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How does digitalization alter the paradox of supply base concentration? The effects of digitalization intensity and breadth

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Abstract

Purpose – The highly uncertain and turbulent environments nowadays intensify the paradoxical effects of supply base concentration on improving cost efficiency while increasing idiosyncratic risk. Digitalization is regarded as a remedy for this paradox, yet its potentially curative effect has not been empirically tested. Leveraging the lenses of paradox theory and information processing theory, this study explores how two distinct dimensions of digitalization, i.e., digitalization intensity and breadth, reconcile the paradoxical effects of supply base concentration.

Design/methodology/approach – Using a panel dataset of 1,238 Chinese manufacturing firms in the period of 2012–2020, this study utilizes fixed-effects regression models to test the proposed hypotheses.

Findings – We discover that supply base concentration enhances a firm's cost efficiency but induces greater idiosyncratic risk. More importantly, it is evidenced that digitalization intensity restrains the amplifying effect of supply base concentration on idiosyncratic risk. However, digitalization breadth weakens the enhancing effect of supply base concentration on cost efficiency and aggravates its exacerbating effect on idiosyncratic risk.

Originality/value – This study advances the understanding of the paradoxical effects of supply base concentration on cost efficiency and idiosyncratic risk from a paradox theory perspective. More importantly, to our best knowledge, our study is the first to untangle the differential roles of digitalization intensity and breadth in reconciling the paradox of supply base concentration. It also provides practitioners with nuanced insights into how they should use appropriate tactics to deploy digital technologies effectively.

Keywords: Supply base concentration; Paradox; Digitalization; Intensity; Breadth; Information processing theory

1. Introduction

The recently drastic-changing environments (e.g., Brexit, COVID-19 pandemic, Sino-U.S. trade war, and Russia-Ukraine war) have brought supply chains into an era of disruption, which has caused dramatic increases in uncertainty and presented knotty challenges for practices of supply base management (Bergstrom *et al.*, 2020; Shih, 2020). Supply base concentration (SBC), as one of the major focuses of supply chain managers, generates continuous tensions between improving cost efficiency and increasing idiosyncratic risk simultaneously (Lanier *et al.*, 2010; Vachon and Klassen, 2006; Wagner and Bode, 2006), making it a persistent paradox of performing in operations and supply chain management (OSCM) (Smith and Lewis, 2011). Specifically, on the one hand, a concentrated supply base, which denotes that the firm has higher cost percentages on a small number of suppliers, reduces transaction costs through streamlined production, intensive information sharing, and stable long-term relationships with key suppliers (Ak and Patatoukas, 2016). This can satisfy the information processing requirements and lead to improved cost efficiency for firms. On the other hand, a concentrated supply base gives rise to higher disruption risks due to the increased dependence on core suppliers, higher switching costs, and greater risks of being exploited by critical suppliers (Lonsdale, 2001; Vachon and Klassen, 2006). This increases the variability of firms' future cash flows and leads to greater idiosyncratic risk, which denotes the volatility of stock prices caused by firm-specific events, such as supply chain disruptions and environmental incidents (Ye *et al.*, 2020). In this case, the paradoxical nature of SBC complicates the structure of supply bases and generates additional information processing needs, posing challenges for firms attempting to effectively manage this paradox. Although the conflicting requirements of SBC have been acknowledged in the OSCM literature (e.g., Lanier *et al.*, 2010; Vachon and Klassen, 2006), scant research has approached this topic from the lens of paradox theory, which falls short of the imminent need for practitioners to effectively manage the performing paradox of SBC.

To bridge this knowledge gap, we draw upon paradox theory (Smith and Lewis, 2011) to examine the performing paradox of SBC by deeply elucidating the contradictory and persistent tensions between improving cost efficiency and reducing idiosyncratic risk. Such tensions have been significantly escalated by today's increasingly complex and volatile environments. It becomes particularly evident during the COVID-19 pandemic that firms with higher levels of SBC have experienced unreliable supply from suppliers (e.g., delays in delivery, prolonged lead time, and severe inventory shortage) and encountered great difficulties in gaining real-time information from suppliers, which entails high disruption risks in operations and supply chains (Ares, 2021; Kutzner, 2020). For example, automobile manufacturers such as Volkswagen experienced a severe shortage of chips and had to halt production during the COVID-19 outbreak due to the limited supply from its highly concentrated semiconductor supply chain (Wayland, 2022). Thus, it is essential for researchers and practitioners to investigate how firms could accommodate the intensified paradoxical tensions between cost efficiency and idiosyncratic risk associated with highly concentrated supply bases under uncertain and volatile environments.

Most recently, paradox researchers advocate that firm-specific capabilities may help ease paradoxical tensions (Berti and Cunha, 2022). Plenty of anecdotal evidence shows that the deployment of digitalization enables real-time and comprehensive information processing capabilities and fulfills the real-time, autonomous, and intensive information processing requirements derived from concentrated supply bases, thereby offering the potential to disentangle the intensified paradoxical effects of cost efficiency and idiosyncratic risk resulting from a high level of SBC (KPMG, 2022; Kutzner and Rajal, 2020; Schrauf and Berttram, 2017). In doing so, undertaking digitalization could help firms harmonize the competing goals of cost efficiency improvement and idiosyncratic risk mitigation. For example, Ericsson has harnessed increased efficiency and flexibility and reduced risks through the implementation of digital technologies (e.g., cloud computing, augmented reality, digital twin, and Internet of Things) in its factories in Sweden, Estonia, and China (Wilson, 2020). This promotes real-time data sharing, autonomous sales and operations planning, and increased traceability and visibility within factories and with suppliers. However, there are divergent views on digitalization practices, with some advocating the benefits of digitalization in terms of improved firm performance (Abou-Foul *et al.*, 2021; Karakas *et al.*, 2021) and others pinpointing the potential downside of digitalization, such as substantial costs and technology uncertainties (Massimino *et al.*, 2018; Yang *et al.*, 2021). As such, it still remains unclear whether the implementation of digitalization can enhance firms' information processing capabilities and further reconcile the paradoxical tensions of SBC, which impedes a fine-grained understanding of how firms could deal with this paradox.

Building on the paradox literature advocating that organizational capabilities can moderate the paradoxical tensions (Berti and Cunha, 2022; Ivory and Brooks, 2018) and information processing theory (IPT) (Galbraith, 1974), we investigate digitalization as a potential response strategy for firms to effectively cope with the performing paradox of SBC. Specifically, we delve deeper into two distinct dimensions of digitalization (i.e., digitalization intensity and breadth) and unravel their different roles in altering the paradoxical effects of SBC. Inspired by previous research on the investment intensity of innovation projects (Klingebiel and Rammer, 2014), we define digitalization intensity as the resource investment per type of digital technology. Furthermore, adapted from Autry *et al.* (2010), digitalization breadth is referred to as the number of types of digital technology that a firm adopts. A high level of digitalization intensity indicates an in-depth adoption of digital technologies, which enhances the firm's capabilities to fulfill the information processing requirements incurred by a highly concentrated supply base (Xie *et al.*, 2022). By contrast, a firm with a broad scope of digital technologies tends to complicate its digital technology portfolio, hinder the full-fledged employment of each digital technology, and boost the difficulty in coordination among digital technologies. This may decrease the firm's information processing capabilities to meet the increased information processing demands from a highly concentrated supply base (Autry *et al.*, 2010; Devaraj and Kohli, 2003; Fitzgerald *et al.*, 2014). In this light, digitalization intensity and breadth might enable firms to develop varying levels of information processing capabilities to fulfill information processing requirements induced by SBC, thereby playing distinct roles in reconciling the paradoxical tensions between cost efficiency and idiosyncratic risk associated with a highly concentrated supply base.

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Against this backdrop, we intend to answer the following research questions: *(1) How does a firm's SBC affect its cost efficiency and idiosyncratic risk? and (2) How do a firm's digitalization intensity and breadth alter the paradoxical effects of SBC?* To address these research questions, we utilize a panel dataset of 1,238 publicly listed Chinese manufacturing firms from 2012 to 2020 and apply fixed-effects regression models to test the proposed hypotheses. The results demonstrate that a higher level of SBC leads to higher cost efficiency but it also results in greater idiosyncratic risk. Furthermore, digitalization intensity lessens the exacerbating effect of SBC on idiosyncratic risk, which is in line with prior research highlighting the pivotal role of digital technologies in firm risk mitigation (Baryannis *et al.*, 2019; Ivanov *et al.*, 2019). Nevertheless, digitalization breadth weakens the enhancing effect of SBC on cost efficiency and aggravates its exacerbating effect on idiosyncratic risk, which reveals the potential downside of digitalization.

This study makes several contributions to the relevant literature. First, this study enriches and expands the paradox literature by identifying and delineating SBC as a paradox of performing with contradictory demands of improving cost efficiency and lowering idiosyncratic risk. More importantly, this study advances the paradox literature by articulating response strategies (i.e., digitalization) to deal with the performing paradox of SBC. By doing so, this study echoes previous research on managing paradoxes, which advocates that firm-specific capabilities could harmonize the competing demands of paradoxes and change them from contradictory to complementary to a certain extent (Berti and Cunha, 2022; Ivory and

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Brooks, 2018). Second, this study extends the digitalization literature by distinguishing two distinct dimensions of digitalization (i.e., intensity and breadth) and investigating their different roles in reconciling the paradox of SBC. Previous studies have primarily considered and examined digitalization as a unidimensional concept (e.g., Cenamor *et al.*, 2017; Shi *et al.*, 2022; Wei and Sun, 2021). Our study steps further by differentiating two distinct dimensions of digitalization, and therefore, sheds light on the digitalization literature. Third, by unraveling the empowerment role of digitalization intensity and the hindering role of digitalization breadth in accommodating the paradoxical effects of SBC, this study advances the literature on digitalization and opens up new opportunities to explore the roles of individual dimensions of digitalization in other OSCM practices.

2. Literature review and hypotheses development

2.1 Industry 4.0 and digitalization

Industry 4.0, which is commonly known as the Fourth Industrial Revolution, has attracted considerable attention from both researchers and practitioners. Originally initiated in Germany as a national manufacturing strategy, Industry 4.0 refers to “the horizontal and vertical integration of production systems driven by real-time data interchange and flexible manufacturing to enable customized production” (de Sousa Jabbour *et al.*, 2018). Previous studies have emphasized that Industry 4.0 involves the adoption of various digital technologies to upgrade firms’ manufacturing facilities and revolutionize their operations and supply chain

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processes (de Sousa Jabbour *et al.*, 2018; Núñez-Merino *et al.*, 2020).

The concept of digitalization is rooted in Industry 4.0 and has gained rapid popularity over the past decade. In general, digitalization refers to “the use of digital technologies to create new processes or transform existing processes to meet changing business and market requirements” (Zhou *et al.*, 2021). The existing OSCM literature on digitalization has underscored that major advanced digital technologies include artificial intelligence, augmented reality, big data analytics, blockchain, cloud computing, digital twin, fintech, identification technology, Internet of Things, and robotics (Choi *et al.*, 2022; Cole *et al.*, 2019; Feng *et al.*, 2022; Tozanli and Saénz, 2022; Rogers *et al.*, 2016). Table 1 summarizes these digital technologies by providing the definition and key characteristics of each digital technology and illustrative examples of related products/software offered by top branded enterprises.

[Insert Table 1 about here]

2.2 Digitalization intensity and breadth

Firms are active in embarking on the deployment of digital technologies. Yet, given that firms have different investment strategies (Nasiri *et al.*, 2022), they might make various decisions on whether they should focus on increasing the investment per type of digital technology or invest in a broader scope (i.e., more types) of digital technologies. As such, considering the complexity of digitalization in terms of variations in intensity and the scope of digital technologies (Nasiri *et al.*, 2022; Lorenz *et al.*, 2020), it will be revealing to examine firms’ digitalization along the intensity and breadth dimensions. This examination is inspired by previous research (Klingebiel and Rammer, 2014), which discusses the intensity and breadth of firms' innovation projects. We aim to capture different attributes of digitalization, reflecting different technology investment strategies of firms.

Specifically, digitalization intensity denotes the resource investment per type of digital technology. It captures the depth or scale of firms' engagement in digitalization. This conceptualization is similar to the approach employed by Klingebiel and Rammer (2014), who operationalize firms' resource investment intensity in innovation projects. Furthermore, inspired by Autry *et al.* (2010), who consider technological breadth as the extent of a firm's technology portfolio, we define digitalization breadth as the number of types of digital technology that a firm has adopted, such as artificial intelligence, blockchain, cloud computing, and digital twin. A higher level of digitalization breadth indicates more types of digital technology implemented by firms. The definition of these two dimensions of digitalization – intensity and breadth – allows us to capture a firm's investment portfolio of digital technologies.

Previous research has primarily investigated the direct effect of digitalization on firm performance (Li *et al.*, 2020), green process innovation (Wei and Sun, 2021), and supplier opportunism (Yang *et al.*, 2021). Although digitalization has been growingly emphasized in managing buyer–supplier relationships, there is a dearth of research that disentangles how different dimensions of digitalization (i.e., intensity and breadth) exert differing influences on the impact of SBC on cost efficiency and idiosyncratic risk. This gap is significant, given that different technology investment strategies may play differential roles in enabling firms to

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resolve the efficiency–risk paradox of SBC. Therefore, our study seeks to narrow this gap by uncovering how digitalization intensity and breadth alter the paradoxical effects of SBC.

2.3 The paradoxical effects of SBC on cost efficiency and idiosyncratic risk

A burgeoning stream of literature has adopted paradox theory to examine different types of paradoxes and the response strategies to address them (Berti and Cunha, 2022; Schad *et al.*, 2016). Paradox is defined as "contradictory yet interrelated elements that exist simultaneously and persist over time" (Smith and Lewis, 2011, p. 382). The contradictory nature of paradoxes generates a constant tug-of-war between their competing elements (Hillmer *et al.*, 2023). Researchers have distinguished four typical types of paradoxes, namely paradoxes of learning, organizing, belonging, and performing (Lüscher and Lewis, 2008; Smith and Lewis, 2011). As a widely discussed paradox and the main focus of this study, performing paradox emerges when the simultaneously pursued goals conflict with each other, which are often imposed by the competing demands of different stakeholders (Smith and Lewis, 2011; Xiao *et al.*, 2019). This type of paradox indicates that firms are required to achieve contradictory and interconnected goals simultaneously and persistently. Given the complex nature and salience of paradoxes, scholars have proposed various response strategies (e.g., acceptance, spatial separation, temporal separation, trade-offs, and dialectics) to deal with these paradoxes (Berti and Cunha, 2022; Hillmer *et al.*, 2023; Maalouf and Gammelgaard, 2016).

Flourishing at the individual, group, and organizational levels of research (Schad *et al.*, 2016), paradox theory has attracted growing attention in studying inter-organizational relationships, among which the major situation is the supply chain (Schad *et al.*, 2016). In particular, the coopetition nature of buyer–supplier relationships and the complex structure of supply bases exhibit intrinsic conflicting and persistent tensions, forming different types of paradoxes in OSCM (Choi and Krause, 2006; Kim *et al.*, 2015; Wilhelm and Sydow, 2018). More recently, the turbulent and volatile environment has dramatically aggravated the contradictory tensions in managing supply chains. An increasing number of OSCM studies have employed paradox theory to identify, make sense of, and manage paradoxes in lean management (Erthal *et al.*, 2021; Maalouf and Gammelgaard, 2016), servitization (Brax *et al.*, 2021), sustainable supply chain management (Matos *et al.*, 2020; Xiao *et al.*, 2019), coopetition in supply networks (Wilhelm and Sydow, 2018), and radical product and process innovation (Hillmer *et al.*, 2023). However, scant research has investigated the contradictory and persistent tensions in managing SBC from a paradox theory perspective, which hampers an in-depth understanding of the paradoxical nature of SBC. More importantly, little is known about how firms could adopt appropriate response strategies to reconcile the paradox of SBC. To this end, our research aspires to advance the literature on paradox theory by offering new insights into the paradox of SBC and the response strategies to accommodate this paradox.

SBC, as an essential characteristic of a supply base, indicates the number of key suppliers on whom a firm spends its purchasing cost (Hu *et al.*, 2022). A high level of SBC implies that buyer firms' purchases go to a few dominant suppliers (Choi and Krause, 2006). Managing the level of SBC creates intrinsic contradictory tensions for firms with simultaneous goals of

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achieving higher cost efficiency and lower risks (Lanier *et al.*, 2010; Vachon and Klassen, 2006; Wagner and Bode, 2006), making it a paradox of performing in OSCM. Specifically, a firm may benefit from a highly concentrated supply base in terms of lower transaction costs and in-depth information sharing but may confront higher risks at the same time (Ak and Patatoukas, 2016; Lonsdale, 2001; Vachon and Klassen, 2006). By contrast, a firm that maintains a broad and diluted supply base has lower disruption risks while facing a lack of in-depth information sharing and higher transaction costs (e.g., contracting and monitoring costs) (Lonsdale, 2001; Vachon and Klassen, 2006). Such contradictory tensions in managing SBC are persistent because we can seemingly address them in the short term, yet they prevail in the long term. Overall, the tensions between improving cost efficiency and increasing idiosyncratic risk associated with a highly concentrated supply base are contradictory, interdependent, and persistent, thus resulting in a performing paradox for firms.

We posit that a higher level of SBC improves firms' cost efficiency, yet it also leads to greater idiosyncratic risk. Specifically, a firm with a higher SBC tends to maintain long-term relationships with its key suppliers, which promotes in-depth information sharing and reduces the uncertainty and coordination costs during transactions (Lanier *et al.*, 2010; Ak and Patatoukas, 2016). The stable buyer–supplier relationships resulting from a higher level of SBC also contribute to higher product quality, more reliable delivery of raw materials and parts, and faster responsiveness, thus enabling the firms to enhance cost efficiency (Choi and Krause, 2006; Ogden, 2006; Steven *et al.*, 2014). In addition, a firm with a highly concentrated supply base has relatively large transaction volumes from a small number of key suppliers, which leads to economies of scale and higher cost efficiency (Cox, 2001). Therefore, a highly concentrated supply base meets the firm's demand for increased cost efficiency.

However, firms with a highly concentrated supply base have a higher dependence on and hence lower bargaining power over their key suppliers, which brings about greater vulnerability and exploitation risks (Kim and Henderson, 2015; Ryals and Rogers, 2006; Wagner and Bode, 2006) and unfulfilled demands for monitoring risks. Firms with a limited number of suppliers are inclined to invest in more relationship-specific assets and source larger transaction volumes from a few suppliers, which increases the switching costs and the lock-in risk (Cox, 2001; Elking *et al.*, 2017; Grover and Malhotra, 2003). Moreover, firms with concentrated supply bases possess fewer backup suppliers and thus are more susceptible to catastrophic events such as natural disasters, political conflicts, and wars, which leads to higher disruption risks (Hendricks and Singhal, 2003; Matsuo, 2015; Vachon and Klassen, 2006). In short, a high level of SBC increases the variability of firms' future cash flows and thus results in greater idiosyncratic risk.

The above discussion suggests that while a higher level of SBC enhances firms' cost efficiency, it also induces greater idiosyncratic risk. Thus, we hypothesize that:

H1. A firm with a higher level of SBC is positively associated with higher cost efficiency.

H2. A firm with a higher level of SBC is positively associated with greater idiosyncratic risk.

2.4 Moderating roles of digitalization intensity and breadth

Paradox theory maintains that while paradoxes are contradictory, interdependent, and persistent, firms can utilize various approaches to manage the paradoxes (Schad *et al.*, 2016; Smith and Lewis, 2011). Proponents of a paradoxical perspective highlight that firms can be more effective if they accept and embrace the coexistence of contradictory elements (Lüscher and Lewis, 2008). Paradox researchers further argue that firms can adopt response strategies to deal with or lessen the paradoxical tensions (Smith and Lewis, 2011). In particular, prior studies underline that the intensity of paradoxical tensions that firms encounter can be moderated by organizational capabilities (Berti and Cunha, 2022).

In our research context, we particularly focus on how digitalization intensity and breadth, which are associated with the development of information processing capabilities, alter the paradoxical effects of SBC on firms' cost efficiency and idiosyncratic risk. IPT is adopted as a useful theoretical lens, through which we examine the moderating effects of digitalization intensity and breadth. Specifically, the IPT holds that in an uncertain and volatile environment, firms need to effectively collect, analyze, and utilize information to reduce uncertainty and complexity (Galbraith, 1974). According to IPT, there are two strategies to deal with uncertainty and complexity (Jia *et al.*, 2020). The first approach is to lower information processing needs by mitigating environmental uncertainties (Zhang *et al.*, 2022). The second is to improve information processing capabilities to facilitate information sharing and alleviate uncertainty and complexity (Srinivasan and Swink, 2015). The increasingly dynamic and uncertain environments complicate the information processing function of a highly concentrated supply base and intensify its intrinsic paradoxical effects on improved cost efficiency and increased idiosyncratic risk. In turbulent and dynamic environments, a higher level of SBC asks for more in-depth, interrelated, immediately responsive, and low-latency information shared by key suppliers to enable efficient processing (Brandon-Jones *et al.*, 2015; Busse *et al.*, 2017), which raises difficulties for firms to fulfill such information processing requirements. Therefore, we posit that digitalization intensity and breadth may amplify or diminish firms' ability to satisfy the greater information processing requirements induced by SBC, which may further modify the efficacy of SBC on cost efficiency and idiosyncratic risk.

We conjecture that digitalization intensity reinforces the enhancing effect of SBC on cost efficiency while lessening its exacerbating effect on idiosyncratic risk. Specifically, when firms increase the investment intensity of digitalization, they are more capable of collecting and processing information across the supply chain (Zhang *et al.*, 2022; Kessler *et al.*, 2022). Deeply engaging in specific digital technologies is advantageous for firms to gain access to on-time information promptly (e.g., transactional data, and levels of raw materials and inventory) and improve supply chain transparency (Xie *et al.*, 2022). For instance, improving investment intensity in blockchain can facilitate increased and consistent information sharing among supply chain partners (Karakas *et al.*, 2021). In-depth engagement in digital technologies can also enhance firms' capacity to process and analyze massive information from different sources (e.g., supply chain channels) (Yang *et al.*, 2021). This is beneficial for firms to better process

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supplier-related information with minimal delay and coordinate with their suppliers promptly, thereby enhancing the efficacy of leveraging SBC to boost cost efficiency. Meanwhile, with improved information processing capabilities, firms possessing higher digitalization intensity are better able to identify, monitor, and cope with the risks of supply chain disruptions engendered by highly concentrated supply bases (Rodríguez-Espíndola *et al.*, 2022), which can help alleviate the exacerbating effect of SBC on idiosyncratic risk.

By contrast, under the circumstance of lower digitalization intensity, firms are less capable of acquiring, integrating, and processing information (Xie *et al.*, 2022), which impairs their abilities to meet the information processing requirements associated with highly concentrated supply bases. This could attenuate the cost benefits derived from SBC. In such a situation, firms may also be in a vulnerable position to tackle the supply chain disruption risks induced by a higher level of SBC (Shi *et al.*, 2022), hence aggravating its exacerbating effect on idiosyncratic risk. Thus, we hypothesize that:

H3a. A firm's digitalization intensity strengthens the enhancing effect of SBC on cost efficiency.

H3b. A firm's digitalization intensity lessens the exacerbating effect of SBC on idiosyncratic risk.

We postulate that digitalization breadth undermines the enhancing effect of SBC on cost efficiency while aggravating the exacerbating effect of SBC on idiosyncratic risk. Specifically, previous researchers have argued that a broad scope of information technologies tends to create pooled and separate instead of reciprocal and connected systems (Autry *et al.*, 2010). In this sense, when firms adopt more types of digital technology at the same time, they are likely to confront the increased complexity of analyzing heterogenous information and managing multiple interfaces between information systems (Kessler *et al.*, 2022). For example, Sundarakani *et al.* (2021) have illustrated a case where the simultaneous implementation of big data analytics and blockchain engenders more risks and fails to create value. In addition, as technological breadth increases, a firm’s finite technology resources (e.g., information technology personnel and physical hardware capacity) are stretched thin because employees have to manage multiple digital applications within and across organizational boundaries (Autry *et al.*, 2010). As such, in the situation of higher digitalization breadth, the firm might encounter more difficulty in adopting each incrementally added digital technology to its full extent. Hence, these potential downsides of a broader scope of digital technologies may harm organizations’ information processing capabilities, which can undermine their capacity to satisfy the information processing requirements and handle the supply chain disruption risks incurred by SBC. In this case, digitalization breadth may weaken the effect of SBC on enhancing cost efficiency and aggravate its effect on increasing idiosyncratic risk.

By contrast, in the situation of lower digitalization breadth, companies implement fewer types of digital technology, which may decrease the difficulty of managing and coordinating multiple technologies and information systems and enable firms to exploit the full potential of each technology. In this case, firms with a lower level of digitalization breadth are in an

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advantageous position to better leverage SBC to elevate cost efficiency and alleviate idiosyncratic risk. Thus, we hypothesize that:

H4a. A firm's digitalization breadth weakens the enhancing effect of SBC on cost efficiency.

H4b. A firm's digitalization breadth worsens the exacerbating effect of SBC on idiosyncratic risk.

Figure 1 portrays the conceptual model of this study.

[Insert Figure 1 about here]

3. Method

3.1 Data

To test our hypotheses, we collect data on Chinese manufacturing firms that are publicly listed on the Shanghai and Shenzhen Stock Exchanges. China is an appropriate context for our research as it is a global manufacturing hub and a vast number of Chinese manufacturing firms have devoted efforts to digitalization.

We obtain supply base data and financial data from China Security Market and Accounting Research (CSMAR). We also collect supplementary supply base data from the Chinese Research Data Services Platform (CNRDS). These two databases have been broadly utilized in OSCM studies (Ge *et al.*, 2022; Shou *et al.*, 2021). In addition, we construct a database of firm-level digitalization by using a computer-aided textual analysis (CATA)

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approach to code the annual reports of Chinese manufacturing firms.

We select the period from 2012 to 2020 since the engagement in digitalization of most Chinese manufacturing firms started in 2012. After dropping firms with missing data, the final sample includes 8,710 firm-year observations across nine years, consisting of 1,238 manufacturing firms in China. Table 2 presents the sample distribution.

[Insert Table 2 about here]

3.2 Measures

Dependent variables. The dependent variables of this study are cost efficiency and idiosyncratic risk. We measure cost efficiency using the ratio of total sales to total operating costs (Shou *et al.*, 2021). Besides, we apply the Fama-French three-factor model to assess the annualized standard deviation of the residuals as a firm's idiosyncratic risk (Ye *et al.*, 2020; Fu, 2009). The following model is used to estimate the idiosyncratic risk for firm *i* in month *m*:

$$R_{i,m} - R_{f,m} = \beta_{0i} + \beta_{1i}(R_{Mm} - R_{fm}) + \beta_{2i} \cdot SMB_m + \beta_{3i} \cdot HML_m + \varepsilon_{im}$$

where $R_{i,m}$ refers to the actual stock return in month m, R_M is the market portfolio return, and R_f is the risk-free return rate. $R_{Mm} - R_{fm}$ refers to the excess return on a broad market portfolio; SMB (small minus big) refers to the difference between the return on a portfolio of small stocks and that on a portfolio of large stocks; and HML (high minus low) refers to the difference between the return on a portfolio of high book-to-market stocks and that on a portfolio of low book-to-market stocks. Then, we estimate the idiosyncratic risk (IR) for firm *i* in year *t* as the annualized standard deviation of the residual (ε_{im}), as shown in the following

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formula:

$$IR_{it} = [\frac{1}{12}\sum_{m=1}^{12}(\varepsilon_{im} - \bar{\varepsilon_{it}})]$$

Independent variable. SBC reflects the distribution of a firm's cost on its suppliers in terms of transaction volume and cost percentage (Hu *et al.*, 2022). A firm with a higher level of SBC purchases raw materials and components from fewer key suppliers. Following Li *et al.* (2022), we use the ratio of the top five suppliers' purchases to total annual purchases to measure a firm's SBC:

$$SBC_{i,t} = \sum_{j=1}^{5}\frac{Sales_{i,j,t}}{Sales_{i,t}}$$

where $Sales_{i,j,t}$ represents firm *i*'s purchases from key supplier *j* in year *t* and $Sales_{i,t}$ represents firm *i*'s total purchases from all suppliers in year *t*.

Moderating variables. The moderating variables of this study are digitalization intensity and breadth. We develop a CATA approach to measure the two variables. CATA is a type of content analysis that measures constructs of interest by analyzing and converting text-based content into frequency-based quantitative data. Following prior studies (Short *et al.*, 2010; McKenny *et al.*, 2018), we perform six steps to measure the variables. For the sake of simplicity, we give a brief description of the approach here and elaborate on the detailed procedures in Appendix A. First, as annual reports are high-quality original documents containing firm information for a given year (Cooper *et al.*, 2022), we obtain a rich collection of 8,710 annual reports from all 1,238 manufacturing firms in our sample to construct the corpus for content analysis. Second, we choose the phrase as the recording unit (Tangpong, 2011), which is appropriate for our approach since a specific digital technology is always termed as a phrase in Chinese. Third, we build a closed dictionary (Hickman *et al.*, 2022) of digital technology phrases to capture our constructs. We screen all the phrases in the dictionary to make sure that they are closely related to OSCM in manufacturing firms. Fourth, ten categories of digital technologies are identified by using a natural language processing (NLP) method to cluster the phrases in the dictionary. Fifth, we develop a longitudinal database by counting all the phrases in the 8,710 annual reports, which is manually cleaned to exclude digital technologies for products or services. This database is then used to measure the moderators. Finally, we conduct a hypothesis validity test to check the validity of the measurements of moderators.

We operationalize digitalization intensity and breadth using the phrase counts from our CATA approach. Prior studies have tried to measure the deployment of digital technologies by constructing a dictionary of digital technology terms and obtaining counts of these terms in firms' financial reports as a proxy for the extent of digital activities (Chen and Srinivasan, 2022). Sousa-Zomer *et al.* (2020) measure firms' digital adoption as the word count of digital technology terms. Inspired by these studies, we measure digitalization intensity (DI) as the ratio of the sum of digital technology phrases to the number of types of digital technology adopted by the firm, which captures the average effort the firm devotes to each type of digital technology. Specifically, the digitalization intensity of firm i in year t is measured using the following formula:

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$$DI_{i,t} = \sum_{k} n_{i,k,t} \Big/ \sum_{k} DT_{i,k,t}$$

where $DT_{i,k,t} = 1$ if the *k*-th digital technology (DT) is mentioned in firm *i*'s annual report of year t at least once, 0 otherwise; and $n_{i,k,t}$ refers to the number of related phrases of the *k*-th DT presented in the annual report of firm i in year t.

The digitalization breadth (DB) of firm i in year t is operationalized using the number of types of digital technology that the firms reported in their annual reports:

$$DB_{i,t} = \sum_{k} DT_{i,k,t}$$

Control variables. We include a number of firm- and industry-level factors that may influence the dependent variables. First, firm size is controlled for and calculated as the natural logarithm of a firm's total sales (Shou *et al.*, 2021). Second, we control for the state ownership of the company with the variable being 1 if the company is a state-owned company, and 0 otherwise (Shou *et al.*, 2021). Third, we control for the working capital ratio, which is measured as the ratio of a firm's current assets less its current liabilities to its total assets (Horvath and Lang, 2021). Fourth, we control for the debt-to-equity ratio as it reflects the capital structure. The debt-to-equity ratio is computed as the book value of debt divided by the market value of the equity (Hendricks and Singhal, 2003; Schmidt *et al.*, 2020).

In addition, we control for three industry-level factors: industry size, industry return on assets (ROA), and industry dynamism. We operationalize industry size by log transforming the sum of all the firms' total assets in the same three-digit CSRC industry (Shou *et al.*, 2021). Industry ROA is operationalized as the average of the firms' ROA in the same three-digit CSRC

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industry (Houston *et al.*, 2016). Industry dynamism is measured by regressing industry sales over the preceding five years against time and utilizing the ratio of standard errors of the regression slope coefficients to industry average sales (Shou *et al.*, 2021). Lastly, we include year dummies in the regression models to account for year-specific effects.

3.3 Estimation method

Based on the dataset of 1,238 manufacturing firms between 2012 and 2020, we apply the panel data model estimation approach to test our hypotheses. We conduct the Hausman test to ascertain the selection of fixed-effects or random-effects panel regression models in our study. The Hausman test results indicate that fixed-effects models are more suitable for our sample ($\chi^2(10) = 243.43, p < 0.01$). Hence, we employ fixed-effects panel regression models and use Stata 15.0 to conduct the regression analysis.

Given that there could be a lag between SBC and its effect on cost efficiency and idiosyncratic risk, we use the following equations to test our hypotheses:

$$\begin{aligned} Cost\ efficiency_{i,t+1} \\ &= \beta_0 + \beta_1 SBC_{i,t} + \beta_2 DB_{i,t} + \beta_3 DI_{i,t} + \beta_4 DB_{i,t} \times SBC_{i,t} + \beta_5 DI_{i,t} \times SBC_{i,t} \\ &+ \beta \boldsymbol{X}_{i,t} + \tau_t + \varepsilon_{it} \end{aligned}$$

$$\begin{aligned} Idiosyncratic\ risk_{i,t+1} \\ &= \beta_0 + \beta_1 SBC_{i,t} + \beta_2 DB_{i,t} + \beta_3 DI_{i,t} + \beta_4 DB_{i,t} \times SBC_{i,t} + \beta_5 DI_{i,t} \times SBC_{i,t} \\ &+ \beta \boldsymbol{X}_{i,t} + \tau_t + \varepsilon_{it} \end{aligned}$$

where i and t are firm and year indices, $\boldsymbol{X}$ is a vector of control variables, as elaborated in Section 3.2, τ_t are year dummy variables, and ε_{it} is the residual term. We mean-center the moderators before generating their interaction terms to avoid multicollinearity (Hu *et al.*, 2022).

4. Results

4.1 Main results

Table 3 reports the descriptive statistics and correlation matrix of the variables. The variance inflation factor (VIF) values of the regression models range from 1.02 to 3.93, suggesting that multicollinearity is not a concern.

[Insert Table 3 about here]

Table 4 presents the results of the fixed-effects regression models. Models 1 and 2 include all the control variables. Models 3 and 4 further include the independent variable, i.e., SBC. Models 5 and 6 add the interaction terms between SBC and digitalization intensity/breadth.

[Insert Table 4 about here]

The coefficient of SBC is significantly positive ($p < 0.05$) across Models 3 to 6, showing that SBC is positively related to the firm's cost efficiency and idiosyncratic risk. Thus, H1 and H2 are supported with strong evidence.

As for the moderating effects of digitalization intensity, the interaction term between SBC and digitalization intensity in Model 5 is not significant ($\beta = -0.0003$, $p = 0.99$) while it is significantly negative in Model 6 ($\beta = -0.004$, $p = 0.04$). This indicates that digitalization

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intensity attenuates the positive association between SBC and idiosyncratic risk. Thus, H3b is supported while H3a is not. For greater clarity, we plot the relationship between SBC and idiosyncratic risk at the low (mean – S.D.) and high (mean + S.D.) values of digitalization intensity. Figure 2 reveals that the slope is no longer positive when digitalization intensity is high.

Regarding the moderating effects of digitalization breadth, the interaction term between SBC and digitalization breadth is significantly negative in Model 5 (β = -0.021, p = 0.04), suggesting that the positive relationship between SBC and cost efficiency becomes weaker when the firm adopts more types of digital technology. To further delineate the interaction impact, we conduct a simple slope analysis. Figure 3 shows that cost efficiency is positively associated with SBC when digitalization breadth is low, while the association becomes weak when digitalization breadth is high. Thus, H4a is supported. Besides, in Model 6, the coefficient of the interaction term between SBC and digitalization breadth is significantly positive (β = 0.012, p = 0.01), indicating that the positive association between SBC and idiosyncratic risk becomes stronger when the firm adopts more types of digital technology. Thus, H4b is supported. Figure 4 demonstrates that the positive association between SBC and idiosyncratic risk becomes greater for firms with higher digitalization breadth.

[Insert Figures 2-4 about here]

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4.2 Robustness checks

We conduct a series of tests to check the robustness of our findings. First, we utilize alternative measures for our main variables. In the main model, the independent variable (i.e., SBC) is measured by the ratio of the top five suppliers' purchases to total annual purchases, which might have systematic bias across industries. Thus, we standardize this ratio according to the industry mean and S.D. (three-digit CSRC code) in the same year to control for potential systematic industry differences. The results in Table B1 are consistent with those in Table 4. In addition, we use the ratio of total operating profits to total operating costs as an alternative measure of the dependent variable (i.e., cost efficiency). Table B2 shows the results, which are in line with those in Table 4.

Second, while the digital technologies in our analysis are closely related to OSCM practices, our results might be sensitive to the classification of digital technologies, which is directly tied to the measurements of the moderating variables. Thus, we conduct a sensitivity analysis to re-run the regression models. We employ alternative measures of digitalization intensity and breadth by focusing on five popular types of digital technology (i.e., artificial intelligence, big data analytics, blockchain, cloud computing, and Internet of Things), which are widely mentioned by researchers and practitioners. The results in Table B3 are consistent with those in Table 4, which displays that our findings are insensitive to the classification.

Third, we implement several remedies to mitigate the potential endogeneity issue and enhance the robustness of our findings. Specifically, we estimate the models by using a lagged independent variable (i.e., SBC), which alleviates the threat of endogeneity. Moreover, to control for the potential endogeneity problem caused by omitted variables (Hill *et al.*, 2021), we include a broad list of control variables that may affect firms' cost efficiency and idiosyncratic risk. The employment of fixed-effects models also helps eliminate time-invariant variables that might be endogenous to the dependent variables. In addition, we apply the Heckman two-stage model to correct the potential sample selection bias (Hill *et al.*, 2021), which can be a major source of endogeneity. To calculate SBC, we only include firms which disclosed the proportion of transactions with their top five suppliers in their annual reports. Yet, this disclosure is voluntary and there may be multiple factors influencing firms' disclosure decisions. Thus, our sample may suffer from selection bias. To address this issue, we use the Heckman two-stage model to calculate inverse Mills ratio (IMR). In the first stage, a total of 18,990 firm-year observations were involved in a Probit regression model. Then, the IMR is computed and included as an additional control variable in the second stage. The results of the second stage are reported in Table B4, which remain consistent with those in Table 4.

5. Discussion and conclusion

5.1 Theoretical contributions

This study makes multiple theoretical contributions. First, this study enriches and extends the paradox literature by identifying SBC as a performing paradox in OSCM and unveiling its paradoxical effects on firms' cost efficiency and idiosyncratic risk. While extant literature has alluded to the contradictory demands of firms when managing the level of SBC (i.e., improving cost efficiency and lowering idiosyncratic risk simultaneously) (e.g., Ak and Patatoukas, 2016; Lanier *et al.*, 2010; Lonsdale, 2001; Vachon and Klassen, 2006), rare efforts have been devoted to addressing its persistent contradictions from the perspective of paradox theory, which largely constrains the identification and resolutions for the performing paradox of SBC. Prior OSCM studies have primarily employed paradox theory to explicate the paradoxical tensions in lean management (e.g., Erthal *et al.*, 2021), servitization (e.g., Brax *et al.*, 2021), sustainable supply chain management (e.g., Xiao *et al.*, 2019) and radical product and process innovation (e.g., Hillmer *et al.*, 2023). Nevertheless, there is a paucity of research that articulates the performing paradox of SBC from the paradox theory perspective. In this sense, our study contributes to the theoretical advancement of paradox theory in the OSCM field by invoking this theory to identify and elucidate the contradictory, interdependent, and persistent tensions of SBC (Berti and Cunha, 2022; Smith and Lewis, 2011). More importantly, our study provides paradox-reconciling strategies for firms based on their capability conditions, thus echoing previous research on managing paradoxes which proposes that firm-specific capabilities can help harmonize the competing requirements of paradoxes (Berti and Cunha, 2022; Ivory and Brooks, 2018; Pagell *et al.*, 2015). By manifesting viable response strategies (i.e., digitalization) to accommodate the contradictory demands and make potential trade-offs between higher cost efficiency and lower idiosyncratic risk, this study essentially advances the paradox literature and broadens the horizon of existing research on SBC.

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Second, this study sheds light on the digitalization literature by distinguishing two important dimensions of digitalization (i.e., intensity and breadth) and elaborating on their distinct roles in reconciling the performing paradox of SBC. Although digitalization has attracted close attention from researchers lately, the majority of studies have examined digitalization as a unidimensional concept (Cenamor *et al.*, 2017; Shi *et al.*, 2022; Wei and Sun, 2021). Yet, considering that firms adopt different investment strategies (Ravichandran and Liu, 2011; Dewan *et al.*, 1998), it is necessary to look into different dimensions of digitalization. To this end, this study explicates two unique attributes of digitalization (i.e., intensity and breadth). To our best knowledge, this is the first empirical research that untangles the distinct roles played by digitalization intensity and breadth in OSCM practices, which advances the digitalization literature and opens a promising avenue to test the effects of digitalization intensity and breadth in other OSCM practices.

Third, this study expands the literature on digitalization and OSCM by disentangling how digitalization intensity and breadth play different roles in addressing the paradoxical effects of SBC. This study sheds light on the implementation strategies for digitalization (i.e., intensity and breadth), especially when firms face limited resources. Overall, our study takes an initial step in elucidating different digitalization strategies and unraveling their differential roles in managing the paradox of SBC. Moreover, this study reveals the empowerment role of digitalization intensity and the hindering role of digitalization breadth in conventional practices of supply base management (Bergstrom *et al.*, 2020; Shih, 2020). Specifically, digitalization

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intensity attenuates the augmenting effect of SBC on idiosyncratic risk. This result echoes the notion of previous studies that increasing the investment intensity in specific digital technologies is beneficial for firms to enhance information processing capabilities to better process the intensive information shared by their suppliers, and thus, lower the disruption risks (Xie *et al.*, 2022). Interestingly, we discover that the contingent impact of digitalization intensity on the link between SBC and cost efficiency is not significant. A plausible reason is that different digital technologies have different stages of maturity. For those emerging digital technologies that are still in the immature stage, their implementation requires extra inputs and efforts, which might counteract the potential cost efficiency generated by a highly concentrated supply base or even result in cost inefficiency (Seyedghorban *et al.*, 2020; Nasiri *et al.*, 2022). Nevertheless, digitalization breadth attenuates the efficacy of SBC on cost efficiency while aggravating its exacerbating effect on idiosyncratic risk. Our finding uncovers the downside of a broader scope of digitalization portfolio in supply base management and provides suggestions on how firms could tailor their digitalization strategies to leverage their SBC and tackle its paradoxical effects on cost efficiency and idiosyncratic risk.

5.2 Managerial implications

This research provides insightful implications for practitioners. First, managers should pay close attention to both the benefits and downsides of SBC. Our findings demonstrate that SBC facilitates firms' cost efficiency, whereas it also contributes to greater idiosyncratic risk. This implies the paradoxical effects of SBC on firm performance in terms of the improvement in

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cost efficiency and the increase in idiosyncratic risk. Thus, managers need to consider this trade-off carefully when deciding and managing the level of SBC, with special awareness of the indulgent effect of SBC on idiosyncratic risk, particularly in today's highly uncertain and volatile environments.

Second and more importantly, managers should be aware that different digitalization strategies play various roles in reconciling the paradox of SBC. Digitalization intensity can alleviate the exacerbating effect of SBC on idiosyncratic risk. As such, it is highly recommended that managers should consider increasing investment in each digital technology that the firm implements, which is effective in easing the increased idiosyncratic risk induced by highly concentrated supply bases. However, when firms adopt a broader scope of digital technologies, the exacerbating effect of SBC on idiosyncratic risk is aggravated. Given this, managers should invest prudently in broadening the breadth of digitalization to avoid the potential counteractive effects. Nevertheless, Chinese manufacturing firms are surprisingly doing almost the opposite of what we have found. Specifically, as illustrated in Figures A2 and A3, firms across industries show a steady trend in expanding their scope of digital technologies but have inadequate and inconsistent investments in digitalization intensity except for the electronic manufacturing industry[1]. In this regard, our findings provide concrete references for managers to formulate digitalization strategies. In addition, when making digitalization strategies, managers may need to deepen their understanding of the maturity and the functions

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[1] Digitalization intensity for most industries experienced a decrease in 2020 except for the industry of textile, clothing, and fur manufacturing. It might be due to the influence of the COVID-19 pandemic.

of each digital technology to avoid complicating their digital technology portfolios. Besides, digitalization is a long-term continual process and often requires substantial investment and supportive systems, which raises barriers and challenges for many firms. Hence, managers may need to plan strategically for digitalization by implementing inter-compatible and mutual-reinforcing digital technologies and providing adequate financial and talent support.

5.3 Limitations and future research directions

Our study has some limitations which also indicate directions for future research. First, we develop a CATA approach for text coding of Chinese manufacturing firms' annual reports, and thus the typical categories of adopted digital technologies may not be identical in other countries (e.g., Lorenz *et al.*, 2020). Nevertheless, our approach is applicable to other contexts and scholars can utilize it to measure digitalization intensity and breadth in other countries, and provide further insights into their roles in altering the paradox of SBC. Second, in the text coding process, we carefully check the co-occurrence of digital technology-related phrases and "product" or "service" in the same sentence to exclude the descriptions of digital products or services from the corpus. Nonetheless, it is possible that such descriptions may go beyond the scope of our inspection. Thus, future research can extend the scope of co-occurrence analysis (e.g., at the paragraph level) to further enhance the precision of coding. Third, our research focuses on firms in manufacturing industries, which may restrict the generalizability of our findings. A promising avenue for future research is to unpack how digitalization reconciles the paradox of SBC in the context of other industries (e.g., service and retail sectors). It is worthwhile to conduct a cross-industry comparison analysis to investigate whether the effect of digitalization varies across industries. Fourth, we evaluate two unique dimensions of digitalization (i.e., intensity and breadth) and offer novel insights into their distinct roles in the paradoxical effects of SBC on cost efficiency and idiosyncratic risk. Future research can advance the digitalization literature by investigating whether these two dimensions of digitalization alter the paradoxical effects of other OSCM practices, such as ISO 14001 certification (Ye *et al.*, 2020) and servitization (Brax *et al.*, 2021). Finally, the efficacy of digitalization intensity and breadth in managing the paradox of SBC may hinge on internal and external factors. Thus, future research is encouraged to unearth firm-specific resources and capabilities (e.g., financial slack, relational capital, and innovation capability) and external environments (e.g., industry competition and industry dynamism) that may influence the differential roles of digitalization intensity and breadth in modifying the paradoxical effects of SBC on cost efficiency and idiosyncratic risk.

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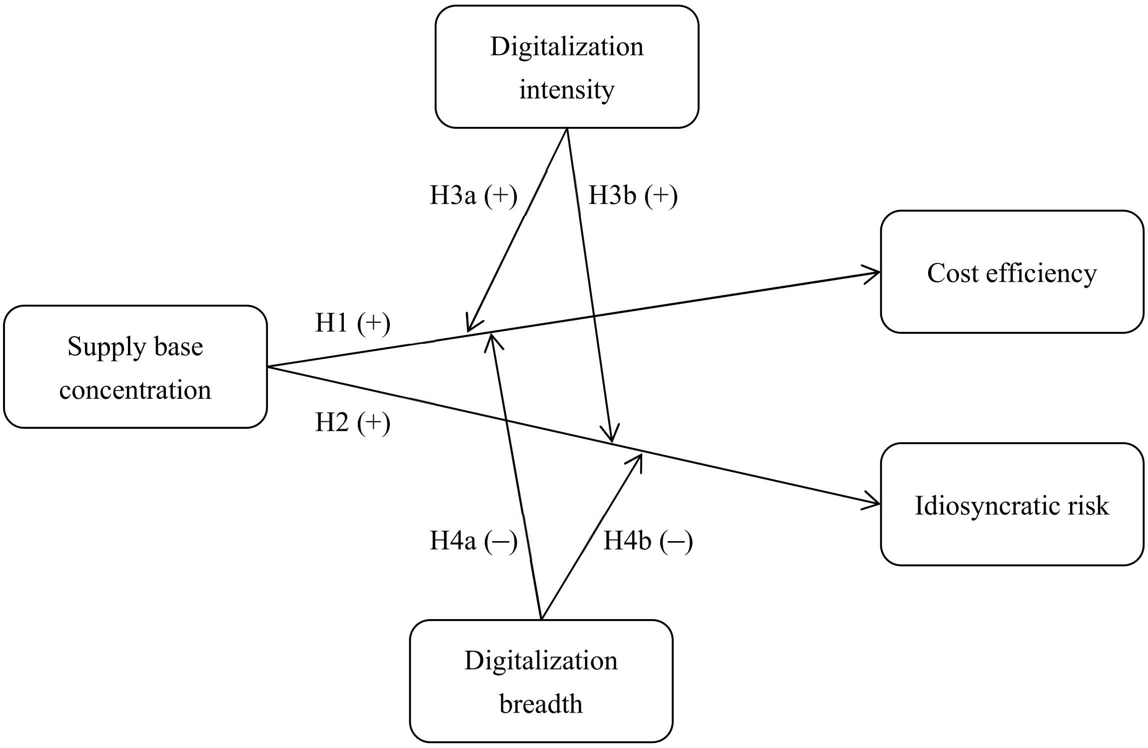

Figure 1. Conceptual model

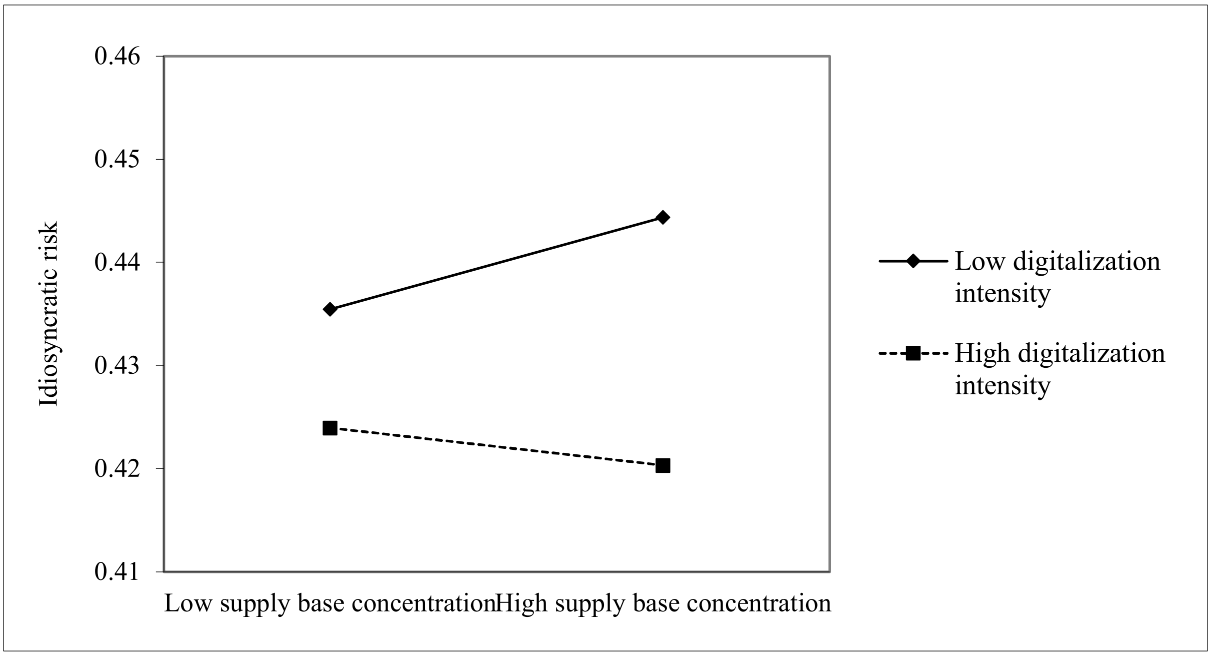

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Figure 2. Moderating effect of digitalization intensity on the link between SBC and idiosyncratic risk

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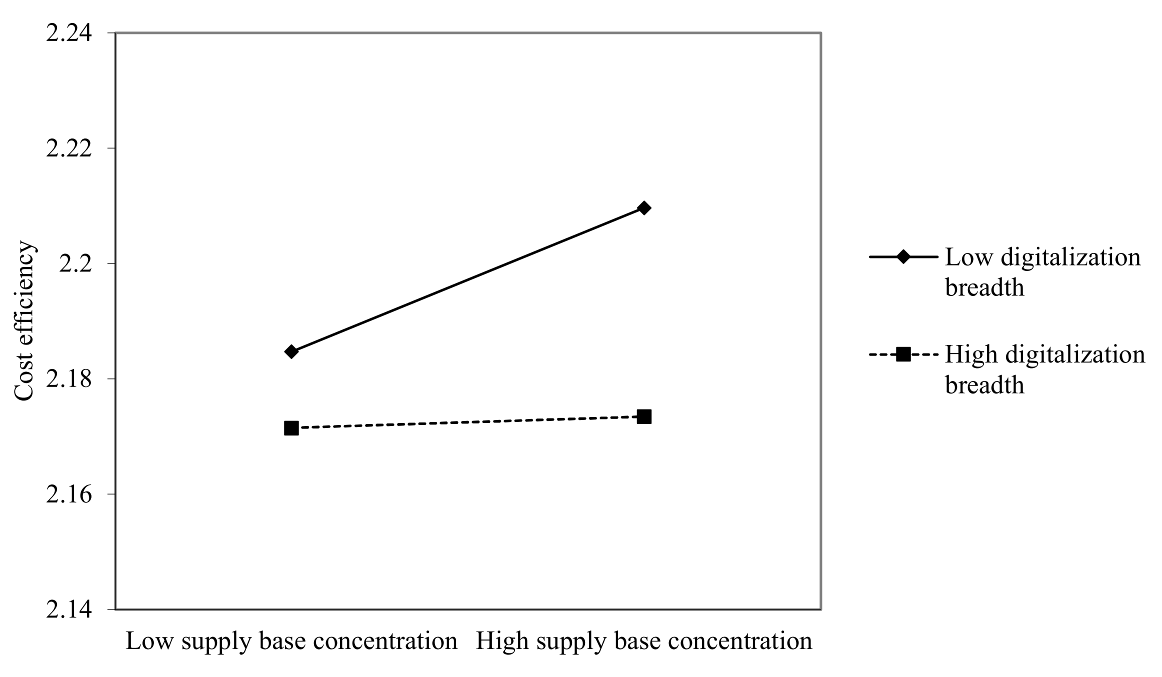

Figure 3. Moderating effect of digitalization breadth on the link between SBC and cost efficiency

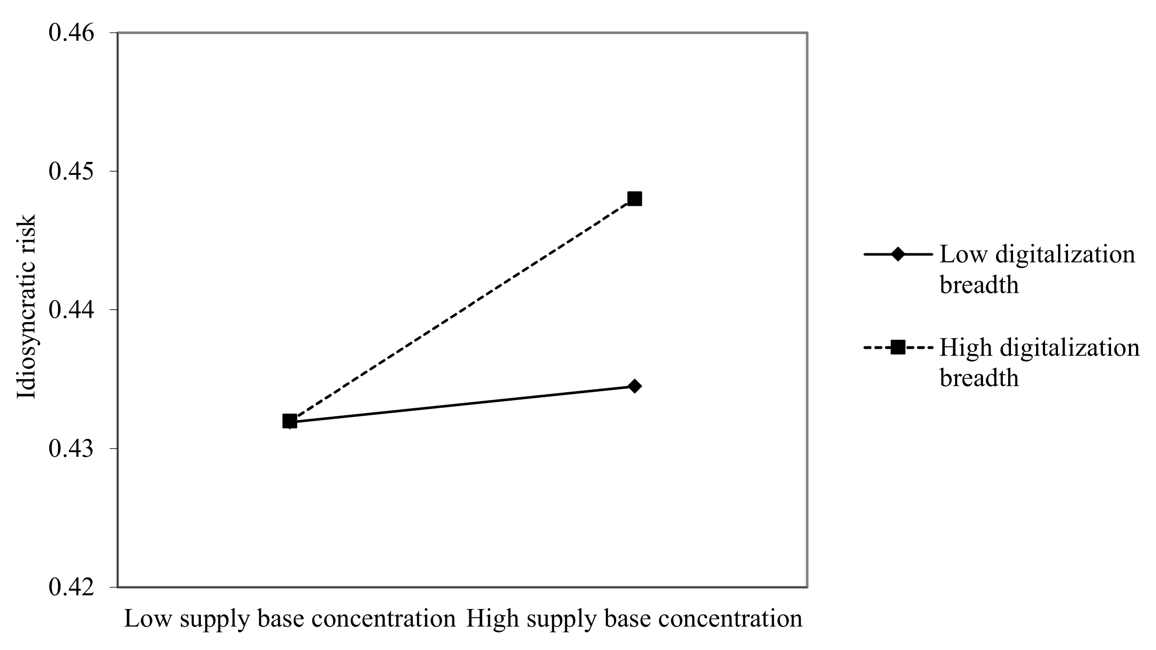

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Figure 4. Moderating effect of digitalization breadth on the link between SBC and idiosyncratic risk

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Table 1. Typical digital technologies

Digital technology	Definition	Key characteristics	Examples
Artificial intelligence	A technology that enables computers to imitate the activities of the human brain to solve complex problems (Leoni *et al.*, 2022)	• Intelligent systems • Mimic human behavioural patterns	• Autonomous vehicles by Tesla • ChatGPT by OpenAI
Augmented reality	A technology that interconnects the physical and digital worlds (Choi *et al.*, 2022)	• Enhanced version of the real physical world • Users can interact with the physical-cyber environment in real time	• IKEA Place • Google AR Glasses
Big data analytics	A technology that is utilized to analyse a massive amount of structured and unstructured data (Choi *et al.*, 2018)	• Apply various techniques (e.g., statistics and data mining) to analyze data characterised by 5 V's • Volume (large amounts of generated data) • Variety (different data sources) • Veracity (ensure the quality of the data) • Velocity (high speed of data generation) • Value (gain insights from data extraction)	• Dremel by Google • Hadoop by Apache • Open Data Platform and Services by Alibaba
Blockchain	A technology that involves the use of cryptographic distributed ledger systems which synchronize data in real time and cannot be changed (Cole *et al.*, 2019)	• Distributed and synchronised across networks • Use of smart contracts • Based on peer-to-peer network • Immutability of data	• IBM Blockchain • JDChain by JD.com
Cloud computing	A technology that enables on-demand use of computer system resources, especially data storage (cloud storage) and computing power (Feng *et al.*, 2022)	• On-demand services and pay per use • Broad network access • Resource pooling • Provide and release computing resources elastically	• Amazon Web Services • Alibaba Cloud • Tencent Cloud
Digital twin	A technology that enables the real-time digital	• Real-time virtual representation	• Azure Digital Twins by

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	counterpart of a physical object (Tozanli and Saénz, 2022)	• Interact with devices and humans	Microsoft • DTwin by Alibaba
Fintech	A technology that uses the Internet to simplify the financial system and improve the efficiency of supply chain financing (Rogers *et al.*, 2016)	• Streamline financial systems • Faciliate financial flows in the supply chain	• Fintech Platform by Chime • Fintech Platform by Ant Financial
Identification technology	A technology that captures the object data and identifies the object (Smith, 2005; Papert *et al.*, 2016)	• Automated identification of objects • Accurate and detailed information about objects	• Biometric identification by iFLYTEK • Fingerprint identification by Apple
Internet of Things	A technology that connects physical objects to other devices and systems and exchanges data through communication networks (Feng *et al.*, 2022)	• Collect real-time data about physical objects • Transmit the data swiftly	• Lab of Things by Microsoft • Sensors by iFLYTEK
Robotics	A technology that enables an intelligent machine to develop the ability to take intelligent actions and make choices (Choi *et al.*, 2022)	• Smart behaviours • Automation • Flexible operations	• Warehouse Robotics by Amazon • Drones by JD.com

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Table 2. Sample statistics

Panel A: The distribution of sample firms by industry

Three-digit CSRC code	Industry	Frequency	Percentage (%)
C13	Farm products processing	217	2.49
C14	Food manufacturing	153	1.76
C15	Wine, drinks and refined tea manufacturing	104	1.19
C17	Textile industry	284	3.26
C18	Textiles, garments, and apparel industry	125	1.44
C19	Leather, fur, feathers and their products and footwear	31	0.36
C20	Wood processing, and wood, bamboo, rattan, palm and grass products	40	0.46
C21	Furniture manufacturing	36	0.41
C22	Paper and paper products industry	143	1.64
C23	Printing and recording media reproduction	49	0.56
C24	Culture and education, arts and crafts, sports and entertainment products manufacturing	97	1.11
C25	Petroleum processing, coking and nuclear fuel processing	77	0.88
C26	Raw chemical materials and chemical products	988	11.34
C27	Pharmaceutical manufacturing	713	8.19
C28	Chemical fiber manufacturing	108	1.24
C29	Rubber and plastic product industry	321	3.69
C30	Non-metallic mineral products	366	4.20
C31	Smelting and pressing of ferrous metals	119	1.37
C32	Smelting and pressing of nonferrous metals	280	3.21
C33	Metal products	341	3.92
C34	General equipment manufacturing	521	5.98
C35	Special equipment manufacturing	725	8.32
C36	Automobile manufacturing	292	3.35
C37	Railway, shipbuilding, aerospace, and other transportation equipment manufacturing	161	1.85
C38	Electric machines and apparatuses manufacturing	742	8.52
C39	Computer, communication, and other electronical device manufacturing	1,311	15.05
C40	Instrument and meter manufacturing	153	1.76
C41	Other manufacturing	212	2.43
C42	Comprehensive utilization of waste resources	1	0.01
Total		8,710	100

Panel B: The distribution of sample firms by year

	Frequency	Percentage (%)
2012	807	9.27
2013	831	9.54
2014	1,009	11.58
2015	1,070	12.28
2016	1,109	12.73
2017	1,168	13.41
2018	1,182	13.57
2019	1,190	13.66
2020	344	3.95
Total	8,710	100

Panel C: The distribution of sample by revenue (RMB Million)

	Frequency	Percentage (%)
<10	5	0.06
10–100	74	0.85
100–1,000	2,742	31.48
1,000–10,000	5,011	57.53
>10,000	878	10.08
Total	8,710	100

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Table 3. Descriptive statistics and correlation matrix

Variable	1	2	3	4	5	6	7	8	9	10	11	12
1. Cost efficiency	1.000											
2. Idiosyncratic risk	0.002	1.000										
3. SBC	-0.045***	0.021*	1.000									
4. Digitalization intensity	-0.015	-0.024**	-0.057***	1.000								
5. Digitalization breadth	-0.023**	-0.026**	-0.113***	0.568***	1.000							
6. Firm size	0.087***	-0.086***	-0.215***	0.056***	0.133***	1.000						
7. Working capital ratio	0.231***	-0.002	-0.028**	0.033***	0.053***	-0.156***	1.000					
8. Debt-to-equity ratio	-0.064***	-0.010	-0.004	-0.007	0.003	0.022**	-0.132***	1.000				
9. State ownership	-0.021*	-0.057***	-0.034***	-0.046***	-0.027**	0.168***	-0.067***	0.019*	1.000			
10. Industry size	-0.015	0.030***	-0.050***	0.082***	0.201***	0.116***	-0.011	-0.006	0.034***	1.000		
11. Industry ROA	0.110***	-0.030***	-0.024**	-0.063***	-0.110***	-0.058***	0.046***	-0.007	-0.026**	-0.134***	1.000	
12. Industry dynamism	-0.005	-0.027**	0.030***	-0.076***	-0.158***	-0.071***	0.015	0.044***	0.026**	-0.339***	0.092***	1.000
Mean	1.065	0.079	0.348	1.517	0.912	9.272	0.226	1.306	0.081	11.830	0.032	0.029
S.D.	0.199	0.077	0.192	3.955	1.441	0.567	0.357	8.253	0.273	0.480	0.022	0.019

Notes: N=8,710. *** p<0.01, ** p<0.05, * p<0.1. All p-values are two-tailed.

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Table 4. Results of fixed-effects regression analysis

Variable	Model 1 Cost efficiency	Model 2 Idiosyncratic risk	Model 3 Cost efficiency	Model 4 Idiosyncratic risk	Model 5 Cost efficiency	Model 6 Idiosyncratic risk
Firm size	0.018**	-0.026***	0.022***	-0.025***	0.022***	-0.023***
	(2.162)	(-6.577)	(2.597)	(-6.277)	-2.654	(-5.719)
Working capital ratio	0.064***	-0.001	0.065***	-0.001	0.065***	-0.001
	(11.006)	(-0.469)	(11.112)	(-0.414)	-11.18	(-0.461)
Debt-to-equity ratio	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	(-1.391)	(-0.425)	(-1.381)	(-0.419)	(-1.354)	(-0.405)
State ownership	0.007	-0.007	0.007	-0.007	0.007	-0.007
	(0.746)	(-1.614)	(0.742)	(-1.617)	-0.745	(-1.583)
Industry size	-0.113***	-0.013	-0.112***	-0.013	-0.110***	-0.009
	(-4.027)	(-0.953)	(-4.011)	(-0.943)	(-3.918)	(-0.650)
Industry ROA	0.302***	-0.045	0.307***	-0.044	0.311***	-0.052
	(3.139)	(-0.984)	(3.188)	(-0.959)	-3.23	(-1.122)
Industry dynamism	0.313**	-0.06	0.320***	-0.058	0.320***	-0.055
	(2.565)	(-1.023)	(2.625)	(-0.992)	-2.622	(-0.943)
Year dummies	Included	Included	Included	Included	Included	Included
SBC			0.055***	0.014*	0.054***	0.013*
			(3.369)	(1.793)	(3.326)	(1.693)
Digitalization intensity (DI)					-0.000	-0.001**
					(-0.167)	(-2.394)
Digitalization breadth (DB)					-0.001	-0.002*
					(-0.639)	(-1.900)
SBC × DI					-0.000	-0.004**
					(-0.008)	(-2.089)
SBC × DB					-0.021**	0.012**
					(-2.062)	(2.522)
Constant	2.267***	0.506***	2.205***	0.491***	2.174***	0.430***
	(6.627)	(3.096)	(6.443)	(2.997)	(6.310)	(2.611)
R-squared	0.043	0.071	0.044	0.071	0.045	0.074

Notes: N=8,710; *** p<0.01, ** p<0.05, * p<0.1 (two-tailed test); t-statistics in parentheses.

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Appendix A: The CATA approach

Given the rich collection of annual reports from all the sampled manufacturing firms over the years, we developed a CATA approach for text coding, which is detailed as follows.

Step 1: We obtained 8,710 annual reports from all the 1,238 Chinese manufacturing firms in our sample to construct the corpus of documents. The annual reports were collected from CNINFO (cninfo.com.cn), which is designated by the China Securities Regulatory Commission (CSRC) to provide information on public firms in China.

Step 2: We determined the recording unit according to the characteristics of the corpus and our approach. Considering the large size of our corpus, the CATA approach is appropriate for analyzing the corpus and we chose the digital technology-related phrase as the recording unit. In Chinese reports, a specific technology is expressed by a phrase with multiple Chinese characters.

Step 3: We built a closed dictionary of digital technology-related phrases to capture the constructs of interest. The dictionary was constructed in two sub-steps.

i. Building the initial dictionary

We collected digital technology-related phrases from two sources. First, we referred to the phrases used in prior studies on the digitalization of Chinese firms (Zhu *et al.*, 2022). Second, to have broad coverage of emerging digital technologies, we also referred to the white papers published by the China Academy of Information and Communication Technology (CAICT), an institute affiliated with the Chinese government and focusing on the investigation of digital technologies in China. We set a criterion that only OSCM-related technologies should be included in the dictionary. Technologies such as “smart home” were excluded. Two coders worked independently to screen the phrases from the two sources and merged their lists through discussion to form the initial dictionary with 40 phrases.

ii. Ensuring the saturation of the dictionary

To ensure the saturation of the dictionary, we adopted a multi-coder approach. In accordance with previous research (Weber, 2005; Berger *et al.*, 2020), we conducted stratified sampling by industry and year with a sampling probability of 2%, and randomly selected 175 annual reports. Then two coders worked independently and manually checked the 175 selected annual reports. If the two coders identified an eligible phrase (i.e., digital technology for OSCM) that is absent in the dictionary, it would be added to the dictionary. One coder identified six new phases (i.e., intelligent fire protection, intelligent camera, intelligent language earphone, intelligent cloud speaker, intelligent driving, and intelligent cockpit) that appeared in three annual reports, resulting an inter-coder reliability rate at 98.3%. The two coders carefully discussed the three reports and agreed that the six phases were all related to digital products/services. Thus, the six phases were not added into the dictionary.

Step 4: We categorized the content of the closed dictionary using a natural language processing (NLP) method. The 40 phrases in the dictionary were clustered iteratively by estimating the similarity between the corresponding technologies. We employed the Tencent AI Lab Embedding Corpora (https://ai.tencent.com/ailab/nlp/en/embedding.html) to calculate the similarity among technologies. The Corpora was trained by the directional skip-gram (DSG) model, a deep learning word vector generation model (Song *et al.*, 2018), with over 12 million high-quality Chinese words and phrases. It provides 200-dimensional vector representations, covering all digital technology-related phrases in Chinese. We calculated the similarity between two technologies using the cosine distance of the corresponding phrases in the 200-dimension space. A specific technology which has high similarity with a more general technology is regarded as a member of the latter, which can be further clustered into a higher-level technology group. For example, “machine learning” and “deep learning” were clustered with “artificial intelligence”, which is a broader concept. We repeated this process until each technology has a shorter cosine distance with member technologies of the same cluster than that with non-member technologies. Finally, we stopped the process after five iterations and found ten categories of technologies, as reported in Table A1.

Step 5: We built a longitudinal database for our variables by counting the frequency of each phrase in each annual report in each year. Some examples of firms’ adoption of digital technologies from the annual reports are listed here:

- In 2017, XCMG Construction Machinery Co., Ltd. accelerated the process of intelligent manufacturing transformation through the application of plasma cutting machine, intelligent robotics, automatic painting, powder spraying system, online detection system, automatic guided vehicle (AGV), and other efficient logistics systems.
- In 2018, Transfar Zhilian Co., Ltd. carried out innovative development in big data and artificial intelligence and applied these technologies in various areas, such as route planning, cargo arrival time prediction, cargo volume prediction, visual measurement of cargo volume, and risk prediction of driving behaviors.
- In 2019, Midea Group Co., Ltd. adopted a facial recognition platform and an optical character recognition platform, which can optimize the efficiency and accuracy of product quality detection.

A firm may mention a particular digital technology in its annual report if it offers a digital technology-enabled product or service. Since we focus on OSCM in this study, we traversed all annual reports by Python to detect the phrases that appear with “product” or “service” in the same sentence, and identified 1118 such sentences in 302 annual reports. Two coders worked independently and manually checked all these sentences. Both coders verified that all these sentences described the use of digital technologies in products or services, with an inter-coder reliability rate at 100%. Accordingly, we removed these sentences from the corpus and de-counted the frequency of the corresponding phases. The final distribution of digital technologies across industries is illustrated in Figure A1. The trends of digitalization intensity and breadth over the years are depicted in Figures A2 and A3.

Step 6: To check the validity of the measurements of digitalization intensity and breadth, we followed previous research (Tangpong, 2011) and performed a hypothesis validity test. Digitalization is accompanied by the applications of emerging digital technologies, which requires firms to invest substantial resources in research and development (R&D) activities

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(Faruquee *et al.*, 2021). Thus, it is suggested that R&D intensity is positively associated with digitalization intensity and breadth. As such, we conducted the validity test by examining the relationship between digitalization intensity/breadth and R&D intensity. We measured R&D intensity using the ratio of a firm's R&D expenditures to sales (Kim and Zhu, 2018) and the number of employees in R&D divided by the total number of employees of a firm (Grimpe *et al.*, 2019). Table A2 shows the results of the partial correlation analysis, which reveals that digitalization intensity and breadth are significantly correlated with R&D intensity after controlling for year dummies and several firm- and industry-level variables (Kim and Zhu, 2018) that could influence corporate investment (i.e., firm size, working capital ratio, debt equity ratio, state ownership, industry ROA, industry size and industry dynamism). This supports the validity of our measurements of digitalization intensity and breadth.

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Table A1. Ten categories of digital technologies

Category	Digital technologies
Artificial intelligence	Artificial intelligence, brain-inspired computing, cognitive computing, deep learning, human-computer interaction, image understanding, machine learning, natural language processing
Augmented reality	Augmented reality, mixed reality, virtual reality
Big data analytics	Big data, data mining, intelligent data analysis, text mining
Blockchain	Alliance chain, blockchain, digital currency, secure multi-party computing
Cloud computing	Cloud computing, distributed computing, graph computing, stream computing
Digital twin	Data visualization, information physical systems
Fintech	Internet finance, digital finance, fintech, mobile payment, NFC payment, third party payment
Identification technology	Authentication, biometrics, facial recognition, semantic recognition, speech recognition
Internet of Things	Internet of Things, Industrial Internet of Things
Robotics	Intelligent robotics, warehouse robotics

Table A2. Partial correlation analysis results for the hypothesis validity test

	R&D expenditures/sales	1-year-lagged R&D expenditures/sales	R&D employees/total employees	1-year-lagged R&D employees/total employees
Digitalization intensity	0.112***	0.097***	0.280***	0.296***
Digitalization breadth	0.140***	0.118***	0.301***	0.312***

Note: *** *p*<0.01 (two-tailed test).

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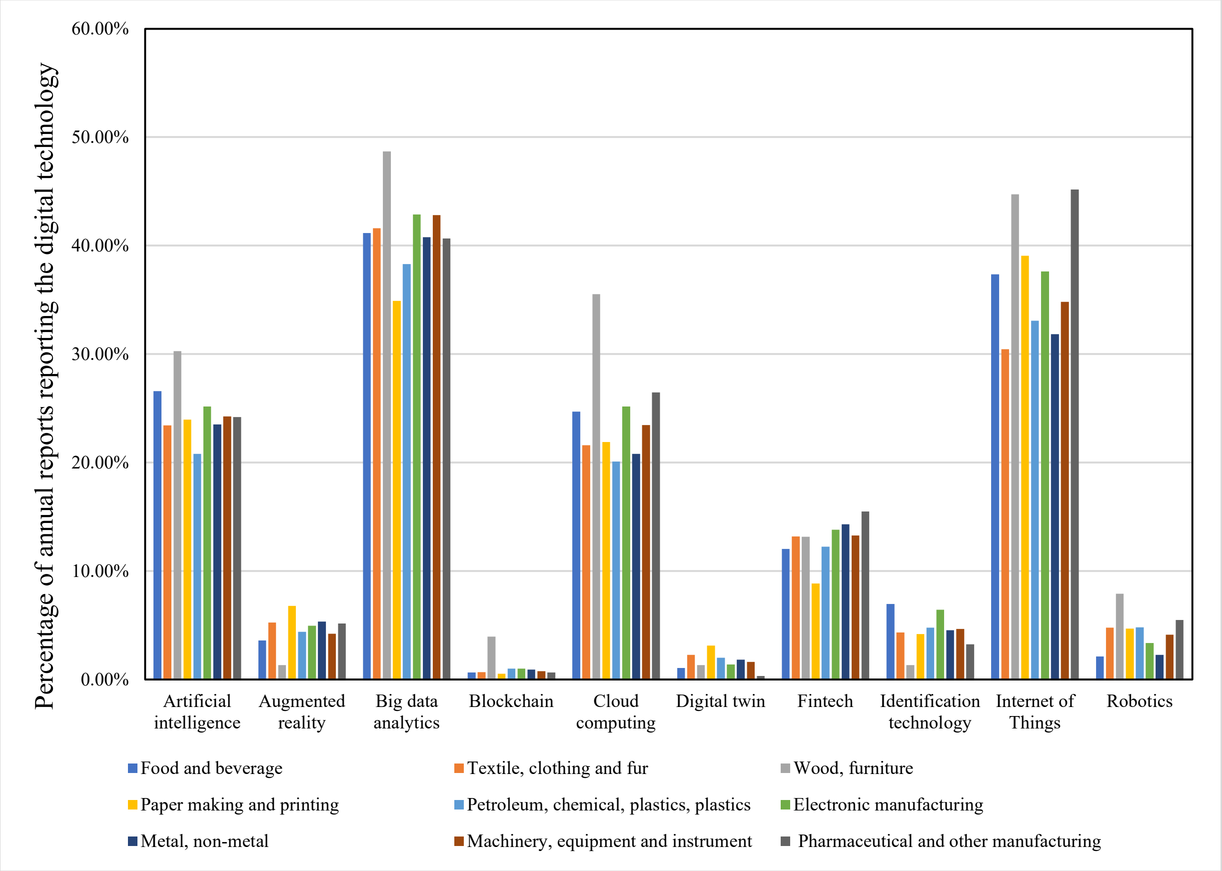

Figure A1. Distribution of digital technologies across industries

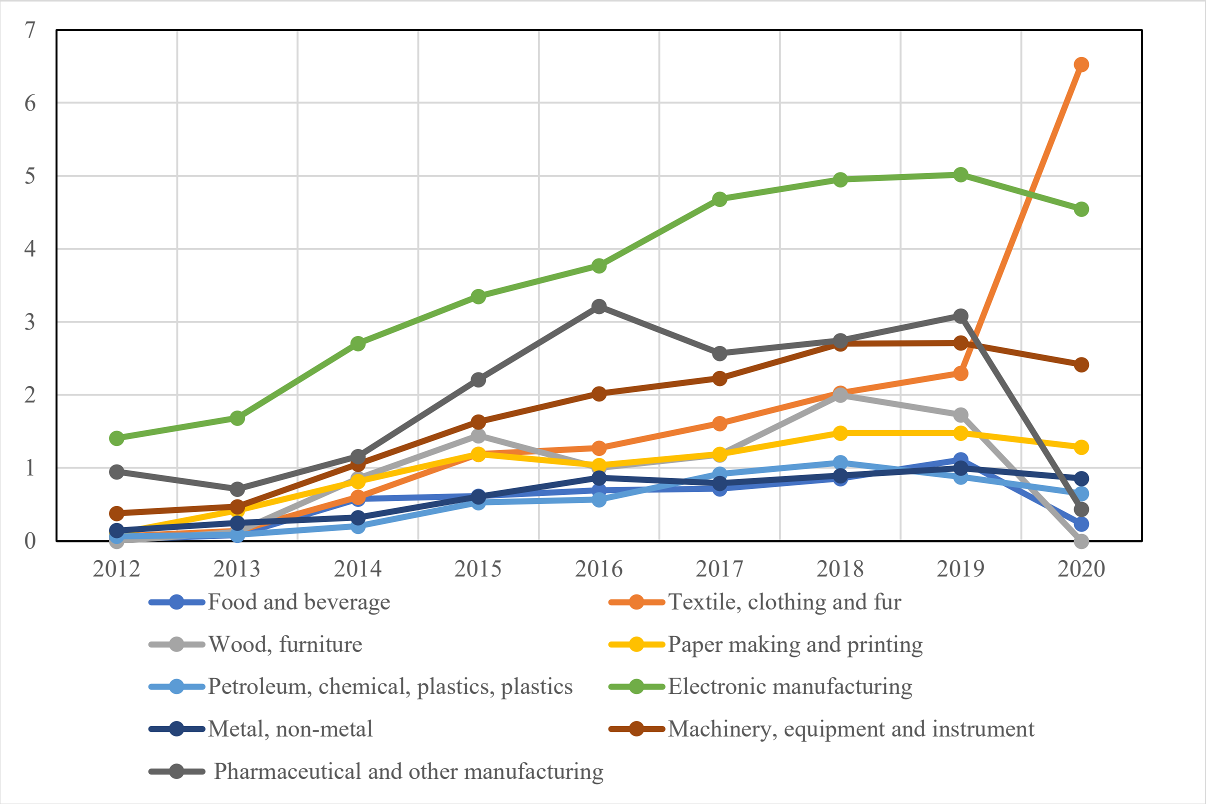

Figure A2. The evolution of digitalization intensity over the years

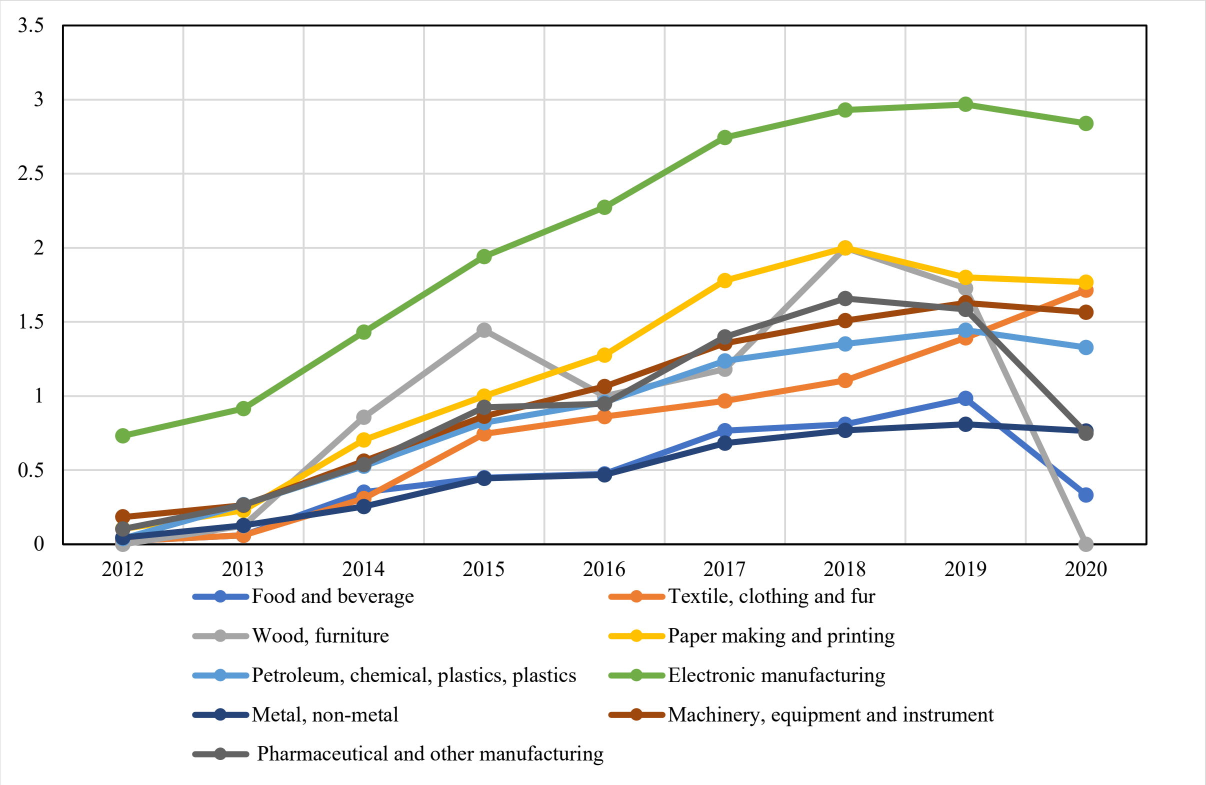

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Figure A3. The evolution of digitalization breadth over the years

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Appendix B: Results of robustness checks

Table B1. Results of an alternative measure of SBC

Variable	Model 1 Cost efficiency	Model 2 Idiosyncratic risk
Firm size	0.022** (2.559)	-0.023*** (-5.674)
Working capital ratio	0.065*** (11.173)	-0.001 (-0.442)
Debt-to-equity ratio	-0.000 (-1.332)	-0.000 (-0.406)
State ownership	0.007 (0.754)	-0.007 (-1.595)
Industry size	-0.110*** (-3.889)	-0.009 (-0.665)
Industry ROA	0.306*** (3.179)	-0.053 (-1.143)
Industry dynamism	0.307** (2.510)	-0.054 (-0.919)
Year dummies	Included	Included
Standardized SBC	0.010*** (3.270)	0.003** (2.367)
Digitalization intensity (DI)	-0.000 (-0.173)	-0.001** (-2.236)
Digitalization breadth (DB)	-0.001 (-0.529)	-0.002** (-2.075)
Standardized SBC × DI	-0.000 (-0.070)	-0.001** (-1.976)
Standardized SBC × DB	-0.004** (-2.399)	0.002** (2.504)
Constant	2.191*** (6.365)	0.435*** (2.642)
R-squared	0.045	0.074

Notes: N=8,710; *** p<0.01, ** p<0.05 (two-tailed test). t-statistics in parentheses.

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Table B2. Results of an alternative measure of cost efficiency

Variable	Model 1 *Profit-cost ratio*	Model 2 *Profit-cost ratio*
Firm size	0.021** (2.551)	0.022*** (2.620)
Working capital ratio	0.065*** (11.094)	0.065*** (11.165)
Debt-to-equity ratio	-0.000 (-1.385)	-0.000 (-1.355)
State ownership	0.006 (0.709)	0.006 (0.713)
Industry size	-0.112*** (-4.007)	-0.110*** (-3.905)
Industry ROA	0.309*** (3.214)	0.313*** (3.253)
Industry dynamism	0.321*** (2.631)	0.321*** (2.628)
Year dummies	Included	Included
SBC	0.054*** (3.335)	0.054*** (3.289)
Digitalization intensity (DI)		-0.000 (-0.147)
Digitalization breadth (DB)		-0.002 (-0.745)
SBC × DI		0.000 (0.010)
SBC × DB		-0.021** (-2.120)
Constant	1.207*** (3.528)	1.172*** (3.403)
R-squared	0.044	0.045

Notes: *N*=8,710; *** *p*<0.01, ** *p*<0.05 (two-tailed test). *t*-statistics in parentheses.

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Table B3. Results of alternative measures of digitalization intensity and breadth

Variable	Model 1 Cost efficiency	Model 2 Idiosyncratic risk
Firm size	0.022*** (2.662)	-0.024*** (-5.886)
Working capital ratio	0.066*** (11.215)	-0.001 (-0.466)
Debt-to-equity ratio	-0.000 (-1.338)	-0.000 (-0.417)
State ownership	0.007 -0.756	-0.007 (-1.587)
Industry size	-0.110*** (-3.905)	-0.010 (-0.715)
Industry ROA	0.310*** (3.215)	-0.052 (-1.122)
Industry dynamism	0.324*** (2.650)	-0.056 (-0.954)
Year dummies	Included	Included
SBC	0.053*** (3.241)	0.014* (1.795)
Digitalization intensity (DI)	0.000 (0.237)	-0.001** (-2.019)
Digitalization breadth (DB)	-0.003 (-1.118)	-0.002 (-1.388)
SBC × DI	0.001 (0.211)	-0.003* (-1.794)
SBC × DB	-0.034*** (-2.861)	0.015*** (2.701)
Constant	2.169*** (-6.304)	0.445*** (-2.704)
R-squared	0.045	0.073

Notes: *N*=8,710; *** *p*<0.01, ** *p*<0.05, * *p*<0.1 (two-tailed test). *t*-statistics in parentheses.

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Table B4. Results of the second stage of Heckman model

Variable	Model 1 Cost efficiency	Model 2 Idiosyncratic risk
Firm size	0.022*** (2.645)	-0.023*** (-5.743)
Working capital ratio	0.065*** (11.098)	-0.002 (-0.616)
Debt-to-equity ratio	-0.000 (-1.297)	-0.000 (-0.288)
State ownership	0.008 (0.849)	-0.006 (-1.362)
Industry size	-0.108*** (-3.849)	-0.007 (-0.511)
Industry ROA	0.310*** (3.215)	-0.053 (-1.156)
Industry dynamism	0.335*** (2.737)	-0.040 (-0.690)
Year dummies	Included	Included
SBC	0.054*** (3.336)	0.013* (1.715)
Digitalization intensity (DI)	-0.000 (-0.103)	-0.001** (-2.262)
Digitalization breadth (DB)	-0.001 (-0.523)	-0.002* (-1.658)
SBC × DI	0.000 (0.039)	-0.004** (-1.991)
SBC × DB	-0.021** (-2.050)	0.012** (2.550)
Inverse Mills ratio	-0.029* (-1.794)	-0.029*** (-3.738)
Constant	2.151*** (6.239)	0.407** (2.472)
R-squared	0.045	0.076

Notes: N=8,710; *** p<0.01, ** p<0.05, * p<0.1 (two-tailed test). t-statistics in parentheses.