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The effect of enterprise digital transformation on supply chain efficiency and its transmission mechanism

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With the widespread adoption of digital technologies across various industries, digital transformation has provided significant benefits to enterprises, including enhanced data sharing, process optimization, and efficiency improvement. Based on the data of A-share listed enterprises in China from 2019 to 2022, this paper explores the impact of digital transformation on supply chain efficiency and its underlying mechanism. The findings reveal that digitalization of enterprises significantly enhances their supply chain efficiency. To be more specific, the transmission mechanism indicates that the digitalization improves the efficiency of supply chain by increasing external transaction costs and enhancing management capabilities, and customer concentration plays a negative moderating role during this process. Moreover, heterogeneity analysis demonstrates that the impact of digitalization on supply chain efficiency is more significant in supply-chain-sensitive industries and large enterprises. This paper not only enriches the research on digital transformation and supply chain efficiency but also provides empirical evidence for enterprises to promote digital transformation, improve supply chain efficiency and achieve sustainable development.

Keywords Digital transformation, Supply chain efficiency, Management capabilities, External transaction costs, Customer concentration

Amid the global wave of digitalization, a new round of technological revolution and industrial transformation is underway in China. The emergence of core digital technologies—such as artificial intelligence, blockchain, cloud computing and big data—has made the development of a digital economy a key national strategy for seizing new opportunities. Technological innovation in this field serves as the core driver of the digital economy and is central to the new round of global competition. Furthermore, given its critical role in national governance, economic development, and public services, gaining a leading position in digitalization has become a core national interest. It is imperative for enterprises to embrace this trend and implement digital transformation. Therefore, it is of great practical and socio-economic value to examine whether digital transformation can help optimize supply structures, alleviate overcapacity, and thereby enhance supply chain efficiency.

Most scholars have studied the driving factors and influencing effects of enterprise digital transformation. In terms of the driving factors of digital transformation, organizational capability and social learning capability have a significant contribution to enterprise digital transformation[1], and enterprises can also complete digital change by reducing operational costs and improving operational efficiency[2]. Meanwhile, chief digital officer (CDO) established by government can also play a positive role in enterprise digital transformation[3]. With respect to the impact effect of digital transformation, it can not only help enterprises increase performance[4], but also reduce the cost of information acquisition and agency costs[5,6]. Besides that, there are also articles that examine the innovation effects of digital transformation. For example, digital transformation can promote enterprise innovation (Thomas and Carsten, 2020, Ref[7].), and customer innovation can significantly influence supplier innovation[8].

In addition to studying the digital transformation for individual enterprises, some scholars also explore the impact of the diffusion of digital transformation among enterprises. For instance, the supply chain has become an economic system for information flow and diffusion[8]. Co-shareholders of the supply chain can continuously obtain and provide feedback on the enterprise's digital development by participating in shareholder meetings to drive digitalization (He et al., 2019,Andrew et al., 2021). Feedback on transactional data will also force upstream

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enterprises to pay attention to the generation, storage, and flow of data elements (Lee et al., 2011), promoting the diffusion of client enterprises' digital transformation to upstream enterprises, and thus facilitating upstream enterprises' digital transformation.

In summary, existing research has primarily focused on the impact of digitalization on micro-enterprises, particularly its effects on enterprise economic efficiency. However, research conducted from a supply chain perspective remains limited. In the existing literature, discussions regarding the conceptual boundaries of supply chains and their optimization methods are often vague, and few scholars have explored the intrinsic connections and pathways between digital transformation and supply chain efficiency. It must be acknowledged that the digitalization of supply chains is increasingly prevalent[9]. In fact, enterprise inventory levels are closely related to economic scale and operational efficiency[10,11], and reducing inventory levels can ensure the continuity and smooth operation of supply chains. the study of[12] also indicates that inventory costs constitute a significant component of supply chain costs, and optimizing inventory management is key to enhancing overall supply chain efficiency. Therefore, this study explores the impact of digital transformation on supply chain efficiency and its driving factors at the inventory turnover level, thereby enriching current academic research.

Compared with existing literature, the contributions of this paper are mainly reflected in three aspects. In terms of research perspective, this paper takes inventory as a breakthrough point to deeply study the impact and mechanism of digital transformation on supply chain efficiency, thereby expanding and enriching the relevant literature on digital transformation and supply chain efficiency. In terms of research content, this paper deepens the analysis of the mechanism by which digital transformation improves supply chain efficiency, examining the channels through which digital transformation affects supply chain efficiency from the perspectives of management capabilities, external transaction costs, and customer concentration. In terms of policy implications, this study offers new insights for governments seeking to encourage enterprises to undertake digital transformation and formulate financial and industrial policies to enhance supply chain efficiency. Government agencies should emphasize the strategic importance of core enterprises in promoting collaboration among supply chains, recognizing and leveraging the positive role of enterprise digitalization. Core enterprises should focus on close interaction with other enterprises in the supply chain, leveraging the digital empowerment effects of core enterprises to enhance overall supply chain operational efficiency and to promote a virtuous economic cycle.

The article proceeds as follows. Section "Theoretical analysis and research hypotheses" "Theoretical analysis and research hypotheses" covers the theoretical analysis and research hypothesis. Section "Methodology" "Methodology" is the research design, in which processes the sample data, describes the variables, and sets the empirical models. Section "Empirical results" "Empirical Results" presents the empirical analysis, including descriptive statistics, benchmark regression, endogeneity test, robustness test, mediator effect test, moderator effect test and heterogeneity analysis. Section "Discussion" "Discussion" discusses the findings of this paper. Section "Conclusions and suggestions" "Conclusions and Suggestions" provides the conclusions and policy recommendations of the research.

Theoretical analysis and research hypotheses

Supply chain relationships have become a hot topic in business operations, and the transformation of enterprise digitalization can change traditional transportation patterns and enhance supply chain messaging transparency, thereby improving supply chain efficiency. For one thing, digital technology is very effective in reducing logistics costs and improving operational efficiency. Digital technology promotes traditional logistics to intelligence transformation, which greatly reduces logistics costs[6]. It has been documented that the use of digital technology to logistics activities enables real-time integration and improvement of response speed[13]. The increase in logistics makes the cash flow cycle shorter, which has a positive effect on the enterprise's supply chain management. In addition to this, digital technology helps enterprises to automate and smarten their operations, reduce their dependence on human labor, optimize route, and reduce transportation costs and energy consumption. At the same time, digital software tools can improve the security of the freight transportation process through real-time monitoring and data analysis, providing customers personalized services and improving customer satisfaction. For another, digital transformation enhances supply chain information transparency. The application of digital technology improves the ability to collect, to process and to analyze information[14], further increasing the transparency of information in the operation chain and management process[15]. also points out that big data technology helps to improve the degree of supply chain information visualization, so that supply chain decision-making is more intuitive and transparent[16]. demonstrates that the blockchain technology empowers the goods traceability, which makes problems in the supply chain discoverable, so that it is easier to adjust with the actual situation, and to improve the supply chain efficiency. It can be said that the accelerated development of artificial intelligence, cloud computing, blockchain and other digital technologies has shown its extensive application value, empowering supply chain efficiency at the enterprise level. Based on the above analysis and logical reasoning, the following hypothesis is proposed:

H1: Enterprise digital transformation can significantly improve supply chain efficiency.

Enterprise digital transformation improves the overall inventory management capabilities of enterprises by optimizing management processes, thereby enhancing supply chain efficiency. From the perspective of management processes, digital transformation improves the ability of enterprises to collect, process, and analyze information, which can improve the speed and quality of management decisions, thereby optimizing internal management processes. From the perspective of management capabilities, digital transformation not only helps shareholders and boards of directors expand their information sources and obtain additional information beyond financial reports, but the introduction of digital technology also enables small and medium-sized shareholders

to reduce supervision costs, significantly enhance the feasibility of supervision, and improve the enterprise's overall management capabilities[17]. Therefore, digital transformation enhances overall inventory management capabilities by optimizing management processes, enabling enterprises to manage their supply chains more efficiently, and ultimately improving supply chain efficiency. Based on the above analysis, this paper proposes:

H2a: Management capabilities play a mediating role in the impact of digital transformation on supply chain efficiency.

By digitalization, enterprises expand their markets and seek suitable partners by moderately increasing external transaction costs, thereby improving supply chain efficiency. Coase first proposed the concept of transaction costs in1937, stating that "the existence of transaction costs leads to the emergence of enterprises." The boundaries of enterprises ultimately depend on the balance between external transaction costs and internal control costs[18]. Specifically, external transaction costs for enterprises can be divided into pre-transaction costs and post-transaction costs, including search costs incurred in finding transaction counterparts, negotiation costs, monitoring costs, and default costs[19]. Enterprises leverage digital technologies such as big data and artificial intelligence to optimize marketing strategies and precisely identify upstream suppliers and downstream customers[20]. Additionally, increased external transaction costs expand the market scope, attracting upstream and downstream partners to join the supply chain and enabling more harmonious and efficient supply chain operations[21]. Furthermore, rising external transaction costs enhance customer satisfaction and loyalty, stabilizing downstream demand within the supply chain. Therefore, digital transformation expands the market by increasing external transaction costs, helping enterprises accurately identify customer preferences and match market demand, thereby strengthening market strategy arrangement, ultimately reducing inventory turnover days and improving supply chain efficiency. Based on this, this paper proposes:

H2b: Digital transformation improves supply chain efficiency by increasing external transaction costs.

Strategic cooperation between core enterprises and their suppliers and customers play a key role in supply chain management. A large body of literature has found that a high concentration of customers facilitates enterprises to form positive, long-term supply chain relationships with each other. Supply chain can help enterprises to obtain resources and information, which plays an important role in enhancing the competitive advantage of enterprises. However, some scholars have found that customer concentration can also bring negative impacts to enterprises[22]. The higher the customer concentration, the easier it is for internal information to be accessed by enterprises in the supply chain, and the risk of information leakage will be greater. At the same time, if the higher the customer concentration, the smaller the enterprise's demand for digital technology, then the overall investment in digital construction will be less. Although the higher the customer concentration, the higher the industry chain dependence, which makes the enterprise relationship closer and can produce the synergistic effect of resources and information[23], however in practice, the supply chain management failure rate is extremely high[24]. When customer concentration is higher, efficiency gains based on trusting relationships can make enterprises perceive technology-based efficiency gains as less important in relative terms[25], which can reduce enterprises innovation and inhibit the role of digital transformation in the supply chain. Based on the above analysis, this paper proposes:

H3: Customer concentration negatively moderates the impact of digital transformation on supply chain efficiency.

Due to varying degrees of sensitivity across industries toward supply chain complexity, stability, timeliness, and dependencies, the effects of digitalization on supply chain efficiency differ. Therefore, this paper distinguishes between supply chain-sensitive industries and insensitive industries in its group regression analysis. Supply chain-sensitive industries typically have multiple supply chain links (e.g., manufacturing industry), high demand volatility (e.g., wholesale and retail industry), stringent requirements for logistics timeliness (e.g., transportation industry), and significant geopolitical risks (e.g., information technology industry). For example, the transportation industry has high requirements for timeliness[15], then digital technology transformation positively impacts supply chain management through value chain integration. In the manufacturing industry, production and sales processes are often carried out by different enterprises, resulting in more complex supply chain processes. Therefore, digital technology plays a more significant role in improving supply chain efficiency. Apart from that, for supply chain-insensitive industries, supply chain fluctuations have a limited impact on business operations. These industries are characterized by high localization with local raw materials and labor (e.g., traditional industries), strong substitutes and low barriers to entry (e.g., construction industry), and stable demand (e.g., utility industry).

Besides that, the application of digital technology has the effect of scale, and larger enterprises can fully utilize their advantages in capital, talents, technology and data, and better play the role of digital technology to enhance the supply chain efficiency. Therefore, this paper divides the 19 industry categories into three categories from the industry level, supply chain-sensitive industries, supply chain-insensitive industries and other industries, and divides the enterprises into large-scale enterprises and small-scale enterprises from the enterprise size level to examine whether there is a heterogeneous effect of digital technology on supply chain efficiency. Based on the above analysis, this paper proposes:

H4a: Supply chain sensitive industries are more likely to be affected by digital transformation, promoting the effective combination of digitalization and business operations, and bringing the result of supply chain efficiency improvement.

H4b: Large-scale enterprises are more likely to be affected by digital transformation, which promotes the effective combination of digitalization and enterprise operation and brings the result of supply chain efficiency improvement.

The research framework of this paper is shown in Fig. 1.

Methodology

Samples and data collection

In this paper, A-share listed enterprises are selected as the research sample from 2019 to 2022. Since the rapid development of digital technology mainly occurs after 2019, the initial year is set as 2019. The data on digital transformation are from the annual reports of enterprises, and other data such as supply chain efficiency are from the China Stock Market and the Accounting Research (CSMAR) database. The raw data are processed as follows: The samples of ST and *ST enterprises are excluded, and the samples with missing main variables are excluded. Additionally, to control extreme values, all continuous variables are subjected to a 1 percent shrinkage of the top and bottom (Winsorize). Then a total of 14,556 sample observations are obtained.

Variable measures

Explained variable

Supply chain efficiency (SCE) is the explained variable. SCE emphasizes increasing the frequency of dialogue and trade between upstream and downstream enterprises, which is manifested in a smooth cycle of product and service turnover. Existing studies have used inventory of non-finished goods as an indicator of SCE; however, using only the level of inventory to characterize SCE ignores factor mobility among enterprises. The research of[26] and[12] indicates that inventory management capability is a core factor influencing an enterprise's supply chain efficiency. Therefore, this paper uses the inventory turnover cycle to reflect the management efficiency of the supply chain. The shorter the inventory cycle is, the faster the inventory converts into cash, the higher SCE is. Based on this, this paper selects the natural logarithm of inventory turnover period to measure SCE. The main reasons for choosing this indicator are as follows: First, inventory turnover is an important indicator of supply chain management performance. It reflects the frequency of transactions between upstream and downstream enterprises in the supply chain, demonstrating the flexibility and responsiveness of the supply chain. Second, it is easier to obtain data based on indicators from the financial perspective.

Explanatory variable

Degree of enterprise digital transformation (Digital) is the explanatory variable. The existing literature has not yet unified for the measurement of digital transformation. The reason is that digital transformation has penetrated various industries, and it is difficult to accurately measure through specific indicators. There are two common measures of digital transformation: (1) Text analysis method. Python grabs the frequency of digitization-related text in the annual reports of listed enterprises, such as artificial intelligence technology, big data technology, cloud computing technology, blockchain technology, the use of digital technology and other

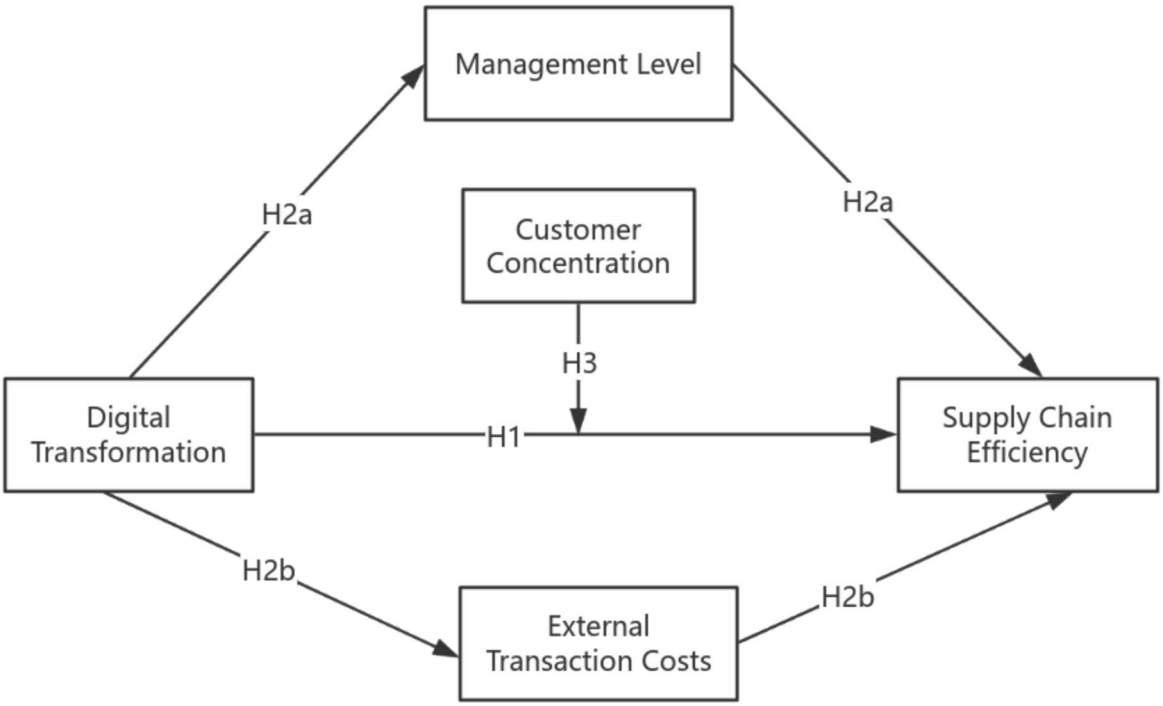

Fig. 1. Research framework diagram.

keywords, then digital transformation indicators are generated based on the word frequency. (2) Measured using the ratio of digitization-related intangible assets to the total amount of intangible assets. Specifically, the intangible assets related to digital transformation include "digitalization" "intelligence" "software" "network ", "client", "e-commerce", "intelligent platform" and other keywords. This paper uses text analysis to obtain the related word frequency, the measurement of digital transformation is the logarithm of the word frequency plus 1.

Control variables

In order to control the endogeneity problem caused by omitted variables, this paper selects the following control variables: enterprise size(Size), asset-liability ratio(Leverage), profitability (ROA), capital expenditure(Capex), equity concentration (Equity Top1), cash flow from operating activities(Cash), growth capability (Growth), nature of property(SOE), gross margin(Margin), and supplier concentration (Supplier Top5). The definitions of the main variables are shown in Table 1.

Empirical modeling

To test the direct impact of digital transformation in on supply chain efficiency(SCE), this paper draws on[8,27] to set up the regression model (1):

$$\mathrm{SCE_{it}}=\beta_0+\beta_1\mathrm{Digital_{it}}+\Sigma\ \mathrm{Controls}\ +\Sigma\ \mathrm{Ind}\ +\Sigma\ \mathrm{Year}\ +\varepsilon_{\mathrm{it}} \quad (1)$$

where the explained variable $\mathrm{SCE_{it}}$ is the supply chain efficiency of enterprise i in year t, the explanatory variable $\mathrm{Digital_{it}}$ is the degree of digital transformation of enterprise i in year t, Σ Controls denotes the set of control variables, Ind denotes the industry fixed effect, Year denotes the year fixed effect, and ε_{it} denotes the disturbance term. If the coefficient β_1 of $\mathrm{Digital_{it}}$ is significantly negative, it indicates that the digital transformation of enterprises can lead to shorter inventory cycles and higher supply chain efficiency, so that digital transformation has a driving effect on the improvement of supply chain efficiency of enterprises.

The indirect effect of digital transformation in on supply chain efficiency includes mediator effect and moderator effect. To verify the hypothesis and unveil the channel mechanism, the regression model (2) & (3) including the mediating variables, and the regression model (4) including the moderating variables are set as follows:

$$M_{\mathrm{it}}=\mathrm{a_0}+\mathrm{a_1Digital_{it}}+\Sigma\ \mathrm{Controls}\ +\Sigma\ \mathrm{Ind}\ +\Sigma\ \mathrm{Year}\ +\varepsilon_{\mathrm{it}} \quad (2)$$

$$\mathrm{SCE_{it}}=\mathrm{b_0}+\mathrm{b_1M_{it}}+\mathrm{b_2Digital_{it}}+\Sigma\ \mathrm{Controls}\ +\Sigma\ \mathrm{Ind}\ +\Sigma\ \mathrm{Year}\ +\varepsilon_{\mathrm{it}} \quad (3)$$

$$\mathrm{SCE_{it}}=\mathrm{c_0}+\mathrm{c_1Digital_{it}}+\mathrm{c_2M_{it}Digital_{it}}+\mathrm{c_3}M_{\mathrm{it}}+\Sigma\ \mathrm{Controls}\ +\Sigma\ \mathrm{Ind}\ +\Sigma\ \mathrm{Year}\ +\varepsilon_{\mathrm{it}} \quad (4)$$

In regression model (2) & (3), $\mathrm{M_{it}}$ represents the mediator variables, the total effect of digital transformation on supply chain efficiency is equal to $\mathrm{b_2}+\mathrm{a_1}\times\mathrm{b_1}$, $\mathrm{b_2}$ is the direct effect after considering the intermediary effect. $\mathrm{M_{it}}$ plays an indirect effect as an intermediary variable when $\mathrm{a_1}$ and $\mathrm{b_1}$ are significant. In the regression model (4), $\mathrm{M_{it}}$ represents the moderator variables, $\mathrm{M_{it}Digital_{it}}$ represents the cross-multiplier term of $\mathrm{Digital_{it}}$ and the moderator variables. If the coefficient of the main effect $\mathrm{c_1}$ and the coefficient of the cross term $\mathrm{c_2}$ are both significant, the moderating variables are demonstrated. If $\mathrm{c_1}$ and $\mathrm{c_2}$ have the same sign, it means that the moderator variable enhances the effect of digital transformation on supply chain efficiency. Conversely, if $\mathrm{c_1}$ and $\mathrm{c_2}$ have different signs, the effect will be weakened.

Variable type	Variable name	Variable symbol	Variable definition
Explanatory variable	Digital transformation	*Digital*	Ln (Frequency of Words Related to Digital Transformation + 1)
Explained variable	Inventory turnover	*SCE*	Ln [365/(Operating Costs/Average Inventory Balance)]
Control variables	Size	*Size*	Ln (Total Asset)
	Asset-Liability Ratio	*Leverage*	Total Liabilities to Total Assets
	Profitability	*ROA*	Net Income to Total Assets
	Capital Expenditure	*Capex*	(Cash paid for fixed assets, Intangible Asset and Other Long-Term Assets)/Total Assets
	Equity Concentration	*Equity Top1*	Top One Shareholder Ratio
	Cash flows from Operating Activities	*Cash*	Net Cash Flows from Operating Activities/Operating Income
	Growth Capability	*Growth*	Revenue Growth Rate
	Nature of Property	*SOE*	Value 1 if the Enterprise is a State-Owned Enterprise and 0 Otherwise
	Gross Margin	*Margin*	(Operating income—operating costs)/Operating income
	Supplier Concentration	*Supplier Top5*	Top Five Suppliers Purchase Ratio
Mediating variables	Management Capabilities	*Management Fee*	Management Expense Ratio
	External Transaction Costs	*Transaction Cost*	Sales Expense Ratio
Moderating variable	Customer Concentration	*Customer Top5*	Top Five Customers Sales Ratio

Table 1. Definition of variables.

Empirical results

Descriptive statistics

Table 2 reports the descriptive statistics of the main variables. The explained variable Supply Chain Efficiency (SCE) has a mean value of 4.582 and a standard deviation of 1.118, which illustrates that there are large differences in inventory turnover across enterprises. The mean value of the core explanatory variable digital transformation (Digital) is 1.738, the minimum and maximum values are 0.000 and 5.236, respectively, indicating that the degree of digital transformation of enterprises in China is still in the preliminary stage of development. The standard deviation is 1.384, which indicates that the degree of digital transformation of enterprises in China is not yet balanced. Moreover, the mean values of Management Capabilities (Management Fee) and External Transaction Costs (Transaction Cost) are 0.073 and 0.077, with maximum values of 0.412 and 0.546, respectively, indicating significant differences in management expense and transaction expense among enterprises. The mean value of Customer Concentration (Customer Top5) is 0.3281, with approximately one-third of sales coming from the top five customers, demonstrating the importance of customer relationships.

Benchmark regression

Table 3 reports the results of the benchmark regression of digital transformation on supply chain efficiency. Only the core explanatory variables are included in column (1) and all control variables are included in column (2). According to the results, the coefficients of Digital are all significantly negative at the 1% level, indicating that the higher the degree of digital transformation, the shorter the inventory turnover period of the enterprise, and thus the higher the supply chain efficiency. What's more, the inventory turnover period decreases by 1.03 days ($e^{0.026}$) with each percentage point increase in Digital. Meanwhile, enterprises with higher ROA, higher cash flows from operating activities and higher capital investments have relatively higher supply chain efficiency. In conclusion, the empirical results confirm that digital transformation has a significant contribution to supply chain efficiency, and H1 is verified.

Endogeneity test

To avoid the problem of endogeneity, this paper draws on[28] to use the instrumental variable method for testing. To be more specific, the mean value of the digital transformation in each province in each year (Digital_mean) is used as the instrumental variable. The reason lies is because the province where the enterprise is located may have different degrees of digitalization, which further affects the supply chain efficiency differently. For instance, a high degree of digital transformation in the province indicates that enterprises in that province pay more attention to digitalization, which causes their supply chain efficiency to be more affected. Table 4 reports the results of the two-stage least squares (2SLS) estimation of the instrumental variable, and the test justifies the instrumental variable. The first stage regression results in column (1) of Table 4 shows that the coefficient of Digital_mean is significantly positive at the 1% level, confirming that the choice of instrumental variable is valid and satisfies the correlation requirement. Therefore, the significant effect of digital transformation on supply chain efficiency still holds after considering the endogeneity issue.

Robustness test

Changing the measurement of digital transformation

Digital technology is an important part of enterprise intangible assets; therefore, digital intangible assets can reflect the overall level of digital transformation. In this paper, the ratio of digital intangible assets to the total amount of intangible assets is used to re-measure the core explanatory variable. The regression results in column (1) of Table 5 shows that the coefficient of the ratio of digital intangible assets (Intangible Asset)

Variables	Sample size	Mean	Median	Standard deviation	Minimum	Maximum
SCE	14,556	4.582	4.634	1.118	0.402	7.807
Digital	14,556	1.738	1.609	1.384	0.000	5.236
Size	14,556	22.303	22.079	1.321	19.905	26.472
Leverage	14,556	0.404	0.395	0.199	0.053	0.897
ROA	14,556	0.039	0.041	0.072	−0.424	0.230
Capex	14,556	0.050	0.037	0.047	0.000	0.239
Equity Top1	14,556	0.331	0.307	0.146	0.041	0.740
Cash	14,556	0.110	0.101	0.167	−0.593	0.693
Growth	14,556	0.300	0.111	0.771	−0.697	6.138
SOE	14,556	0.287	0.000	0.452	0.000	1.000
Margin	14,556	0.307	0.272	0.185	−0.034	0.883
Supplier Top5	14,556	0.342	0.301	0.194	0.016	0.918
Management Fee	14,556	0.073	0.058	0.059	0.007	0.412
Transaction Cost	14,556	0.077	0.037	0.103	0.000	0.546
Customer Top5	14,556	0.340	0.285	0.236	0.002	0.975

Table 2. Descriptive statistics of variables.

Variables	(1) SCE	(2) SCE
Digital	−0.026***	−0.047***
	(−3.95)	(−7.47)
Size		0.00
		(0.40)
Leverage		−0.059
		(−1.05)
ROA		−2.203***
		(−14.42)
Capex		−1.744***
		(−10.90)
Equity Top1		−0.302***
		(−6.07)
Cash		−0.522***
		(−7.68)
Growth		0.116***
		(9.05)
SOE		−0.045**
		(−2.41)
Margin		1.855***
		(26.71)
Supplier Top5		−0.125***
		(−2.80)
Constant	4.965***	4.678***
	(45.43)	(25.91)
Industry/Year fixed effect	Control	Control
Observations	14,556	14,556
r2_a	0.43	0.50

Table 3. Benchmark regression results. *Note.* ***, ** and * respectively indicate that the parameter estimation is significant at the levels of 0.01, 0.05 and 0.1.

is significantly negative at the 5% level, indicating that the impact of digital transformation on supply chain efficiency improvement is robust.

Changing the measurement of supply chain efficiency
Supply chain efficiency also includes the operating cycle in the supply chain's time dimension (Kojima et al., 2008; Wang et al., 2020). It is the period when enterprise purchases, sales and recovery cash. Based on this, this paper re-measures the explained variable using the natural logarithm of the business cycle (lnOperation). The formula for the operating cycle is prepayment cycle + inventory cycle + accounts receivable cycle. The regression results in column (2) of Table 5 shows that the coefficient of Digital is significantly negative at the 1% level, indicating that the shorter the net operating cycle, the higher the supply chain efficiency. Therefore, the basic conclusion that the digital transformation significantly contributes to the supply chain efficiency is robust.

Higher order fixed effects
The cross-multiplier terms of year (Year) and segment industry (ind) are added to the testing model, and the results are shown in column (3) of Table 5. The coefficients of the cross-multiplier terms are all significantly negative at the 1% level, indicating a robust and reliable conclusion.

Time lag effect test
It takes a certain amount of time for enterprise digitalization construction from input to final use and resulting impact. So, the degree of enterprise digital transformation is regressed one period lagged to verify the time lag. Table 5 column (4) shows that the coefficient of the lagged one period variable L.Digital is significantly negative at the 1% level, which demonstrates that the time lag effect of digital transformation empowering supply chain efficiency is significant.

Reducing sample size
If enterprises do not undergo digital transformation, their impact on supply chain efficiency cannot be detected. By removing the value of zero of digital transformation, the number of observations is reduced to 11,347. Column (5) of Table 5 shows that the coefficient of digital transformation is significantly negative at the 1% level, which suggests that the screened-out data have a significant effect on supply chain efficiency.

Variables	(1) First stage regression Digital	(2) Second stage regression SCE
Digital		−0.222***
		(−3.47)
Digital_mean	0.341***	
	(12.07)	
Size	0.172***	0.034**
	(19.00)	(2.56)
Leverage	0.054	−0.054
	(0.86)	(−1.11)
ROA	−0.488***	−2.302***
	(−3.29)	(−19.14)
Capex	−1.570***	−2.000***
	(−7.63)	(−10.85)
Equity Top1	−0.066	−0.312***
	(−1.01)	(−6.23)
Cash	−0.409***	−0.595***
	(−6.81)	(−11.10)
Growth	0.036***	0.121***
	(2.92)	(12.40)
SOE	−0.169***	−0.075***
	(−7.26)	(−3.57)
Margin	0.530***	1.956***
	(7.54)	(29.84)
Supplier Top5	−0.627***	−0.236***
	(−12.42)	(−4.20)
Constant	−2.895***	4.229***
	(−12.23)	(17.27)
Industry/Year fixed effect	Control	Control
Observations	14,556	14,556
r2_a	0.427	0.472

Table 4. Endogeneity test. *Note.* ***, ** and * respectively indicate that the parameter estimation is significant at the levels of 0.01, 0.05 and 0.1.

In summary, the conclusions of this paper remain robust.

Mediator effect test

This paper uses management capabilities as the mediating variable. The management capabilities variable is measured by the management expense ratio (Management Fee), which is the ratio of management expenses to operating income. The smaller the value of this indicator, the less the enterprise spends on management and the higher the level of enterprise management. As shown in column (1) and column (2) in Table 6, the coefficients of management capabilities are both significantly negative at the 1% level, meaning that the lower the management expense ratio, the greater the role of digitalization. It is indicated that the digital transformation can improve the supply chain efficiency by reducing the management expenses, optimizing the management process, and improving the overall management capabilities, which is consistent with the expectation of H2a.

In addition to this, this paper also uses external transaction costs as a mediating variable. External transaction costs are measured by the sales expense ratio (Transaction Cost), which is the ratio of sales expenses to operating income. The larger the value of this indicator, the higher the enterprise's marketing expenditures and the higher the transaction costs. As shown in columns (3) and (4) of Table 6, the coefficients of transaction costs are both significantly positive at the 1% level, meaning that the higher the marketing expense ratio, the greater the effect of digitalization. This suggests that digital transformation can improve supply chain efficiency by increasing marketing expenses, increasing transaction costs, and improving overall marketing, which is consistent with the expectation of H2b.

Moderator effect test

Customer concentration (Customer Top5) is the ratio of the top five customers sales to the annual sales. It reflects the degree of dependence on customers, which implies the measurement of relationship embeddedness[29]. Therefore, this paper draws on[30] to consider the impact of customer concentration on the relationship between digital transformation and supply chain efficiency. The regression results in Table 7 show that the

	(1)	(2)	(3)	(4)	(5)
Variables	**SCE**	**InOperation**	**SCE**	**SCE**	**SCE**
Digital		−0.069***	−0.045***		−0.046***
		(−10.30)	(−5.84)		(−5.45)
L.Digital				−0.038***	
				(−5.29)	
Intangible Asset	−0.107**				
	(−1.99)				
Size	−0.01	0.037***	0.00	0.01	−0.001
	(−1.31)	(5.14)	(0.28)	(0.55)	(−0.14)
Leverage	−0.093	0.721***	(0.06)	−0.137**	−0.017
	(−1.57)	(13.09)	(−0.98)	(−2.08)	(−0.26)
ROA	−2.084***	−2.047***	−2.230***	−2.563***	−2.139***
	(−12.85)	(−14.21)	(−12.49)	(−14.64)	(−12.14)
Capex	−1.845***	−0.650***	−1.825***	−1.615***	−1.949***
	(−10.61)	(−3.89)	(−7.56)	(−8.72)	(−10.30)
Equity Top1	−0.305***	−0.031	−0.296***	−0.295***	−0.311***
	(−5.83)	(−0.62)	(−3.43)	(−5.00)	(−5.41)
Cash	−0.484***	−0.120**	−0.510***	−0.449***	−0.477***
	(−6.46)	(−2.01)	(−5.54)	(−5.60)	(−6.11)
Growth	0.131***	0.063***	0.116***	0.130***	0.118***
	(9.80)	(5.44)	(5.94)	(8.54)	(8.43)
SOE	−0.03	0.116***	(0.04)	−0.046**	−0.044**
	(−1.58)	(6.30)	(−1.39)	(−2.16)	(−2.06)
Margin	1.780***	2.743***	1.869***	1.889***	1.751***
	(23.08)	(43.55)	(12.72)	(23.56)	(21.26)
Supplier Top5	−0.116**	−0.124***	−0.138*	−0.099*	−0.066
	(−2.45)	(−2.80)	(−1.79)	(−1.89)	(−1.32)
Constant	4.934***	3.102***	4.408***	4.683***	4.838***
	(26.19)	(16.72)	(20.48)	(21.56)	(23.58)
Industry/Year fixed effect	Control	Control	Control	Control	Control
Observations	13,237	14,556	14,543	9,960	11,347
r2_a	0.50	0.41	0.52	0.53	0.49
F	291.50	132.60	45.72	236.90	272.60

Table 5. Robustness test. *Note*. ***, ** and * respectively indicate that the parameter estimation is significant at the levels of 0.01, 0.05 and 0.1.

regression coefficient of the cross-multiplier term through digital transformation and customer concentration (Digital*Customer) is 0.001, which is significant positive at the 5% level, indicating that customer concentration plays a negative moderating role in the promotion of digital transformation on supply chain efficiency. In other words, customer concentration reduces the investment in digitalization construction, then inhibits the digital transformation's impact on supply chain efficiency, which is consistent with the expectation of H3.

Heterogeneity analysis

The degree of digital technology application varies across enterprises, and there are also large differences in supply chain characteristics across industries; therefore, this paper examines whether there are heterogeneous effects of digital technology on supply chain efficiency at the enterprise level and the industry level, respectively. According to the 2012 version of the SEC's industry classification standards, this paper divides the 19 industry categories into three categories, supply chain-sensitive industries, supply chain-insensitive industries, and other industries. Based on Hypothesis 4, this paper takes the following four industries--manufacturing + wholesale and retail + transportation + information technology as supply chain-sensitive industries. Apart from that, the supply chain-insensitive industries are four industries--agriculture, forestry, animal husbandry, fishery + mining + construction + water conservancy, environment, and public facility management. The rest of the industries are other industries. Columns (1)-(3) of Table 8 indicate the results of grouped regressions according to different industries. It is demonstrated that the digital transformation of industries that are supply chain-sensitive are significantly negative at the 1% level, while those supply chain-insensitive industries are not significant. This suggests that supply chain-sensitive industries like manufacturing, wholesale and retail trade, transportation, warehousing and postal services, and information transmission, software and information technology services are more likely to be affected by digital transformation, which facilitates effective integration

Variables	(1) Management fee	(2) SCE	(3) Transaction cost	(4) SCE
Digital	−0.002***	−0.042***	0.006***	−0.041***
	(−6.06)	(−6.80)	(13.28)	(−6.56)
Management Fee		2.180***		
		(9.59)		
Transaction Cost				−0.868***
				(−5.59)
Size	−0.007***	0.019**	−0.002***	0.001
	(−17.05)	(2.51)	(−3.42)	(0.20)
Lev	−0.032***	0.01	0.031***	−0.032
	(−8.86)	(0.21)	(7.21)	(−0.57)
ROA	−0.381***	−1.372***	−0.317***	−2.478***
	(−32.54)	(−8.28)	(−23.91)	(−15.01)
Capex	0.01	−1.759***	−0.126***	−1.853***
	(0.81)	(−11.08)	(−10.45)	(−11.47)
Equity Top1	−0.021***	−0.257***	0.015***	−0.289***
	(−8.25)	(−5.18)	(4.14)	(−5.80)
Cash	−0.029***	−0.459***	−0.080***	−0.591***
	(−5.88)	(−6.87)	(−15.00)	(−8.43)
Growth	0.002**	0.112***	−0.004***	0.112***
	(2.22)	(8.76)	(−5.32)	(8.74)
SOE	0.007***	−0.059***	−0.004***	−0.049***
	(6.89)	(−3.19)	(−3.61)	(−2.61)
Margin	0.137***	1.557***	0.355***	2.163***
	(31.35)	(21.23)	(51.14)	(22.53)
Supplier Top5	−0.013***	−0.098**	−0.011***	−0.135***
	(−5.17)	(−2.18)	(−3.59)	(−3.01)
Constant	0.247***	4.139***	0.030**	4.704***
	(21.46)	(22.26)	(2.43)	(26.06)
Industry/Year fixed effect	Control	Control	Control	Control
Observations	14,556	14,556	14,556	14,556
r2_a	0.48	0.51	0.672	0.501
F	85.20	381.60	161.00	304.60

Table 6. Mediator effect test. *Note.* ***, ** and * respectively indicate that the parameter estimation is significant at the levels of 0.01, 0.05 and 0.1.

of digitalization with business operations and further improves their supply chain efficiency, which is consistent with the expectation of H4a.

Additionally, large enterprises usually have stable upstream and downstream channels, they are more capable to ensure that the industrial supply chain is not blocked or interrupted in the face of uncertainty[31]. Because of that, this paper uses the median enterprise size as the division criterion, samples are divided into large and small enterprises to analyze the heterogeneous impact. Columns (4)-(5) of Table 8 show the results of grouped regressions according to different enterprise sizes. The result shows that the heterogeneity effects of both large and small-sized enterprises are both significantly negative at the 1% level. The coefficients for large enterprises and small enterprises are close, −0.059 and −0.031, respectively. Then the Bootstrap method is used 1,000 times to obtain the "empirical value of p" to test the significance of the coefficient difference between the groups. The empirical p-value obtained by Bootstrap method is 0.000, which is significant at 1% level, indicating that the digital transformation of large enterprises is more effective in improving supply chain efficiency, which is consistent with the expectation of H4b.

Discussion

By selecting the data of A-share listed enterprises from 2019 to 2022, this paper empirically tests the relationship between digital transformation, management capabilities, external transaction costs and supply chain efficiency, and examines the moderating role of customer concentration. To make up for the shortcomings of previous scholars' research, this paper selects inventory turnover period as the entry point for supply chain efficiency research. The results show that digital transformation can significantly enhance supply chain efficiency by enhancing overall management capabilities and increasing external transaction costs, ultimately improving

Variables	(1) SCE
Digital × Customer	0.065**
	(2.47)
Digital	−0.045***
	(−7.20)
Customer Top5	0.122***
	(3.18)
Size	0.01
	(0.89)
Leverage	−0.054
	(−0.96)
ROA	−2.209***
	(−14.45)
Capex	−1.773***
	(−11.03)
Equity Top1	−0.305***
	(−6.12)
Cash	−0.519***
	(−7.65)
Growth	0.113***
	(8.85)
SOE	−0.045**
	(−2.41)
Margin	1.871***
	(26.97)
Supplier Top5	−0.157***
	(−3.42)
Constant	4.580***
	(25.34)
Industry/Year fixed effect	Control
Observations	14,556
r2_a	0.50
F	286.60

Table 7. Moderator effect test. *Note.* ***, ** and * respectively indicate that the parameter estimation is significant at the levels of 0.01, 0.05 and 0.1.

supply chain efficiency. When examining the moderating effect of customer concentration, it weakens the effect of digital transformation on supply chain efficiency.

Distinguished from previous studies that examined how digital transformation affects supply chain efficiency from the perspectives of information asymmetry[32], supply chain transparency and supply chain agility[33], this paper selects the management expense ratio and sales expense ratio, two internal factors of enterprises, as the research path of supply chain bar efficiency. Digital transformation has optimized management processes and improved management capabilities, promoting overall management improvements, as reflected in lower management expense ratios. And improvements in inventory management have enabled enterprises to manage their supply chains more efficiently, ultimately improving supply chain efficiency. In addition, digital transformation expands marketing by increasing external transaction costs, which is reflected in higher sales expense ratios. This helps enterprises accurately understand customer preferences and match market demand, thereby strengthening market strategy arrangements, ultimately reducing inventory turnover days and improving supply chain efficiency. Besides that, few scholars have considered the moderating role of customer concentration in the relationship between digitization and supply chain efficiency, and the research in this paper confirms that the higher the customer concentration, the greater the negative impact of digital transformation on the enhancement of supply chain efficiency. Therefore, enterprises should appropriately reduce overhead rates and diversify customer concentration.

Conclusions and suggestions

In the background of the rapid construction in digital economy, digital society and digital government, the digitalization and supply chain are in the progress of optimization. This paper empirically examines the effect of digital transformation on supply chain efficiency and its transmission mechanism by 2019–2022 financial data

Variables	(1) Supply chain-sensitive industries SCE	(2) Supply chain-insensitive industries SCE	(3) Others SCE	(4) Large-sized enterprises SCE	(5) Small-sized enterprises SCE
Digital	−0.038***	0.00	−0.118***	−0.059***	−0.031***
	(−6.52)	(0.10)	(−3.51)	(−6.49)	(−3.62)
Size	−0.017**	0.05	0.107***	0.01	0.01
	(−2.45)	(1.30)	(3.07)	(1.19)	(0.51)
Leverage	−0.093*	−0.529**	0.38	0.01	−0.096
	(−1.72)	(−2.20)	(1.46)	(0.16)	(−1.51)
ROA	−2.156***	−5.050***	−0.861	−2.612***	−1.949***
	(−14.62)	(−6.60)	(−1.13)	(−14.46)	(−13.77)
Capex	−1.190***	−4.098***	−7.758***	−2.612***	−0.999***
	(−7.87)	(−4.56)	(−7.52)	(−10.94)	(−5.01)
Equity Top1	−0.343***	−0.823***	−0.126	−0.526***	−0.170**
	(−7.28)	(−3.57)	(−0.53)	(−7.93)	(−2.41)
Cash	−0.699***	0.543*	−0.290**	−0.512***	−0.620***
	(−9.17)	(1.78)	(−2.09)	(−7.81)	(−9.92)
Growth	0.110***	0.170***	0.079***	0.098***	0.119***
	(7.74)	(3.12)	(3.31)	(7.43)	(9.08)
Margin	1.983***	1.343***	1.480***	2.049***	1.801***
	(28.83)	(3.55)	(5.51)	(25.32)	(25.95)
Supplier Top5	−0.161***	−0.334	0.28	−0.028	−0.227***
	(−3.84)	(−1.20)	(1.45)	(−0.50)	(−4.28)
Constant	4.810***	4.679***	0.71	4.334***	4.589***
	(29.87)	(5.86)	(0.85)	(14.90)	(11.09)
Industry/Year fixed effect	Control	Control		Control	Control
Observations	12,194	999	1,363	7,263	7,293
r2_a	0.45	0.36	0.65	0.58	0.40
F	339.30	32.50	174.00	117.10	57.22
Experienced p-value				0.000***	

Table 8. Heterogeneity analysis. *Note.* ***, ** and * respectively indicate that the parameter estimation is significant at the levels of 0.01, 0.05 and 0.1.

of A-share listed enterprises. It is found that digital transformation contributes to the growth of supply chain efficiency. Furthermore, digitalization can improve supply chain efficiency by increasing external transaction costs and enhancing the overall management capabilities. Meanwhile, customer concentration plays a negative moderating role in this promotion. Heterogeneity analysis shows that the impact of digital transformation depends on the industries' supply chain sensitivity and enterprises' sizes. The impact of digital transformation on supply chain efficiency is more significant for enterprises in supply chain-sensitive industries, such as manufacturing industry, wholesale and retail industry, transportation industry, and information technology industry. What's more, the digital transformation of large-scale enterprises is more likely to improve supply chain efficiency. Based on the above findings, this paper makes recommendations from the following two aspects.

At the corporate level, enterprises must seize opportunities to enhance digitalization, and core enterprises should leverage the digital empowerment among supply chain. However, it is important to recognize that overlaying digital technologies does not simply improv supply chain efficiency. Instead, it requires continuous exploration and adjustment of the transformation process to achieve the gradual integration of digital technologies with management capabilities, market expansion, and other dimensions. Additionally, enterprises can establish inventory management systems with the assistance of digital technologies, which play a crucial role in enhancing inventory operational efficiency and improving supply chain efficiency eventually.

At the policy level, government should continuously promote digital implementation and emphasize the strategic importance of core enterprises in promoting collaboration among supply chains. Furthermore, industry heterogeneity should be fully considered, the promotion of digital transformation must be customized according to different industries. Specifically, the government support supply chain-insensitive industries by applying digital technologies, enabling more enterprises to benefit from digitalization and enhance the efficiency of supply chain collaboration.

Data availability

All the data used in this paper are openly available from China Stock Market and the Accounting Research (CSMAR) database and for more details on the website: [https://data.csmar.com/].

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References

1. Michela, M. et al. Digital transformation and customer value creation in Made in Italy SMEs: A dynamic capabilities perspective. *J. Bus. Res.* **123**, 642–656. https://doi.org/10.1016/j.jbusres.2020.10.033 (2021).
2. Chen, X. M. & Wu, M. The Value of Reputation in Trade: Evidence from Alibaba. *Rev. Econ. Stat.* **103**(5), 1–45. https://doi.org/10.1162/rest_a_00932 (2020).
3. Firk, S. et al. Chief digital officers: An analysis of the presence of a centralized digital transformation role. *J. Manag. Stud.* https://doi.org/10.1111/joms.12718 (2021).
4. Marcus, F. et al. Strategy archetypes for digital transformation: Defining meta objectives using business process management. *Inform. Manag.* **57**(5), 103262–103262. https://doi.org/10.1016/j.im.2019.103262 (2020).
5. Brynjolfsson, E. & Mcelheran, K. Digitization and Innovation The Rapid Adoption of Data-Driven Decision-Making. *Am. Econ. Rev.* https://doi.org/10.1257/aer.p20161016 (2016).
6. Goldfarb, A. & Tucker, C. Digital Economics. *J. Econ. Lit.* **57**(1), 3–43. https://doi.org/10.1257/jel.20171452 (2019).
7. Bi, S. et al. Can " Zero waste city" policy promote green technology? Evidence from econometrics and machine learning. *J. Environ. Manage.* **370**, 122895 (2024).
8. Isaksson, H. O., Simeth, M. & Seifert, W. R. Knowledge spillovers in the supply chain: Evidence from the high tech sectors. *Res. Policy* **45**(3), 699–706. https://doi.org/10.1016/j.respol.2015.12.007 (2016).
9. Verhoef, C. P. et al. Digital transformation: A multidisciplinary reflection and research agenda. *J. Bus. Res.* https://doi.org/10.1016/j.jbusres.2019.09.022 (2019).
10. Cannon, R. A. Inventory improvement and financial performance. *Int. J. Prod. Econ.* **115**(2), 581–593. https://doi.org/10.1016/j.ijpe.2008.07.006 (2008).
11. Capkun, V., Hameri, A. P. & Weiss, L. A. On the relationship between inventory and financial performance in manufacturing companies. *Int. J. Oper. Prod. Manage.* **29**(8), 789–806. https://doi.org/10.1108/01443570910977698 (2009).
12. Zahran, K. S. & Jaber, Y. M. Investigation of a consignment stock and a traditional inventory policy in a three-level supply chain system with multiple-suppliers and multiple-buyers. *Appl. Math. Model.* **44**, 390–408. https://doi.org/10.1016/j.apm.2017.01.084 (2017).
13. Gunasekaran, A., Subramanianm, N. & Papadopoulos, T. Information Technology for competitive advantage within logistics and supply chains: A Review. *Transp. Res. Part E* **99**, 14–33. https://doi.org/10.1016/j.tre.2016.12.008 (2016).
14. Cenamor, J., Sjödin, R. D. & Parida, V. Adopting a platform approach in servitization: Leveraging the value of digitalization. *Int. J. Prod. Econ.* **192**, 54–65. https://doi.org/10.1016/j.ijpe.2016.12.033 (2016).
15. Wang, G. et al. Big data analytics in logistics and supply chain management: Certain investigations for research and applications. *Int. J. Prod. Econ.* **176**, 98–110. https://doi.org/10.1016/j.ijpe.2016.03.014 (2016).
16. Lu, Q. & Xu, X. Adaptable Blockchain-Based Systems: A Case Study for Product Traceability. *IEEE Softw.* **34**(6), 21–27. https://doi.org/10.1109/MS.2017.4121227 (2017).
17. Lafarre, A. & Christoph, V. D. E. Blockchain Technology for Corporate Governance and Shareholder Activism. *Soc. Sci. Electron. Publish.* https://doi.org/10.2139/ssrn.3135209 (2023).
18. Coase, R. H. The nature of the firm. *Economica* **4**(16), 386–405 (1937).
19. Williamson, O. E. *The Economic Institutions of Capitalism* (Free Press, 1985).
20. Carter, C. R., Kosmol, T. & Kaufmann, L. Toward a supply chain practice view. *J. Supply Chain Manag.* **53**(1), 114–122 (2017).
21. Rajaguru, R. & Matanda, M. J. Effects of inter-organizational compatibility on supply chain capabilities: Exploring the mediating role of inter-organizational information systems (IOIS) integration. *Ind. Mark. Manage.* **42**(4), 620–632 (2013).
22. Gerwin, D. & Meister, D. Coordinating new product development in an international joint venture. *Int. J. Technol. Manage.* https://doi.org/10.1016/S0167-6636(97)00050-1 (2002).
23. Wang, J. Do firms' relationships with principal customers/suppliers affect shareholders' income?. *J. Corp. Finance* **18**(4), 860–878 (2012).
24. Gerwin, D. Coordinating New Product Development in Strategic Alliances. *Acad. Manage. Rev.* **29**(2), 241–257 (2004).
25. Wu, A., Wang, Z. & Chen, S. Impact of specific investments, governance mechanisms and behaviors on the performance of cooperative innovation projects. *Int. J. Project Manage.* **35**(3), 504–515. https://doi.org/10.1016/j.ijproman.2016.12.005 (2016).
26. Shirley, C. & Winston, C. Firm inventory behavior and the returns from highway infrastructure investments. *J. Urban Econ.* **55**(2), 398–415. https://doi.org/10.1016/j.jue.2003.11.001 (2003).
27. Chu, Y., Tian, X. & Wang, W. Corporate Innovation Along the Supply Chain. *Manage. Sci.* **65**(6), 2445–2466. https://doi.org/10.1287/mnsc.2017.2924 (2019).
28. Erickson, T. Constructing Instruments for Regressions with Measurement Error When No Additional Data Are Available: Comment. *Econometrica* https://doi.org/10.1111/1468-0262.00185 (2001).
29. Uzzi, B. & Gillespie, J. J. Knowledge spillover in corporate financing networks: embeddedness and the firm's debt performance. *Strat. Manag. J.* **23**(7), 595–618. https://doi.org/10.1002/smj.241 (2002).
30. Zhong, W. et al. Customer Concentration, Executive Attention, and Firm Search Behavior. *Acad. Manag. J.* https://doi.org/10.5465/amj.2017.0468 (2020).
31. Hosseini, S. et al. Resilient supplier selection and optimal order allocation under disruption risks. *Int. J. Prod. Econ.* **213**, 124–137. https://doi.org/10.1016/j.ijpe.2019.03.018 (2019).
32. Yu, Z. et al. Does digitalization improve supply chain efficiency?. *Financ. Res. Lett.* **67**, 105822. https://doi.org/10.1016/j.frl.2024.105822 (2024).
33. Wang, J., Cui, L. & Xu, M. Impact of digital transformation on supply chain efficiency: a parallel mediation model. *J. Organ. Chang. Manag.* **37**(5), 945–964. https://doi.org/10.1108/JOCM-10-2023-0411 (2024).

Author contributions

Ms. Zhen is responsible for the organization and collection of data, as well as the overall idea structure. She is also responsible for conceptualizing the overall framework and methodology of the study, and ensuring that the study is scientific and innovative. Ms Shang is responsible for collecting and reviewing relevant literature, providing theoretical background and existing research basis for the study, and participating in the writing of the paper.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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