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Research paper

Digital technology deployment and firm resilience: Evidence from the COVID-19 pandemic

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ABSTRACT

Although many firms are aggressively deploying diverse digital technologies (DTs) at inter- and intra-organizational levels, not all firms have achieved the anticipated resilience, especially in the face of supply chain disruptions caused by "black swan" events such as the COVID-19 pandemic. To demystify this phenomenon, we draw on the asset orchestration perspective to investigate how breadth (i.e., the scope) and depth (i.e., the scale) of DT deployment influence a firm's resilience to supply chain disruptions. Survey data from 162 Chinese manufacturing firms show that the depth of DT deployment exerts a positive effect on firm resilience. Interestingly, the breadth has a non-significant effect on firm resilience. Moreover, while the breadth and depth of DT deployment both enhance supply chain coordination, supply chain coordination mediates only the relationship between DT deployment depth and firm resilience. Finally, market acuity positively moderates the relationship between supply chain coordination and firm resilience. We contribute to the literature by providing new theoretical explanations for the inconsistency in the reported relationship between technology deployment and resilience. Our study also helps firms reevaluate their DT deployment.

1. Introduction

In today's volatile and unpredictable environment, every firm is vulnerable to disruption in the supply chain (Kalubanga & Gudergan, 2022; Kumar & Sharma, 2021). For example, over 86% of global supply chains were disrupted and 94% of the global top 1000 firms suffered supply chain disruptions caused by the COVID-19 outbreak (Singh, Kumar, Panchal, & Tiwari, 2020). Given that supply chain disruptions impair the flow of products or services along a supply chain and further incurs negative consequences on operational, financial, and market performance (Kalubanga & Gudergan, 2022), firms need to be able to deal with them effectively (Blessley & Mudambi, 2022). A firm's *resilience* to supply chain disruptions refers to the ability of a firm to sense, adapt to, and quickly respond to the changes imposed in the supply chain (Ambulkar, Blackhurst, & Grawe, 2015), and it is widely regarded as an effective way to manage risk and recover (Gölgeci & Kuivalainen, 2020).

Because building resilience requires firms to utilize digital technologies (DTs) to monitor and control their supply chains, the literature has discussed the relationship between DTs and resilience (Ivanov, 2021). Some studies argue that DTs help a firm improve the transparency, visibility, and responsiveness of its supply chain (Ali & Govindan, 2021), thus contributing to a firm's resilience to supply chain disruptions (Dubey et al., 2021; Dubey, Gunasekaran, Bryde, Dwivedi, & Papadopoulos, 2020). However, other studies find that DTs may lead to capability loss as humans are replaced by machines (Ralston & Blackhurst, 2020). Besides, given that the parties and the environments a firm interacts with may be beyond its control, DTs may incur some undesirable outcomes (Son, Kim, Hur, & Subramanian, 2021). For example, Fay (2020) showed that during the COVID-19 pandemic, some smaller firms faced bankruptcy because of their lack of control over intellectual property related to DTs. Another example is that despite the widespread use of DTs before the COVID-19 outbreak, only 21% of firms have established a highly resilient supply chain network (Taghizadeh &

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Taghizadeh, 2021).

A major reason for the inconsistent views in the literature is that extant studies primarily focus on the potential of specific DTs, such as big data analytics (Papadopoulos et al., 2017) and blockchain technology (Dubey et al., 2020), in facilitating resilience to supply chain disruptions. Due to the specific inherent benefits and drawbacks of different DTs, firms seldom deploy a single DT in daily operations, but rather a mix of multiple DTs (Li, Dai, & Cui, 2020). *DT deployment* refers to how a firm adopts diverse DTs at inter- and intra-organizational levels (Ye et al., 2022). Hence, focusing on specific DTs, instead of DT deployment more generally, may ignore the synergies between different DTs and result in an oversimplified understanding of the role of DTs in building resilience to supply chain disruptions (Ye et al., 2022).

The asset orchestration perspective suggests that deploying assets reasonably is an important process for firms to create competitive advantages in a turbulent environment (Helfat et al., 2007). Because DTs are important assets for firms (Ye et al., 2022), and because building resilience can help firms maintain operations when facing supply chain disruptions (Gölgeci & Kuivalainen, 2020), the asset orchestration perspective provides a possible lens through which to understand the relationship between DT deployment and firm resilience. From the asset orchestration perspective, Ye et al. (2022) suggest that there are two ways to reflect how a firm deploys its DTs. *Breadth* refers to the diversity and scope of DT deployment, with broad DT deployment indicating that a firm aggressively shares DTs among its supply chain members (Ye et al., 2022). *Depth* is defined as the intensity and scale of DT deployment, with in-depth DT deployment indicating that a firm vigorously uses DTs to supplement its existing organizational practices (Ye et al., 2022). Accordingly, our first research question is: *What are the relationships between the breadth and depth of DT deployment and a firm's resilience to supply chain disruptions?*

Studies also suggest that to build resilience to supply chain disruptions, firms should effectively manage their supply chains (Gölgeci & Kuivalainen, 2020; Kumar & Sharma, 2021). *Supply chain coordination* refers to a series of coordination activities carried out by supply chain members, usually in marketing, sales, production, procurement, and logistics (Hill & Scudder, 2002). Because the use of DTs can help firms build a coordinated supply chain via information sharing and joint decision-making (Cao & Zhang, 2011), which may enhance the three major components of resilience, that is, transparency, visibility, and velocity (Dubey et al., 2020; Ivanov, 2021; Kamalahmadi & Parast, 2016; Rozak, Adhiatma, Fachrunnisa, & Rahayu, 2021), supply chain coordination should be a factor that links the relationship between DT deployment and firm resilience. Moreover, although supply chain coordination allows a firm to obtain a large amount of information about its supply chain (Cao & Zhang, 2011), it may be wasted when lacking strategic insight. *Market acuity* is defined as the ability of a firm to forecast and respond to customers' evolving needs (Ojha, Salimath, & D'Souza, 2014), which is closely related to strategic insight. Given that building resilience requires firms to take action in advance (Blessley & Mudambi, 2022), firms with a high level of market acuity should theoretically better leverage information from their coordinated supply chains and finally form a resilient supply chain network. According to the above arguments, we propose the following two research questions: *Does supply chain coordination mediate the relationship between DT deployment and a firm's resilience to supply chain disruptions? If so, does market acuity moderate the relationship between supply chain coordination and a firm's resilience to supply chain disruptions?*

Because the COVID-19 pandemic is the pre-eminent "black swan" event that has caused supply chain disruption in recent years (Rapaccini, Saccani, Kowalkowski, Paiola, & Adrodegari, 2020), and because many Chinese firms have shown extraordinary resilience in the face of it (Ye et al., 2022), we conducted our study by examining Chinese firms. Data from 162 Chinese manufacturing firms that had achieved varying degrees of DT deployment allow us to systematically analyze the relationships among DT deployment, supply chain coordination, market acuity, and firm resilience, leading to three key theoretical contributions.

First, unlike those studies that focus on the effect of specific DTs on resilience (Dubey et al., 2020; Papadopoulos et al., 2017), we take an asset orchestration perspective and consider two major dimensions of DT deployment, namely, breadth and depth. Interestingly, we find that merely deploying DTs does not necessarily lead to resilience, but a nuanced approach needs to be taken such that firms need to focus on the depth, rather than breadth of DT deployment. These findings thereby provide new explanations for the unexpected relationship between DTs and resilience.

Second, although prior studies suggest that some supply chain factors, such as supply chain agility and supply chain risk management culture, can positively influence resilience (Brusset & Teller, 2017; Dubey et al., 2019), little research investigates this from a coordination viewpoint. In this paper, we find that while the breadth and depth of DT deployment both enhance supply chain coordination, that coordination mediates only the relationship between DT deployment depth (not breadth) and a firm's resilience to supply chain disruptions. These findings thereby enrich the understanding of the role of supply chain factors in promoting resilience.

Third, past studies primarily investigate the role of market acuity in boosting innovation (Menor & Roth, 2007; Menor & Roth, 2008). Because market acuity captures management's strategic insights into the market, and because it is an important element in ensuring a firm's growth and survival in turbulent environments (Ojha et al., 2014), investigating the role of market acuity in enhancing resilience to supply chain disruptions is also necessary. In this paper, we demonstrate how market acuity moderates the relationship between supply chain coordination and a firm's resilience to supply chain disruptions, thus expanding the existing knowledge of the effects of market acuity.

The remainder of this paper is organized as follows: In Section 2, we introduce a novel theoretical perspective and propose our hypotheses. In Section 3, we describe data sources, measurement of variables, and bias tests. In Sections 4 and 5, we present the estimated results and compare our findings with previous studies. Finally, we summarize our study and suggest some limitations in Section 6.

2. Theory and hypotheses

2.1. Asset orchestration perspective on DT deployment

The asset orchestration perspective, derived from the dynamic capability theory, emphasizes two primary processes—asset selection and asset deployment—for firms to create competitive advantages in a turbulent environment (Helfat et al., 2007; Sirmon et al., 2011). The selection process requires firms to identify valuable assets and make investments related to them (Helfat et al., 2007), whereas the deployment process requires firms to coordinate specialized assets and determine the specific market segment or field to which the assets are applied (Helfat et al., 2007).

DTs are key assets for firms (Pagani & Pardo, 2017; Ritter & Pedersen, 2020). Although past studies have analyzed the outcomes of DTs (Li, 2022; Li et al., 2022), most are based on the resource-based view or dynamic capability theory (Gupta, Drave, Dwivedi, Baabdullah, & Ismagilova, 2020; Wamba et al., 2017). Sirmon et al. (2011) argue that possessing certain resources (or capabilities) alone may not guarantee the development of competitive advantages; indeed, the full value of the resources that create competitive advantage can be realized only when firms leverage and manage certain resources effectively. In other words, resource-focused actions, rather than the resources themselves, play a more important role in obtaining competitive advantages (Helfat et al., 2007). Overall, on the one hand, assets are an important part of organizational resources (Helfat et al., 2007); on the other hand, compared with the resource-based view and dynamic capability theory, in the asset orchestration perspective, the emphasis is on how a firm selects and deploys its assets (Sirmon et al., 2011). Hence, the asset orchestration perspective may provide a better understanding of the outcomes of DTs.

Given that researchers have extended the asset orchestration perspective to the different means of asset deployment (Ye et al., 2022; Zhang, Xue, & Dhaliwal, 2016), in this paper we regard breadth and depth as the two major means of DT deployment. *Breadth* is connected to the diversity and scope of DT deployment, whereas *depth* is associated with the intensity and scale of DT deployment.

2.2. DT deployment and firm resilience

Resilience is a multidisciplinary concept (Dubey et al., 2019). We present some definitions of resilience at the organizational level in Table 1. Generally, resilience describes the capacity of a firm to respond to and recover from disruptive events (Baz & Ruel, 2020; Dabhilkar, Birkie, & Kaulio, 2016; Essuman, Boso, & Annan, 2020; Faruquee, Paulraj, & Irawan, 2021; Gölgeci & Kuivalainen, 2020; Hosseini, Ivanov, & Dolgui, 2019; Sharma, Rangarajan, & Paesbrugghe, 2020; Subramanian & Abdulrahman, 2017; Yu, Jacobs, Chavez, & Yang, 2019). Because there are various types of disruption, and because every firm is entrenched in a supply chain, we primarily focus on disruptions related to the supply chain (Kalubanga & Gudergan, 2022). A *supply chain disruption* refers to an occurrence that inhibits the flow of products or services (Kumar & Sharma, 2021; Parast, 2020; Revilla & Saenz, 2017). A lockdown imposed because of an outbreak of COVID-19 is a typical example of a supply chain disruption (Rapaccini et al., 2020). Motivated by the work of Ambulkar et al. (2015), in this paper we define a firm's *resilience* to supply chain disruptions as the ability of a firm to sense, adapt to, and promptly respond to supply chain disruptions.

Past studies argue that the transparency, visibility, and velocity of the supply chain are the three major components of resilience to supply chain disruptions (Dubey et al., 2020; Ivanov, 2021; Kamalahmadi & Parast, 2016; Rozak et al., 2021). *Transparency* refers to a firm disclosing information to its stakeholders about its supply chain processes and the conformance of its products (Sodhi & Tang, 2019). *Visibility* refers to a firm's ability to see the upstream and downstream operations of its supply chain (Barratt & Oke, 2007). *Velocity* refers to the speed at which a firm is able to respond to market changes or events (Scholten & Schilder, 2015). Because DT deployment provides firms with the functions of simulation, planning, intelligence, optimization, monitoring, tracking, and forecasting (De Luca, Herhausen, Troilo, & Rossi, 2021; Dubey, Bryde, Blome, Roubaud, & Giannakis, 2021; Kamalaldin, Linde, Sjödin, & Parida, 2020; Zhang & Xiao, 2020), it should enhance the transparency, visibility, and velocity of the supply chain, thereby positively influencing a firm's resilience to supply chain disruptions.

Table 1
Definitions of resilience at the organizational level.

Definition	Reference
"The capacity to cope with unanticipated dangers as they become manifest, learning to bounce back."	Wildavsky (1988)
"A unique blend of cognitive, behavioral, and contextual properties that increase a firm's ability to understand its current situation and to develop customized responses that reflect that understanding"	Lengnick-Hall and Beck (2005)
"A firm's ability to recover from disruptive events"	Blackhurst, Dunn, and Craighead (2011)
"The capability of the firm to be alert to, adapt to, and quickly respond to changes brought by a supply chain disruption."	Ambulkar et al. (2015)
"The ability of systems to absorb and recover from shocks, while transforming their structures and means for functioning in the face of long-term stresses, change, and uncertainty."	van der Vegt, Essens, Wahlström, and George (2015)
"The process by which an actor (i.e., individual, organization, or community) builds and uses its capability endowments to interact with the environment in a way that positively adjusts and maintains functioning prior to, during, and following adversity."	Williams, Gruber, Sutcliffe, Shepherd, and Zhao (2017)

In particular, broad DT deployment requires a firm to share diverse DTs across the supply chain based on inter-firm relationships (Ye et al., 2022). Because DT sharing facilitates the interchange of information among supply chain members, it should increase the supply chain's transparency and visibility (Hastig & Sodhi, 2020; Kittipanya-ngam & Tan, 2020). For example, blockchain technology has been applied in the food supply chain to allow the focal firm to track the flow of goods, while other stakeholders can monitor the entire food production process of the focal firm (Rogerson & Parry, 2020). More recently, the widespread deployment of the Internet of Things in the supply chain has allowed firms to capture any object or process that needs to be monitored, connected, and interacted with in real-time (Paiola & Gebauer, 2020), thus helping them know in time to what extent their suppliers have been affected by COVID-19 (Belhadi et al., 2021).

In contrast, in-depth DT deployment necessitates a firm to actively utilize DTs to supplement its organizational practices (Ye et al., 2022), which may help a firm redesign its supply chain to build an agile supply chain network (Shashia, Centobelli, Cerchionec, & Ertz, 2020), thereby enhancing supply chain velocity and preventing adverse events. For instance, many firms, such as Midea and Amazon, now employ big data analytics and artificial intelligence to predict the possibility of their supply chain being affected by rapid changes in the prevalence of COVID-19, which allows them to formulate appropriate emergency plans and respond rapidly to adverse events (Riom & Valero, 2020; van Hoek, 2020). Another example is the "last mile" delivery service of JD.com, which is made possible by the deep application of DT in unmanned vehicles; more importantly, such a service can ensure supply chain velocity by delivering goods on time, even when COVID-19 has reduced the number of drivers at work (Mak & Max Shen, 2021). Based on the above observations, we propose that:

H1a. DT deployment breadth is positively associated with firm resilience.

H1b. DT deployment depth is positively associated with firm resilience.

2.3. The role of supply chain coordination

Because an exclusive focus on the direct link between DT deployment and firm resilience may overlook some underlying processes, in the following we discuss the indirect effects of DT deployment on firm resilience. Given that DT deployment is a cross-organizational variable (Zhang et al., 2016), and that resilience in the present study is mainly related to supply chain disruptions (Ambulkar et al., 2015), we primarily focus on supply chain factors, and supply chain coordination in particular.

Supply chain coordination refers to a sequence of operations that supply chain members do to coordinate their marketing, sales, manufacturing, procurement, and logistics (Hill & Scudder, 2002). Moreover, coordination among supply chain members is an important means of integrating the resources of individual organizations across organizational boundaries (Huo, Zhang, & Zhao, 2015). Building resilience requires firms to develop flexibility in their sourcing, distribution, production scheduling, and response to changing customer demand, as well as activities to share information with, to integrate with, and to collaborate with supply chain members (Chowdhury & Quaddus, 2017; Huo et al., 2015). All these activities are related to coordination among supply chain members and generally require the use of certain DTs (Huo et al., 2015), so we investigate the role of supply chain coordination in the relationships between DT deployment and firm resilience.

We first focus on the relationship between DT deployment and supply chain coordination. According to the work of Arshinder, Kanda, and Deshmukh (2008), information sharing and joint decision-making are two major mechanisms that enable supply chain members to achieve coordination. *Information sharing* refers to the extent to which supply chain members share information related to the demand, orders, inventory, and others (Huo, Zhao, & Zhou, 2014). *Joint decision-making* reflects how supply chain members synchronize their planning and operations (Cao & Zhang, 2011). Broad DT deployment indicates that a firm actively promotes technological advances and digitization of business processes among its supply chain members (Schniederjans, Curado, & Khalajhedayati, 2020). Because technological advances and digitization of business processes theoretically enable firms to rapidly exchange real-time information by linking the point of production seamlessly with the point of delivery or purchase, as well as enhancing effective communication (Pagani & Pardo, 2017), broad DT deployment should promote information sharing among supply chain members. In fact, Müller, Veile, and Voigt (2020) have suggested that leveraging DTs to share information within supply chains is a central prerequisite to implementing Industry 4.0. In contrast, in-depth DT deployment helps a firm to use supply chain members' technical knowledge to supplement its own organizational practices (Ye et al., 2022), thus enhancing the possibility of implementing collaborative planning, forecasting, and replenishment with supply chain members. For example, because DTs have provided many benefits in aspects of simulation, planning, optimization, and forecasting (Pagani & Pardo, 2017), to improve forecast accuracy, and lower inventory costs, two or more parties in the supply chain are increasingly leveraging DTs to collaboratively work on forecasts, as well as production and replenishment procedures (Choi, Wallace, & Wang, 2018). Overall, given that broad and in-depth DT deployment may promote information sharing and joint decision making, we propose the following:

H2a. DT deployment breadth is positively associated with supply chain coordination.

H2b. DT deployment depth is positively associated with supply chain coordination.

We then consider the relationships between supply chain coordination and firm resilience. Past studies have shown that information sharing is one of the most important drivers of resilience. For example, based on an agent-based computational framework, Datta, Christopher, and Allen (2007) find that information sharing, flexibility, monitoring, and a decentralized structure are four key drivers of resilience. By utilizing graph theory and interpretive structural modeling (ISM) approach that includes ten drivers, Soni, Jain, and Kumar (2014) identify information sharing, visibility, and collaboration as three separate drivers of resilience. Papadopoulos et al. (2017), in their analysis of 36,422 items from social media, find that information sharing is positively linked to resilience in supply chain networks. In addition to information sharing, joint decision-making related to supply chain coordination may play an important role in helping a firm to develop resilience to supply chain disruptions. Specifically, joint decision-making requires firms to create links between various resources owned by different supply chain partners, allowing them to be combined into resource bundles (Cao & Zhang, 2011). Theoretically, when an adverse event occurs, such resource bundles allow firms to capture the use of resources of all parties in their supply chain in a timely manner, thereby quickly allocating resources to adapt to unexpected market changes (Shashia et al., 2020). Overall, greater coordination among supply chain members, on the one hand, indicates tighter information sharing, which facilitates the transparency and visibility of the supply chain; on the other hand, it is related to better joint decision making, which can improve the velocity of the supply chain. Hence, we postulate that:

H3. Supply chain coordination is positively associated with firm resilience.

2.4. The moderating role of market acuity

Market acuity refers to the ability of a firm to forecast and respond to changing markets (Ojha et al., 2014). Studies have found that market acuity captures management's strategic insights into the market and is critical for a firm's development and survival in a turbulent environment (Menor & Roth, 2008). When facing supply chain disruptions, firms must not only acquire critical information but also immediately alter current resource structures (Kumar & Sharma, 2021; Shashia et al., 2020). Because supply chain coordination enables firms to collect more information before and after a supply chain disruption occurs, as well as perform joint decision-making with supply chain members to quickly adjust existing resource structure (Arshinder et al., 2008), we believe that market acuity primarily moderates the relationship between supply chain coordination and firm resilience.

Specifically, supply chain coordination allows a firm to obtain a large amount of information about suppliers, customers, and the market, and perform collaborative planning, forecasting, and replenishment with supply chain members. However, if it lacks strategic insight, the benefits from information sharing and joint decision-making may be wasted. For example, Corbett (2018) has shown that while most firms actively collect and store data from various points in their business processes, the reality is that 90% of all data stored is never used. McKinsey (2020) has also reported that in the COVID-19 crisis, although many firms have struggled to coordinate their supply chains, they often still do not know where their secondary or even tertiary suppliers are, limiting their ability to make joint decisions and respond quickly to supply chain disruptions.

Market acuity is closely related to insight (Ojha et al., 2014). Firms can better predict emerging developments if they have refined market acuity, as acuity gives them more lead-in time for new product development (Ojha et al., 2014). Moreover, firms that are able to respond to market signals can monitor and evaluate whether their current business strategies are effective, and then decide whether to continue or terminate them (Ojha et al., 2014). Wang, Hong, Li, and Gao (2020) have reported that many firms with high market acuity quickly developed new business streams to survive the COVID-19 pandemic. Overall, when a firm possesses stronger market acuity, it is more likely to fully exploit the information gathered from a coordinated supply chain and expand the benefits of joint decision-making. Hence, we infer that:

H4. Market acuity positively moderates the relationship between supply chain coordination and firm resilience.

Based on the above arguments, the framework of the present study is summarized in Fig. 1.

3. Methods

3.1. Data collection

We focus on manufacturing firms because they are located in the middle of most supply chains, and manufacturing difficulties may have an enormous impact on the whole supply chain (Ye et al., 2022).

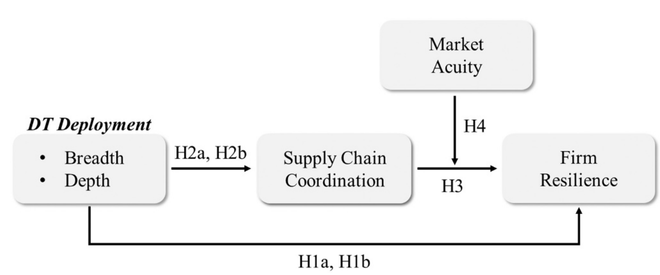

Fig. 1. Research framework.

Furthermore, the sample consists of Chinese firms, because China is the global manufacturing engine and has the largest scope of technological innovation among the emerging economies (Zhang et al., 2016). Moreover, China was one of the first major nations to suffer from the COVID-19 pandemic, and yet numerous Chinese firms have demonstrated outstanding resilience (Wang et al., 2020). In short, investigating Chinese manufacturing firms not only matches our research purpose but also provides a reference for firms facing similar disruptions in other regions.

To find potential firms as quickly and accurately as possible, we paid for the assistance of an online market survey agency with a database covering >30,000 Chinese companies. The agency assigned an employee to assist with the distribution of questionnaires. We informed the survey agency both that respondents to our survey should all be operations managers, IT managers, business managers, or top executives in Chinese manufacturing firms, and that the firms they represented must have adopted at least one type of DT before the survey. The survey agency then sent an email with our questionnaire and a cover letter at random to the firms on its database that met our study criteria. Respondents who completed the questionnaire within a specified time frame were immediately rewarded with a valuable e-gift card from the survey agency. After 423 firms had been contacted by the survey agency, 162 of them had provided with usable responses, representing a response rate of 38.30%. Table 2 provides the sample characteristics of the respondents and their firms. It can be seen that small and medium-sized enterprises (SMEs) accounted for the majority of the sample because many responded firms were privately owned (67.28%) and had <500 employees (54.94%).

3.2. Measures

Our measurement items were derived from the literature on information systems, supply chain management, and marketing; each item was rated on a seven-point Likert scale. Appendix A gives the items in full. To measure the breadth and depth of DT deployment, we adapted eight items from Zhang et al. (2016). Three items adapted from Hill and Scudder (2002) were used to measure supply chain coordination. We also adapted three items from Ojha et al. (2014) to measure market acuity. Finally, to measure firm resilience, three items were adapted from Ambulkar et al. (2015). Control variables in the present research included ownership (dummy coding and setting shareholding as the benchmark), firm age (continuous variable, measured as the number of years the firm had been established, up to 2021), and firm size (continuous variable, measured as the number of employees).

3.3. Non-response bias and common method bias

We first checked for non-response bias and found no significant difference ($p > 0.10$) between the first quarter of all survey responses and the last quarter in respect of firm age and size. Then, we used two approaches to check for common method bias. The first approach was Harman's single-factor model (Podsakoff, MacKenzie, Lee, & Podsakoff, 2003), that is, loading all items into a single factor in the confirmatory factor analysis. The model fit was poor ($\chi^2 = 387.488$, $df = 119$, $\chi^2/df = 3.256$, incremental fit index (IFI) = 0.811, comparative fit index (CFI) = 0.809, and root mean square error of approximation (RMSEA) = 0.118). The second approach was the marker-variable technique (Lindell & Whitney, 2001). We set the work experience (years at work) of the respondent as a marker variable because it should theoretically be irrelevant to the focal variables in this study. As expected, we found no significant correlation between the marker variable and the focal variables (see Table 3). Moreover, controlling for common method bias did not change the correlations between variables to statistical non-significance. Overall, common method bias was not a serious concern in this study.

4. Results

4.1. Scale validity and reliability

We performed a confirmatory factor analysis to check the validity and reliability of the items. The results, summarized in Appendix A, indicate a good model fit, with $\chi^2 = 184.307$, $df = 109$, $\chi^2/df = 1.691$, IFI = 0.947, CFI = 0.946, and RMSEA = 0.066. Most factor loadings are above 0.7 and Cronbach's α for each variable is also over 0.7, both of which indicate good reliability (Fornell & Larcker, 1981). Second, to evaluate composite reliability (CR) and convergent validity, we calculate the CR and the average variance extracted (AVE) and find that, for each variable, CRs and AVEs are above the cutoffs of 0.7 and 0.5, respectively (Fornell & Larcker, 1981). Third, to assess discriminant validity, we compare whether the square roots of AVEs are above the inter-construct correlations (Fornell & Larcker, 1981) and present the results in Table 3. As expected, all variables meet this criterion.

Table 2
Sample characteristics ($N = 162$).

Firm information	Frequency	Percentage	Respondent information	Frequency	Percentage
Ownership			Gender		
State-owned	23	14.20%	Male	94	58.02%
Privately owned	109	67.28%	Female	68	41.98%
Foreign	12	7.41%	Respondent age		
Shareholding	18	11.11%	25 and below	1	0.62%
Firm age (years established, to 2021)			26–35 years old	63	38.89%
10 and below	47	29.01%	36–45 years old	66	40.74%
11–20 years	57	35.19%	45 and above	32	19.75%
21–30 years	37	22.84%	Educational level		
31 years and above	21	12.96%	High school degree or below	1	0.62%
Firm size (number of employees)			Associate degree	11	6.79%
<100	25	15.43%	Bachelor's degree	105	64.81%
100–500	64	39.51%	Postgraduate degree	45	27.78%
500–1000	41	25.31%	Respondent title		
1000–2000	18	11.11%	Operations/IT manager	79	48.77%
>2000	14	8.64%	Business unit manager	54	33.33%
Top four DTs			Top manager	29	17.90%
Big data analytics	136	83.95%			
Cloud computing	99	61.11%			
Internet of Things	86	53.09%			
Artificial intelligence	65	40.12%			

Table 3
Correlation matrix and discriminant validity.

	1	2	3	4	5	6	7	8	9	10	11
1. Breadth	**0.803**										
2. Depth	0.667***	**0.729**									
3. Market acuity	0.533***	0.604***	**0.737**								
4. SCC	0.643***	0.681***	0.616***	**0.764**							
5. Resilience	0.397***	0.499***	0.612***	0.499***	**0.756**						
6. Firm age	0.064	−0.007	0.088	0.022	0.112	**n/a**					
7. Firm size	0.059	−0.011	0.024	−0.001	−0.022	0.345***	**n/a**				
8. State-owned	0.011	0.064	−0.050	0.048	0.029	0.212***	−0.039	**n/a**			
9. Privately owned	−0.001	−0.011	0.099	0.037	−0.046	−0.277***	−0.124	−0.583***	**n/a**		
10. Foreign	−0.157**	−0.195**	−0.157**	−0.257***	−0.015	0.234***	0.311***	−0.115	−0.406***	**n/a**	
11. MV	0.026	0.090	0.066	0.108	0.141	0.312***	−0.122	0.257***	−0.096	−0.139	**n/a**
Mean	5.383	5.546	5.634	5.642	5.405	19.321	1120	0.142	0.673	0.074	9.781
Standard deviation	0.895	0.844	0.792	0.833	0.815	16.317	2745	0.350	0.471	0.263	5.243

Notes: *** and ** represents *p-values* < 0.01 and 0.05, respectively; the numbers on the diagonal are the square root of AVEs. SCC and MV are the abbreviations of supply chain coordination and marker variable. Because ownership is a categorical variable, we use dummy coding and set shareholding as the benchmark.

4.2. Hypothesis testing

Similar to the work of Song and Di Benedetto (2008), we first averaged all items belonging to each variable to obtain the overall value for each construct and standardized them. We then conducted a collinearity test. The variance inflation factors (VIFs) of explanatory variables in different models were well below the cutoff of 10 (Neter, Wasserman, & Kutner, 1990). Finally, we used the hierarchical regression analysis to test our model and present the results in Table 4.

In Model 2, DT deployment breadth ($\beta = 0.331$, $p < 0.01$) and depth ($\beta = 0.436$, $p < 0.01$) both show significant effects on supply chain coordination, supporting H2a and H2b. In contrast, in Model 4 DT deployment depth ($\beta = 0.443$, $p < 0.01$) but not breadth ($\beta = 0.105$, $p = 0.264$) has a positive effect on firm resilience, thereby supporting H1b but rejecting H1a. When DT deployment breadth, DT deployment depth, and supply chain coordination are incorporated in the estimated model, Model 5 shows that DT deployment depth ($\beta = 0.306$, $p < 0.01$) and supply chain coordination ($\beta = 0.315$, $p < 0.01$) have significant impacts on firm resilience, but the impact of DT deployment breadth on firm resilience ($\beta = 0.001$, $p = 0.992$) is still non-significant. These results support H3. Finally, Model 6 reveals that the interaction between supply chain coordination and market acuity ($\beta = 0.121$, $p < 0.05$) has a positive relationship with firm resilience to supply chain disruptions, thus supporting H4.

4.3. Additional analysis

According to the results in Table 4 and following the logic of the stepwise regression (Wang, Li, & Chang, 2016), we can initially infer that supply chain coordination partially mediates the relationship between DT deployment depth and firm resilience. To verify the above mediating effect, we used the PROCESS macro embedded in SPSS 23.0 (Hayes, 2013). In particular, we set DT deployment depth as the independent variable, supply chain coordination as the mediating variable, firm resilience as the dependent variable, and firm age, firm size, ownership, and DT deployment breadth as covariates. By setting 95% confidence interval (CI) and 20,000 of bootstrap samples, we find that the direct path from DT deployment depth to firm resilience (direct effect = 0.306, SE = 0.101, 95% CI [0.107, 0.504]) is significant and positive and that the indirect path from DT deployment depth to firm resilience through supply chain coordination (indirect effect = 0.137, SE = 0.048, 95% CI [0.048, 0.236]) is also significant and positive. However, when we further test the moderated-mediation effect of market acuity and supply chain coordination, the index is non-significant because its 95% CI [−0.014, 0.102] includes zero. Moreover, we find that only when the value of market acuity is located in the 84th percentile, the indirect effect of DT deployment depth on firm resilience (indirect effect = 0.884, SE = 0.119, 95% CI [0.018, 0.211]) is significant and positive. Overall, the above results confirm the partial mediation effect of supply chain coordination but do not reveal a significant moderated-mediation effect.

Moreover, past studies have suggested that firms that undergo digital transformation tend to use multiple types of DTs (Faruquee et al., 2021; Li et al., 2020). To increase the robustness of our results, we use binary coding to measure whether the responded firms have adopted big data analytics, cloud computing, the Internet of Things, and artificial intelligence, where “1” indicates that the responded firms have adopted corresponding DT, and “0” indicates non-adoption. We then identify the

Table 4
Estimated results.

	Supply chain coordination		Firm resilience			
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
DT deployment breadth		0.331***		0.105	0.001	0.002
DT deployment depth		0.436***		0.443***	0.306***	0.186†
Supply chain coordination (SCC)					0.315***	0.166†
Market acuity (MA)						0.480***
SCC × MA						0.121**
Firm age	0.004	0.002	0.006	0.006	0.005	0.003
Firm size	0.000	0.000	0.000	0.000	0.000	0.000
State-owned	−0.206	−0.039	−0.118	−0.023	−0.011	0.055
Privately-owned	−0.244	−0.022	−0.141	0.017	0.024	−0.075
Foreign	−1.348***	−0.488†	−0.361	0.246	0.399	0.471
Constant	0.194	0.015	−0.004	−0.141	−0.146	−0.096
R^2	0.082	0.543	0.018	0.273	0.318	0.448
Adjusted R^2	0.052	0.522	0.000	0.239	0.282	0.412
F value	2.770**	26.166***	0.579	8.241***	8.910***	12.268***

Notes: ***, **, and † represent significance at 0.01, 0.05, and 0.1 levels, respectively.

four variables as potential instrumental variables for DT deployment breadth and depth because they are not significantly related to firm resilience (the largest correlation is 0.112, $p > 0.10$). By performing a two-stage least squares (2SLS) regression analysis with the breadth and depth of DT deployment as explanatory variables, respectively, we find that DT deployment breadth shows a positive relationship with supply chain coordination ($\beta = 0.882$, $p < 0.01$) but a non-significant relationship with firm resilience ($\beta = 0.274$, $p = 0.193$). In contrast, DT deployment depth shows significant relationship with both supply chain coordination ($\beta = 0.738$, $p < 0.01$) and firm resilience ($\beta = 0.327$, $p < 0.10$). These results provide support for partial hypotheses again.

5. Discussion

Building resilience to potential disruptions has become one of the main challenges in improving the effectiveness and efficiency of industrial markets (Blessley & Mudambi, 2022; Gölgeci & Kuivalainen, 2020; Sharma et al., 2020; Tuan, 2022). Given that DTs can help firms monitor and control their supply chains (Shashia et al., 2020), existing studies primarily investigate the effect of specific DTs, such as big data analytics (Papadopoulos et al., 2017) and blockchain technology (Dubey et al., 2020), on a firm's resilience to supply chain disruptions. Moreover, because the COVID-19 pandemic is a pre-eminent supply chain disruption event (Sharma et al., 2020), recent studies have widely discussed how a firm should handle disrupted supply chains caused by the pandemic (Blessley & Mudambi, 2022; Rapaccini et al., 2020), especially from the perspective of dynamic capabilities (Kalubanga & Gudergan, 2022).

Compared with past studies related to the usage of DTs and building resilience to supply chain disruptions, we investigate from an asset orchestration perspective and obtain some novel results. In particular, while DT deployment depth exerts a positive effect on firm resilience, DT deployment breadth does not. The major reasons are that although DT deployment breadth enables firms to acquire a variety of forms of data through its inter-firm relationships, data volume is not always a matter of the bigger the better. Too much data may interfere with the firm's judgment, especially in emergency situations. Past findings in general scenarios support this view. For example, in their investigation of 239 managers in the United States, Ghasemaghaei and Calic (2020) find that data volume does not have a significant influence on fostering innovation. Using data from the Google Play Store, Cappa, Oriani, Peruffo, and McCarthy (2021) similarly find that larger volumes of data have a negative influence on firm performance. In contrast, DT deployment depth enables a firm to supplement its existing organizational practices. In the context of innovation, Zhang and Xiao (2020) use survey data of 148 Business-to-Business (B2B) innovation projects and fin that customer as data provider (CDP) and customer as data analyst (CDA) can both facilitate B2B product innovation, thereby providing indirect support for the significant role of DT deployment depth.

Second, Hill and Scudder (2002) argue that electronic data interchange (EDI) is an important coordination activity at the inter-firm level. García-Dastugue and Lambert (2003) also suggest that the Internet facilitates the integration of business processes across the supply chain by simplifying the information flows necessary for coordinating business activities. Similar to the findings of these two studies, in the context of the digital revolution, we find that both the breadth and depth of DT deployment improve supply chain coordination. Moreover, based on data collected from 617 manufacturing firms, Huo et al. (2015) find that the relationship between information technology and supply chain performance is mediated by supply chain coordination with both suppliers and customers. However, we show that supply chain coordination mediates only the relationship between DT deployment depth and a firm's resilience to supply chain disruptions, not that between DT breath and resilience. One possible reason is that although broad DT deployment can facilitate the exchange of information among firms, such information interchange is extremely likely to make only marginal contributions to a firm's resilience to supply chain disruptions.

Third, we investigate the influence of market acuity on resilience and find that the relationship between supply chain coordination and firm resilience is positively moderated by market acuity. Firms often rely on two key types of insight when making decisions: data-driven insights and management's strategic insights (Bresciani, Ciampi, Meli, & Ferraris, 2021; Ojha et al., 2014). In the face of events such as the supply chain disruptions caused by the COVID-19 outbreak, firms do not always obtain the corresponding data in advance and in a timely manner, and, thus, data-driven insights may be limited. In such circumstances, strategic insights based on managers' prior experience are particularly important (Liao, Fei, & Liu, 2008). In other words, to deal with the challenges posed by various disruptions, firms must synthesize different types of insights, rather than relying solely on unilateral insights. Past studies related to customer agility can support the above argument to some extent. In particular, Hajli, Tajvidi, Gbadamosi, and Nadeem (2020) define customer agility as the capability of a firm to sense and respond to customer-based opportunities for innovation and competitive action; through a case study approach, they unpack the interplay of data aggregation tools, data analysis tools, and customer agility in new product success.

5.1. Theoretical implications

We contribute to the literature in two respects. *First*, increasing a firm's resilience to potential supply chain disruption events (e.g., the COVID-19 pandemic) has become one of the streams for industrial market research (Blessley & Mudambi, 2022; Rapaccini et al., 2020). However, past studies hold that the relationship between DTs and resilience may be positive (Dubey et al., 2020), negative (Ralston & Blackhurst, 2020), or non-significant (Ghasemaghaei & Calic, 2020). We attribute this inconsistency to the fact that the focus has mainly been on the potential of a single DT (e.g., big data analytics or blockchain technology) in building resilience (Dubey et al., 2020; Papadopoulos et al., 2017), while ignoring the impact of different DT combinations. In this paper, we draw on the asset orchestration perspective (Adner & Helfat, 2003) and find that DT deployment depth, rather than breadth, has a positive effect on a firm's resilience to supply chain disruptions. The major reasons are that DT deployment depth can help firms supplement their existing organizational practices, whereas the increase in data volume brought by DT deployment breadth is not always a matter of the bigger the better. These findings, thereby, provide new explanations for the inconsistency in the relationship between DTs and resilience.

Second, studies related to the industrial market also emphasize that firms should effectively manage their supply chains to deal with disruptions (Gölgeci & Kuivalainen, 2020; Kumar & Sharma, 2021). Although prior studies have investigated the effect of supply chain reengineering, supply chain collaboration, supply chain agility, supply chain risk management culture, and marketing-supply chain management alignment on resilience (Baz & Ruel, 2020; Fan, Stevenson, & Li, 2020; Gölgeci & Kuivalainen, 2020; Kamalahmadi & Parast, 2016), they fail to highlight the influence of supply chain coordination on resilience (Flynn, Huo, & Zhao, 2010). Moreover, past studies mainly investigate the role of market acuity and other similar constructs (e.g., customer agility) in boosting innovation (Hajli et al., 2020; Menor & Roth, 2007; Menor, Tatikonda, & Sampson, 2002). Because supply chain coordination aims to improve the overall functions and benefits of the supply chain (Huo et al., 2015), and because market acuity (which is closely related to management's strategic insights) is a critical factor for a firm's survival in a turbulent environment (Ojha et al., 2014), understanding how supply chain coordination and market acuity may impact a firm's resilience to supply chain disruptions is critical. In this paper, we demonstrate that supply chain coordination mediates the positive relationship between DT deployment depth and firm resilience. Moreover, market acuity positively moderates the relationship between supply chain coordination and firm resilience. These findings enrich the current understanding of the role of supply chain coordination and market acuity, especially in promoting resilience.

5.2. Managerial implications

Because our sample is mostly composed of SMEs, some corresponding managerial insights are as follows. First, DT deployment not only directly enhances resilience but also indirectly influences resilience through the mediation of supply chain coordination. Hence, to develop resilience to deal with supply chain disruptions, SEMs should prioritize the depth of DT deployment, that is, vigorously using DTs to supplement their organizational practices. However, while SMEs are the most inventive and dynamic segment of the economy (Rehm & Goel, 2017), when using DTs to supplement organizational practices, they frequently confront the two dilemmas of being unable to utilize technology and being short on funds (Cenamor, Parida, & Wincent, 2019). In this case, the majority of SMEs should develop a variety of low-cost, easy-to-use, and quick-to-market digital empowerment products or services to enhance their organizational practices. Only in this way can the endogenous motivation of SMEs be stimulated and the value of DT deployment be continuously increased.

Second, although DT deployment breadth does not directly help build resilience to supply chain disruptions, it can enhance supply chain coordination, which is one of the major drivers of resilience. Because the digital infrastructure of most SMEs is relatively weak on the whole, mostly between Industry 2.0 and 3.0, joining the digital platforms built by giant firms is an effective approach for SMEs to expand the breadth of their DT deployment. For example, Huawei, Midea, and other large manufacturing firms have not only realized their digitalization, but their industrial Internet platforms have also facilitated this for many SMEs. Zhijun Xu, the rotating chairman of Huawei, stated that, by the end of 2020, Huawei had formed >40 industrial Internet innovation centers across China, providing digitalization transformation services for >20,000 industrial enterprises across >30 industrial clusters.

Third, because market acuity positively moderates the relationship between supply chain coordination and firm resilience, SMEs cannot rely solely on data-driven insights; they must also continuously improve top managers' awareness of market changes. For this purpose, SMEs should have a thorough understanding of the numerous dynamic and systemic elements impacting market changes in aggregate, as well as attempt to predict potential future hazards and formulate countermeasures in advance. Specifically, SMEs should forecast and estimate market trends based on political, economic, social, technological, environmental, and legal aspects. Additionally, analyzing market trends is not a one-time job, but a continuous process. Finally, SMEs should develop countermeasures that are beneficial to the firm according to market changes. In fact, many observations have shown that only companies that successfully monitor and respond to market changes can stand out from the fierce competition and create competitive advantages (Menor & Roth, 2008; Ojha et al., 2014).

6. Conclusion

Drawing on the asset orchestration perspective, we investigate how the breadth and depth of DT deployment may affect a firm's resilience to supply chain disruptions. The empirical results from 162 Chinese manufacturing firms show that DT deployment depth, rather than breadth, has a positive effect on a firm's resilience to supply chain disruptions. Moreover, although the breadth and depth of DT deployment both enhance supply chain coordination, supply chain coordination mediates only the relationship between DT deployment depth and firm resilience. Lastly, market acuity positively moderates the relationship between supply chain coordination and firm resilience. Our findings provide new explanations for the inconsistency in the reported relationship between technology deployment and resilience, thus making theoretical contributions to the existing literature. Our findings also provide managerial guidance for firms on how to effectively deploy their DTs at inter- and intra-organizational levels.

Despite these major contributions, several aspects of the study and its findings warrant further research. First, although we focus on manufacturing firms, we do not differentiate between types of manufacturing firms. Given that different types of manufacturing firms have specific characteristics, such as automobile manufacturing being capital-intensive and technology-intensive and textile manufacturing being labor-intensive, future work could explore a more detailed manufacturing industry classification. Second, our data are collected from China, which may limit the generalizability of our results. Hence, future research could test our model in the context of other countries. Third, in this paper, we regard supply chain coordination as a holistic construct. Because supply chain coordination can be divided into supplier coordination and customer coordination (Huo et al., 2015), investigating such sub-dimensions may provide some new understandings. Fourth, the focus of this study is on resilience associated with supply chain disruptions. Given that various types of disruption require firms to develop different capabilities and resources, whether the proposed theoretical framework is applicable to other types of disruptive events deserves further investigation.

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Appendix A

DT deployment breadth (CR = 0.845; AVE = 0.645; Cronbach's α = 0.845)

- The proportion of total partners with whom you interact through DTs.
- The proportion of total partner transactions done through DTs.
- The proportion of overall interactions with partners carried out through DTs.

DT deployment depth (CR = 0.850; AVE = 0.532; Cronbach's α = 0.848)

- The extent to which DTs are used in production.
- The extent to which DTs are used in procurement management.
- The extent to which DTs are used in delivery (e.g., distribution, warehousing, and logistics).
- The extent to which DTs are used in invoicing and payment processing.
- The extent to which DTs are used in demand management.

Market acuity (CR = 0.781; AVE = 0.543; Cronbach's α = 0.779)

- We are able to sense the shifting boundaries of our industry during COVID-19.
- We have the ability to understand customer requirements better than our competitors during COVID-19.
- We have the ability to typically foresee new competitive threats and opportunities during COVID-19.

Supply chain coordination (CR = 0.807; AVE = 0.584; Cronbach's α = 0.795)

- We developed different procedures and systems to accommodate different suppliers' and customers' preferences.

- We consider our suppliers and customers to be our partners.
- Our company is taking an active role in the implementation of incentives with our suppliers and customers.

Firm resilience (CR = 0.799; AVE = 0.571; Cronbach's α = 0.797)

- We are able to cope with changes brought by the supply chain disruption during COVID-19.
- We can provide a quick response to supply chain disruptions caused by COVID-19.
- We can maintain high situational awareness at all times during COVID-19.

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