities and digital supply chain platforms as information exchange channels with upstream suppliers, downstream customers and other partners. The findings support IPT by confirming that information processing capabilities and high information quality contribute to performance (Premkumar et al., 2005). Moreover, environmental conditions determine the requirements for informational processing capabilities and information quality (Melville and Ramirez, 2008; Chan et al., 2016). The moderating effect of environmental dynamisms implies that manufacturing firms should access sufficient information internally and externally and enhance their information processing capabilities to match their high levels of information-processing requirements. The effect of fit between information processing capabilities and requirements is therefore demonstrated in this study. Overall, the empirical findings are consistent with the IPT perspective, suggesting that IPT is a useful way to characterize both the effects and contextual conditions of digital technologies for Industry 4.0 and digital supply chain platforms.

6.2. Managerial implications

The findings in our study also provide some managerial insights for manufacturing firms. In the era of Industry 4.0, front-end technologies such as the Internet of Things, cloud computing, big data and analytics have been adopted to gain competitive advantages (Dalenogare et al., 2018). To promote sustainable development, manufacturing firms are recommended to use these digital technologies to enhance their economic and environmental sustainability. It should be recognized that operations and environmental management activities in the present business environment are highly information-intensive. Firms that obtain accurate and real-time information can thus have superiority in competition. The adoption of digital technologies for Industry 4.0 is primarily for collecting and processing information related to products and production, thereby supporting decision making effectively and efficiently. A digitally enabled technology infrastructure will be a necessary choice for manufacturing firms to obtain the success of both operations and environmental management.

The findings further reveal that manufacturing firms should extend their use of digital technologies into supply chain processes and establish digital supply chain platforms with upstream suppliers, downstream customers and other partners. Previous studies have highlighted the significance of supply chain relationships in achieving sustainability (Jadhav et al., 2018). Our study emphasizes that in the era of Industry 4.0, digital supply chain platforms still matter much to the improvement of economic and environmental sustainability. In particular, managers need to recognize the crucial role of supply chain platforms in realizing the value of digital resources when firms compete in a highly dynamic environment that is characterized by frequent and rapid changes in customer demand, production modes and government regulations. In sum, for sustainable development, firms should not only apply digital technologies within organizational boundaries but also establish digitally enabled platforms across supply chains.

6.3. Limitations and future research

Although the findings provide theoretical and managerial insights for researchers and practitioners, there are still several limitations in this study that also direct future research. First, we focus on economic and environmental performance, which are two dimensions of sustainability performance. Prior studies suggest a "triple bottom line" perspective to capture sustainability (Kamble et al., 2018). Hence, we recommend including the social dimension of sustainability to fully explore the relationship between digital technologies for Industry 4.0 and sustainability performance. Second, in this study, we refer digital technologies to the Internet of Things, cloud computing, big data and analytics. We recognize these innovative technologies are integrated and interconnected in the era of Industry 4.0 thus a reflective model is used to measure digital technologies. In the future, with the growing new digital technologies, some of which might not naturally integrated or interconnected, thus a formative model to measure digital technologies might needed. Lastly, to test the proposed hypotheses, this study conducted a survey in China, which is regarded as an emerging market. In recent years, Industry 4.0 technologies have been widely adopted and well developed in the Chinese manufacturing industry. Future research may test the model in developed markets to compare the potential differences in the application of digital technologies and supply chain platforms.

CRediT authorship contribution statement

Ying Li: Conceptualization, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Jing Dai:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Li Cui:** Writing - review & editing, Supervision.

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