How does digital technology innovation enhance firm value? A dual route model

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This study was partially funded by the National Natural Science Foundation of China (72303168)

Abstract: Differs to digital innovation, which is application-oriented of digital technologies, digital technology innovation focuses on developing and creating new digital technologies (creation-oriented). Thus, digital technology innovation forms the foundation of digital innovation. Increasingly, firms, especially those in manufacturing, are recognizing the crucial role of digital technology innovation in shaping their intangible value. In order to determine whether digital technology innovation can enhance firm value and the specific mechanism involved, this study draws on patent data (the fields of digital technology are defined based on IPC) and annual report data of listed manufacturing firms in China to reveal the specific relationship between digital technology innovation and the enhancement of firm value. We find that that digital technology innovation can make a significant contribution to firm value; more important, the relationships between digital technology innovation and lowering costs, upgrading efficiency can be characterized as an inverted U-shaped pattern and a U-shaped pattern, respectively. These results hold after the several robustness checks. Additional analyses show that these relationships differ significantly across types of state ownership, firm size, and location feature. Finally, our mechanism analysis suggests that lowering costs and upgrading efficiency driven by digital technology innovation is a key component of the value-enhancing effect. Overall, this study offers

theoretical insights into value enhancement at firm level through digital technology innovation, as well as practical guidance for firm and society looking to embrace digital technology innovation.

Keywords: Digital technology innovation; firm value; lowering costs; upgrading efficiency; nonlinear relationship.

1. Introduction

The current economic society has entered the digital economy age, the development and application of digital technology are changing across aspects of society such as products' forms, organizational structures, and even overturned traditional innovation theories (Hylving and Schultze, 2020; Yoo et al., 2010). With the infiltration and integration of various digital technologies and components into the process of business models transformation derived from digital technology innovation are emerging constantly, greatly expanding the functions, significance, and connotations of innovation management in the traditional sense (Llopis-Albert, Rubio, & Valero, 2021; Verhoef et al., 2021). Such integration of digital technology has surpassed the boundaries of traditional innovation management theories, and the increasing digitalization of organizational processes presents new challenges for understanding the continually emerging technological innovation models (Hanelt et al., 2021;). At the same time, the business, cooperation, and competition models of firm organization are undergoing profound changes. Therefore, digital technology innovation is receiving more and more attention from both the academic and society communities.

The creation of digital technology and its integration with the process of industrial innovation is a fundamental characteristic of digital technology innovation (Wiesböck,and Hess, 2020). Through such creation and integration, different knowledge communities and technological resources, can be brought together to produce new digital technology-driven products and services. Emerging digital

technology breaks through spatial and social-technical limitations, reduces the resource threshold for innovation, and as the foundation of digital innovation (Saarikko et al., 2020), such as virtual teams, open forums, or crowdsourcing forms. Consequently, digital technology innovation has improved connectivity between innovation participants, resource utilization efficiency, and transparency in the innovation process through the sharing of technology and knowledge, as well as effective use of digital components. For example, Twitter (a communication platform for innovation participants) and YouTube (a knowledge sharing platform) both provide interfaces and channels for obtaining digital innovation. In addition, digital technology innovation is not only limited to software products. For instance, General Electric and Procter & Gamble have co-established innovative forms to quickly and efficiently discover new product ideas and solutions (Von Hippel, 2009). IBM's Innovation Jams is a crowdsourcing innovation platform enabled by digital technology (Majchrzak and Malhotra, 2013).

In general, digital technology innovation and digital innovation are two closely related terms. However, there are some differences between the two that are worth noting. On the one hand, digital technology innovation means that the creation and development of new digital technologies or the improvement of existing ones (Ciarli et al., 2021; Fitzgerald et al., 2014). It refers to use of digital tools, processes, and systems to drive business growth, reduce costs, and increase efficiency. Examples of digital technology innovation include the development of new hardware, software, or communication technologies. Digital technology innovation often involves significant research and development efforts. Digital innovation is a broader term, on the other hand, that refers to the application of digital technology into business models and strategies to create new market opportunities (Cheng and Wang, 2022; Nambisan et al., 2017). Accordingly, while both digital technology innovation and digital innovation involve the integration of digital technology, the focus and scope of each are different.

Digital technology innovation focuses on developing and refining technologies, while digital innovation is a broader term that encompasses the transformation of businesses and industries through the use of digital technology. Based on these discussions, this study posits that digital technology innovation is fundamental and original, and digital innovation is application-oriented and focuses on the output of digital technology innovation (see Figure 1). Therefore, the focus of this study is digital technology innovation.

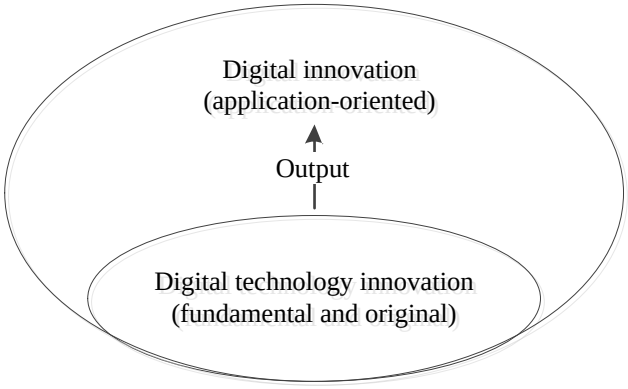

Figure 1. The differences between digital technology innovation and digital innovation

Previous studies have explored the value-capture problem of digital innovation (Autio et al., 2018). However, whether innovation in digital technology can enhance firms value is remaining to be explored. In particular, social change conducted by digital technology innovation will be a complex issue (Zhuo and Chen, 2023). In this study, we focus on two aspects, including lowering costs and upgrading efficiency. As the aforementioned, the originality and foundational characteristics of digital technology innovation make it difficult to observe immediate benefits in terms of firms' costs and efficiency. Accordingly, the relationships between digital technology innovation and lower costs and upgrading efficiency may be non-linear, whereas there is no research to examine such non-linear relationships. In addition, the mechanisms of lowering costs and upgrading efficiency between digital technology innovation and firm value enhancement also remain underdeveloped.

To address the research gaps, drawing on firm-level data in China manufacturing

industry, firstly, this study argues that firms value can benefit from digital technology innovation. Secondly, we posit that the effect of digital technology innovation on lowering costs and upgrading efficiency is nonlinear. Thirdly, we argue that a firm's value can be enhanced through digital technology innovation not only by adopting digital technology innovations to reduce its costs, but also by improving its internal operational efficiency. Thus, our conceptual framework is shown in Figure 2.

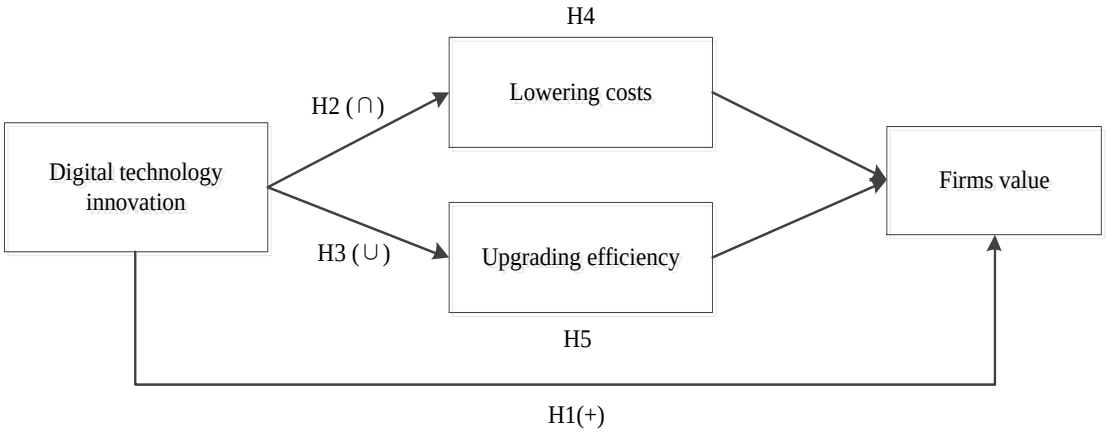

Figure 2. Conceptual framework.

Accordingly, this study makes several contributions. First, extant literature has mainly documented that firms should embrace digital innovation (Liu et al., 2023; Nambisan et al., 2017). We provide a well understanding of the difference between digital technology innovation and digital innovation; meanwhile, the linking conducting digital technology innovation and firm value is also examined. Second, regarding social change, lowering costs and upgrading efficiency are proposed to further explore the underlying mechanism of the digital technology conduction-value relationship. Third, we join the discussion of nonlinear effects of digital technology innovation on lowering costs and upgrading efficiency; that is, the conduction of digital technology innovation is a long-term process, this observation extends understanding of the role digital technology innovation plays in the firm value enhancement.

2. Comparison between digital innovation and digital technology innovation

As mentioned before, digital technology and digital innovation are the two main concepts. These two concepts are two interrelated concepts that have become increasingly important in our modern world, especially with the emergence of the digital economy (Li et al., 2020). The relationship between digital technology and digital innovation is a close one, as digital innovation relies heavily on digital technology. Without digital technology, digital innovation would not be possible, as it provides the tools and infrastructure needed to develop and implement innovative ideas.

Digital innovation can be broadly defined as a novel innovation form which relies on the combination and application of digital technology and then result in digital objects that deliver value to individuals or organizations (Cheng and Wang, 2022; Sanasi et al., 2020). On one hand, studying digital innovation is mainly focuses on how digital-enabled arrangements arise in varying fields or organizations (Hinings et al., 2018). This idea particular concern the interplay between existing and new emerging organizational arrangements (Agostini et al., 2020; Dougherty and Dunne, 2011), that is, implying the new arrangements replace or complement existing ones. For example, Airbnb and traditional hotel coexisting in the tourism industry. In addition, the existing arrangements can also enable new ones. For example, the Uber platform in USA or DiDi platform in China is a new form that disrupts the existing taxi industry. This digital innovation creates a novel form regarding existing taxi services by applying digital technology (Gerwe, 2021; Morton et al., 2022; Nambisan Wright & Feldman, 2019). On the other hand, existing research has confirmed that digital innovation refers to the implication of information technology (IT) for structuring and managing innovation within organizations (Hensen & Dong, 2020; Kohli & Melville, 2019). In recent, increasingly scholars have emphasized the central role of IT in creating innovation opportunities and outcomes (Bhimani et al., 2019; Wei et al., 2022). IT-based digital innovation pays attention to the digitalization of technology and concerns about the involvement of IT components in the individual or organizational innovation process

and outcomes.

Digital technology innovation means that the development and creation of new digital technologies (Ciarli et al., 2021; Fitzgerald et al., 2014). Differs to digital innovation level, digital technology innovation pays attention to how digital technology is developed and created, leading to improvements in efficiency and quality (Litvinenko, 2019), it thus is often conduct by changing non-digital technology innovation from to digital fields. Meanwhile, it is changing the nature of existing technology innovation, as it creates new opportunities for non-digital technology fields. Moreover, digital technology innovation is reshaping markets and industries, with some firms and industries being disrupted while others are able to leverage digital technology for competitive advantage (Rogers and Euchner, 2022). The impact of digital technology innovation can be seen in various industries. In the healthcare industry, digital technology has revolutionized the way healthcare services are delivered. Patients can now access healthcare services remotely, and healthcare providers can access patient information electronically, which has improved the quality of care and reduced costs. In the finance industry, digital technology has changed the way we do business. Customers can now access banking services from anywhere, and businesses can accept payments online, which has improved efficiency and reduced costs.

To sum up, digital technology innovation and digital innovation are two distinct concepts that have different impacts on various industries. Digital technology innovation is essential for driving digital innovation. Without digital technology innovation, there would be no new digital products, services, or business models. Digital technology innovation enables digital innovation by providing the necessary infrastructure and tools for achieving digitalization performance (Beltagui et al., 2020; Teece, 2018).

3. Hypotheses development

3.1 Digital technology innovation and firm value

To date, digital technology is beneficial in promoting the integration of production elements and emerging technologies, breaking the resource boundaries of tangible production elements, and upgrading of industrial structure (Leng et al., 2019). As data has become a new production element, it has penetrated into various aspects of firm value creation and value acquisition (Li, 2020; Sjödin et al., 2021). The ability for firms to accurately acquire and analyze internal and external data with the help of digital technology has become the key to making the right decisions and seizing opportunities. Digital technology has improved computing capabilities, developed data mining, analysis, and storage abilities, making it possible for data to flow quickly and for massive amounts of information to be analyzed. This helps firms alleviate information asymmetry, optimize internal processes, thereby improving productivity (Manita et al., 2020). In addition, digital technology can accelerate the digitization process and the improvement of corporate performance will inevitably spill over to the firm value level. Thus, we propose our core hypothesis:

H1. Digital technology innovation will enhance firm value.

3.2 Digital technology innovation and lowering costs: an inverted U-shaped pattern

Existing literature indicated that technological innovation positively related to lowering costs (Chen and Yoon, 2022; Kamau et al., 2019). The development of technology provides an excellent opportunity to reduce costs. For digital technology, it will provide more flexibility and higher efficiency in the production process for firms, and will also provide greater transparency for data generation and resource consumption, resulting in cost savings for businesses (Cagno et al., 2021). Meanwhile, digital technology will also disrupt the organization and business models of traditional industries, prompting firms to reform their existing business processes and organizational management structures, effectively reducing internal and external operating costs, breaking down industry barriers, and ultimately helping them gain cost

advantages in the market.

In this study, we argument the studies by positing that digital technology innovation lowers firm costs in an inverted U-shaped pattern. On one hand, in the short term, digital technology innovation may have a negative impact on lowering costs. Because the conduction of digital technology innovation requires firms to invest the replacement of equipment and other production factors (Marchiori et al., 2022), implementing digital technology innovation often requires significant financial investments; in addition, digital technology innovation will have a substitutive effect on low-skill labour, reducing the salary expenditure of existing employees to lower operating costs. But the demand for higher-skill labour, changes in production processes, and updates to production equipment will significantly offset such cost reduction, resulting in increase in firms' costs (Acemoglu and Restrepo, 2018). Finally, the initial investment in digital technology innovation may not immediately yield significant returns on investment. On the other hand, the application of digital technology to optimize firms' organizational structure and production processes is a long-term result. Once firms deploy digital technology innovation to a certain level, it becomes more easily for them to apply mature digital technology and then reduce costs. Meanwhile, as digital technology innovation increases, firms can proactively identify market fluctuations, effectively reducing errors in predicting future demand, while also gaining a deeper understanding of relevant marketing information and reducing external coordination costs. Therefore, after digital technology innovation exceeds a certain level, it opens up an opportunity of cost-saving for firm. On this basis, this study put forward the hypothesis below:

H2. The relationship between digital technology innovation and lowering costs characterized by an inverted U-shaped pattern.

3.3 Digital technology innovation and upgrading efficiency: a U-shaped pattern

Previous studies have suggested that the technological innovation has an important impact on varying domains, such as promoting the optimization and economic growth

(Cheng et al., 2021; Maradana et al., 2017). In the current study, the importance of digital technology innovation is gradually highlight in a high level of efficiency upgrading of firm, which is the inevitable result of the digital economy. However, for firms, digital technology innovation is not something that can be achieved overnight. A significant investment in the early stages may decrease the efficiency of the firms. Only after a certain degree has been reached will the improvement of efficiency become evident. Thus, we argument the literature by suggesting that digital technology innovation affects firm efficiency upgrading in a U-shaped way.

In the initial stages, affected by competitive effect, digital technology innovation may lead to decreased efficiency towards firms. The competitive effect refers to more resources are invested in one profitable activity (e.g., digital technology innovation), less resources are invested in other firm activities (e.g., purchasing new equipment and advertising) (Jia, 2020; Randrianasolo and Semenov, 2022). Due to limited resources, a firm cannot evenly allocate them into all profitable activities. The increase resources in investment in digital technology innovation, the decrease in investment in other activities. Such adjustment of resources allocation may disrupt the balance of efficiency of firms, and then reduces firm efficiency.

In the long term, synergic effect (Ma and Yasir, 2023) of digital technology innovation dominate, firms can achieve organic matching and effective integration of various resources, optimizing resources allocation easily through methods, such as precision marketing with big data in the production process, flow process, and marketing process, promoting precise matching between supply and demand of resources (Aceto et al., 2020), and then enhances operational and management efficiency. In accordance with the discussions above, this study hypothesizes that:

H3. The relationship between digital technology innovation and upgrading efficiency typified by a U-shaped pattern.

3.4 Channel effects

Drawing on the above hypotheses, this study further explores the mechanisms of lowering costs and upgrading efficiency between digital technology innovation and firm value. As the above discussion, the empowering effect of digital technology innovation on promoting high-quality development of firms are first manifested in lowering costs and upgrading efficiency. Through the innovation of digital technology, firms are able to streamline their operations and optimize resources. Meanwhile, by leveraging digital technology innovation, they can also increase agility and flexibility in responding to changing market conditions and customer needs. This enables them to stay competitive and adapt quickly to industry disruptions. Furthermore, digital technology innovation provides a firm with more accurate and timely data, allowing them to identify new growth opportunities. Overall, digital technology innovation leads to the reduction of costs and inefficiencies, and thus promoting firms value. Therefore, this propose that:

H4. Lowering costs mediates the positive relationship between digital technology innovation and firm value.

H5. Upgrading efficiency mediates the positive relationship between digital technology innovation and firm value.

4. Methodology

4.1 Data collection

In this study, manufacturing firms are used as our sample selection for the following reasons: (1) digital technology innovation allows manufacturers to strengthen their competitive edge. By introducing innovative products and services, firms can differentiate themselves from their competitors and capture new markets; (2) digital transformation has become a critical global topic for the manufacturing industry (Vogelsang et al., 2018), digital technology is a core part of manufacturing firms' digital transformation strategies.

Our sample data include manufacturing firms listed on the Shanghai and Shenzhen

stock exchanges from 2012 to 2021 (As of now, a part of firms have not yet released their annual report for 2022, so this study does not contain data for 2022). We collected data on these firms from two main sources: patent data, obtained from the China National Intellectual Property Administration (CNIPA), and financial data, obtained from the Chinese Stock and Market Accounting Research (CSMAR). To ensure data accuracy and consistency with prior studies (Xu et al., 2022), we excluded several categories of firms: (1) special treatment (ST or *ST) firms; (2) delisted firms; (3) firms with incomplete data. Meanwhile, all of the continuous variables are winsorized at 1% and 99% in order to reduce outliers effect. Finally, our sample data consist of 18,140 firm-year observations.

4.2 Measures

4.2.1 Dependent variable

Firm value (*Firm_value*): existing literature has mainly adopted Tobin's Q to measure firm value (Liu et al., 2023). Following this logistic, this study also uses the annual Tobin's Q to measure the value of firm.

4.2.2 Independent variable

In this study, we measure digital technology innovation from patents perspective. In practice, patents have long been recognized as a valid indicator of innovation in practice (Sasaki and Sakata, 2021; Singh et al., 2021), we thus have utilized the IPC code to identify specific technological fields. Prior studies have indicated that digital technology is closely related to IT (Ciarli et al., 2021; Si et al., 2022), following this logic, this study selects ten IPC codes (4-digit level) (e.g., G06C, G06F, G06K, G06N, G06Q, G06T, G11B, H03H, H03M, H04L) that are relevant to IT fields to represent digital technology areas. For example, G06C is described as "digital computer for mechanical"; thus, it is appropriate to be used to determine a patent whether belong to digital technology innovation or not.

To measure digital technology innovation (*Digital_tech_inn*), we count the number

of patents that belong to the digital technology fields in year *t* to measure it. In practice, a patent may hold multiple IPC codes, whereas the patent is assigned a unique code known as the IPC focal classification code (in general, it is the first-ranked), which is used to organize and retrieve the primary technical field of the patent (Harris et al., 2010). Drawing on this, we can determine whether a patent is digital technology innovation by distinguishing whether the focal IPC code belongs to the fields of digital technology.

4.3.3 Meditator variables

To understand the internal mechanism of digital technology innovation on firm value, this study employs two meditator variables, including lowering costs (*Costs*) and upgrading efficiency (*Efficiency*). We use the logarithm number of a firm's operation costs to measure *Costs* (Kong et al., 2020). In addition, efficiency usually can be measured as a ratio of output to input (Sarkis, 2000). Following prior literature (Li et al., 2019), *Efficiency* constructed by using DEA. Sales revenue as the output indicator, and six input indicators used are as follows: (1) R&D expenditure; (2) selling and administrative expenditure; (3) net intangible assets; (4) net inventory; (5) net fixed assets and (6) net goodwill. Empirically, MaxDEA 8 Basic software is applied to calculate to the efficiency.

The summary statistics are shown in Table 1. We also include several control variables such as firm size (*Size,* the logarithm number of a firm's employees) and age (*Age,* the logarithm number of years since the firm was listed), ROA, R&D. Furthermore, VIF values of independent, meditator and control variables is between 1.021 and 5.510, which are all below 10. Hence, we conclude that multicollinearity is not a severe issue.

Table 1. Summary statistics

Variable	Mean	SD	Min	Max	VIF
Firm_value	2.176	1.312	0.798	8.379	

Digital_tech_inn	1.657	1.548	0	9	1.313
Costs	9.661	2.418	0.000	21.505	2.440
Efficiency	0.215	0.163	0.000	0.651	2.601
Size	21.681	1.164	17.779	27.486	1.929
Age	2.746	0.0419	0.631	4.241	2.154
ROA	0.041	0.062	-0.203	0.512	2.681
R&D	0.101	0.181	0.000	0.682	1.696
Ownership	0.294	0.406	0	1	5.510
Leverage	0.368	0.177	0.038	0.776	4.456
HHI	0.220	0.265	0.010	0.876	3.503

4.3.5 Model specification

To test the impact of digital technology innovation on firm value, we construct the following benchmark regression model:

$$Firm\_value_{i,t+1} = \beta_0 + \beta_1 Digital\_tech\_inn_{i,t} + \beta_2 Control_i + Year_i + Regional_i + \varepsilon \quad (1)$$

Where $Year_i$, $Regional_i$, represent year-fixed effects and regional-fixed effects, respectively.

Second, to test the non-linear effect of digital technology innovation on lowering costs and upgrading efficiency, the model is specified as follows:

$$Costs_{i,t+1}/Efficiency_{i,t+1} = \beta_0 + \beta_1 Digital\_tech\_inn_{i,t} + \beta_2 Digital\_tech\_inn_{i,t}^2 \beta_3 Control_i + Year_i + Regional_i + \varepsilon \quad (2)$$

Third, the following models, described by Baron and Kenny (1986) and Li et al. (2023), are established to explore the internal mechanism of digital technology innovation:

$$Firm\_value_{i,t+1} = \beta_0 + \beta_1 Digital\_tech\_inn_{i,t} + \beta_2 Control_i + Year_i + Regional_i + \varepsilon \quad (3)$$

$$Costs_{i,t+1}/Efficiency_{i,t+1} = \beta_0 + \beta_1 Digital\_tech\_inn_{i,t} + \beta_2 Control_i + Year_i + Regional_i + \varepsilon \quad (4)$$

$$Firm\_value_{i,t+1} = \beta_0 + \beta_1 (Costs_{i,t+1}/Efficiency_{i,t+1}) + \beta_2 Control_i + Year_i + Regional_i + \varepsilon \quad (5)$$

$$Firm\_value_{i,t+1} = \beta_0 + \beta_1 Digital\_tech\_inn_{i,t} + \beta_2 (Costs_{i,t+1}/Efficiency_{i,t+1}) + \beta_3 Control_i + Year_i + Regional_i + \varepsilon \quad (6)$$

5. Empirical results

5.1 Main regression

In this study, generalized least squares (GLS) model at firm-fixed level is used to examine our hypotheses. As shown in Table 2, first, the result of only independent variable is included in column (1) indicates that when a firm performs digital technology innovation, its firm value would be enhanced. In column (2), control variables are added; meanwhile, the double fixed effects of year and regional are also controlled. We can see that the estimated coefficient of *Digital_tech_inn* passes the test at the 1% confidence level, which revalidates the positive role of digital technology innovation in firm value. Thus, H1 is supported. The results of column (3) show that *Digital_tech_inn* is positive and significant, whereas *Digital_tech_inn*^{2} is negative and significant. These results confirm an inverted U-shaped pattern for the relationship between digital technology innovation and lowering costs, corroborating H2. Similarly, regarding upgrading efficiency, *Digital_tech_inn* is negative and significant, whereas its squared term is positive and significant (as shown in column (4)). A U-shaped pattern emerged from the estimation of the digital technology innovation and upgrading efficiency, implying that the latter decreases at the initial stage of digital technology innovation investment, but progressively increases as conduction exceeds a certain level. This finding lends to support to H3.

Table 2. Regression results

Dependent variable	*Firm_value*		*Costs*	*Efficiency*
	(1)	(2)	(3)	(4)

Digital_tech_inn	0.269***	0.053***	0.104***	-0.151***
	(5.80)	(3.73)	(5.11)	(-4.90)
Digital_tech_inn^2			-0.025***	0.017***
			(-4.29)	(3.78)
Size		0.119***	0.097**	0.036*
		(8.23)	(2.07)	(1.77)
R&D		0.101***	0.057***	0.035**
		(5.18)	(5.20)	(2.20)
Age		0.072**	0.094*	0.051
		(2.13)	(1.81)	(0.81)
HHI		0.000	0.010	0.002
		(0.57)	(0.79)	(1.02)
Ownership		0.081***	-0.073***	-0.051
		(3.35)	(-3.07)	(-1.17)
ROA		0.001*	0.002***	0.005***
		(1.83)	(3.62)	(4.26)
Leverage		0.201***	0.157**	0.129*
		(4.18)	(2.34)	(1.84)
Constant	4.399***	3.368***	5.816***	-4.117***
	(6.41)	(7.59)	(4.48)	(5.31)
Year-fixed	No	Yes	Yes	Yes
Regional-fixed	No	Yes	Yes	Yes
Observations	18,140	16,937	16,937	16,937
R^2	0.270	0.549	0.401	0.451

Notes: All reported t-statistics in parentheses are adjusted for clustering at firm level; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$ levels, respectively. Same below

5.2 Mechanism analysis

Column (2) in Table 3 reports that the impact of lowering costs and upgrading efficiency on firm value is significantly negative and positive, respectively. Column (3) in Table 3 is involved to test the indirect effects, indicating that the conduction of digital technology innovation can reduce costs and improve efficiency, and in turn enhance firm value. Thus, H4 and H5 are supported. Furthermore, the Sobel tests (*Costs*: Z=1.97,$\rho < 0.05$; *Efficiency*: Z=2.89,$\rho < 0.01$) confirm the existence of the channel effects.

Table 3. Mechanism analysis results

	(1)	(2)		(3)		(4)	
	Step 1: X→Y	Step 2: X→M		Step 3: M→Y		Step 4:X,M→Y	
	Firm_value	*Costs*	*Efficiency*	*Firm_value*		*Firm_value*	
Digital_tech_inn	0.053***	-0.017***	0.031**			0.051***	0.029**
	(3.73)	(-4.42)	(2.28)			(3.52)	(2.40)
Costs				-0.073**		-0.011***	
				(2.65)		(-3.66)	
Efficiency					0.024***		0.015***
					(2.99)		(3.04)
Size	0.119***	0.280***	0.191***	0.090***	0.187***	0.056***	0.088*
	(8.23)	(2.90)	(3.36)	(3.13)	(2.93)	(2.70)	(1.79)
R&D	0.101***	0.096***	0.101***	0.109***	0.020***	0.043*	-0.008
	(5.18)	(6.36)	(4.15)	(6.99)	(3.98)	(1.87)	(-0.24)
Age	0.072**	0.023*	0.018***	0.019*	0.073***	0.013*	0.047***
	(2.13)	(1.83)	(3.29)	(1.71)	(3.83)	(1.80)	(3.01)
HHI	0.000	0.052	0.006*	0.005	0.000	-0.000	0.011**
	(0.57)	(1.33)	(1.82)	(0.97)	(0.12)	(-0.00)	(2.41)
Ownership	0.081***	0.045***	0.062***	-0.036**	0.029***	0.006	0.038**
	(3.35)	(3.00)	(3.03)	(-2.33)	(5.25)	(0.29)	(2.71)

ROA	0.001*	0.004***	0.000	0.001***	0.008***	-0.003	0.005
	(1.83)	(2.70)	(0.91)	(4.88)	(4.07)	(-0.36)	(0.47)
Leverage	0.201***	-0.030	0.107***	0.157***	0.167***	0.185**	0.208***
	(4.18)	(-0.96)	(2.83)	(4.15)	(7.21)	(2.21)	(3.94)
Year-fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Regional-fixed	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16,937	16,937	16,937	16,937	16,937	16,937	16,937
R^2	0.549	0.314	0.325	0.761	0.693	0.456	0.481

5.3 Robustness checks

In the main analysis, we have confirmed that digital technology innovation can help enhance firms value and its internal mechanism. In order to validity the results' reliability, this study conducts several robustness checks as follows:

First, ROA has been widely used to measure a firm's market performance (Liu et al., 2023), we use it as the alternative operationalization of firm value. We re-estimated our models and find strong support for our main findings (As shown in Table 4).

Second, changing in the external policy environment can trigger adjustments to the development strategy of firms. In 2017, the term "digital economy" was first included in the government work report in China. Firms that went listed in A-share after 2017 are more likely to place more emphasis on digital technology innovation than those prior to 2017, which may result in biased estimation of results. Therefore, this paper re-estimates the sample data of firms that went listed in A-share before 2016, and the results are shown Table 5. After removing exogenous shock, digital technology innovation still significantly affects firm value, which verifies the robustness of the main regression results.

Third, whether conducting digital technology innovation or not is a spontaneous and selective decision made by a firm. Thus, there may be bias caused by self-selection.

In order to address this issue, we implement the matching technique to create a group of firms that conduct digital technology innovation (treatment group) and a group of firms that are similar to those in the treatment group but do not conduct digital technology innovation (control group). Then, we use the difference-in-difference (DID) technique as the main regression specification. To construct the treatment and control groups, we use all control variables as match specifications to derive the sample. The propensity score matching (PSM) results based on the one-on-one nearest-neighbor matching approach. Finally, digital technology innovation scale is used to discriminate the treatment group (*treat*) and the control group. If the scale in the top 20% in year t, *treat* equals 1 and 0 otherwise Then, the following model is considered the DID regression specification:

$$Firm\_value_{i,t+1} = \alpha + \beta_1 treat_{i,t} + \beta_2 post_{i,t} + \beta_3 (treat_{i,t} * post_{i,t}) + \gamma Controls_{i,t} + Year_i + Region_i + Industry_i + e_{i,t}, \quad (7)$$

where $treat_{i,t}$ is a dummy that equals 1 if firm $i's$ digital technology innovation scale is in the top 20% in year t and 0 otherwise, and $post_{i,t}$ is a time dummy variable that equals 1 if the year t is on or after the digital technology scale of firm i and 0 otherwise.

As shown in Table 6, the interaction term $treat * post$ is significant and positive, indicating that digital technology innovation can enhance the value of firm and confirming our results are reliable.

Table 4. Results of Robustness check (alternative independent variable)

	(1)	(2)		(3)	(4)	
	Step 1: X→Y	Step 2: X→M		Step 3: M→Y	Step 4:X,M→Y	
	ROA	*Costs*	*Efficiency*	*Firm_value*	*Firm_value*	
Digital_tech_inn	0.013***	-0.055**	0.049***		0.024***	0.062**
	(2.83)	(-2.35)	(3.25)		(4.13)	(2.29)
Costs				-0.041***	-0.002**	

				(3.29)		(-2.46)	
Efficiency					0.061**		0.042***
					(2.79)		(4.91)
Control variables and fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16,937	16,937	16,937	16,937	16,937	16,937	16,937
R^2	0.321	0.411	0.394	0.529	0.601	0.474	0.501

Table 5. Results of Robustness check 2 (remove data of 2017)

	(1)	(2)		(3)	(4)	
	Step 1: X→Y	Step 2: X→M		Step 3: M→Y	Step 4:X,M→Y	
	Firm_value	*Costs*	*Efficiency*	*Firm_value*	*Firm_value*	
Digital_tech_inn	0.053***	-0.034***	0.037***		0.044***	0.095**
	(2.82)	(-3.56)	(3.56)		(4.50)	(4.25)
Costs				-0.100***	-0.008*	
				(3.01)	(-1.88)	
Efficiency					0.091***	0.019**
					(4.09)	(2.56)
Control variables and fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Observations	12,213	12,213	12,213	12,213	12,213	12,213
R^2	0.306	0.393	0.357	0.491	0.476	0.439	0.471

Table 6. Results of Robustness check 3 (DID)

	(1)	(2)		(3)	(4)	
	Step 1: X→Y	Step 2: X→M		Step 3: M→Y	Step 4:X,M→Y	
	Firm_value	*Costs*	*Efficiency*	*Firm_value*	*Firm_value*	
Digital_tech_inn	0.077***	-0.021***	0.014***		0.051***	0.032**
	(4.78)	(-3.35)	(4.01)		(3.73)	(2.00)

Costs				-0.012*		-0.011*	
				(1.85)		(-1.86)	
Efficiency					0.060***		0.031***
					(3.20)		(3.52)
Control variables and fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4,560	4,560	4,560	4,560	4,560	4,560	4,560
R^2	0.351	0.293	0.400	0.392	0.500	0.436	0.501

5.4 Heterogeneity analysis

As the above discussion, the conduction of digital technology innovation can significantly enhance firm value. In fact, for microscopic attributions at the firm level, there are some differences in the conduction of digital technology innovation. For example, compared to small- and medium-sized firms, large-scale firms—with their competitive advantage in the market—are more likely to conduct digital technology innovation; thus, they are more inclined to take advantage of digital technology innovation to increase their firm value. Therefore, discussing the differences is beneficial for the differentiation of digital technology innovation strategies.

In this study, we focus on heterogeneity effects in three aspects: state ownership (*Ownership*), firm size (*Size*), and location feature (*Location*). The following moderate model is used to test the heterogeneity effects:

$$Firm\_value_{i,t+1} = \beta_0 + \beta_1 Digital\_tech\_inn_{i,t} + \beta_2(Ownership_{i,t}/Size_{i,t}/Location_{i,t}) + \beta_3 Digital\_tech\_dummy_{i,t} * (Ownership_{i,t}/Size_{i,t}/Location_{i,t}) + \gamma Controls_{i,t} + Year_i + Region_i + Industry_i + e_{i,t}, \quad (8)$$

Where *Ownership* equals 1 denotes a firm is state-owned (otherwise, it equals 0); *Size* equals 1 denotes a firm belongs to large-scale (otherwise, it equals 0); *Location* equals 1 denotes the location of a firm in eastern China (otherwise, it equals 0)

First, we conduct the heterogeneity effects on firm value. Column (1) in Table 7 reports that non-state firms are more likely to leverage digital technology innovation to enhance their firm value. On the on hand, state-owned firms, with monopoly rights in the market and outright subsidization from the government (Din et al., 2021), have less motivation to the conduction of digital technology innovation. On the other hand, non-state firms without endorsement from government (Zhou et al., 2017), considering the comparative advantage of market competition, they are more motivated to leverage digital technology innovation to enhance their firm value. Column (2) in Table 7 shows that large-scale firms are more motivated to innovative in digital technology compared to small- and medium-sized firms. Due to large-scale firms hold natural advantages in gathering information and resources, as a result, they are more likely to invest effort and time in digital technology innovation. Column (3) reveals that those firms located in central and western China are more willing to conduct digital technology innovation to enhance their firm value. Due to the disadvantage of geographical location, firms in central and western China have fallen behind those in eastern regions. Therefore, they are more eager to enhance their market competitiveness through digital technology innovation.

Table 7. Heterogeneity regression results (firm value as independent variable)

	Firm_value		
	(1)	(2)	(3)
Digital_tech_inn	0.037***	0.058***	0.077***
	(4.29)	(5.79)	(4.54)
Ownership	-0.026		
	(0.77)		
Digital_tech_inn * *Ownership*	-0.035*		
	(-2.07)		
Size		0.105***	

		(6.07)	
Digital_tech_inn Size*		0.017**	
		(2.25)	
Location			0.199***
			(5.51)
Digital_tech_inn Location*			-0.029**
			(-2.01)
Control variables and fixed effect	Yes	Yes	Yes
Observations	16,937	16,937	16,937
R^2	0.552	0.534	0.600

Second, we examine the heterogeneity effects on the two nonlinear relationships. Following the processes of Ma and Yasir (2023), the results of columns (1) to (3) in Table 8 reveal that state ownership, firm size, and location feature positive moderate the inverted U-shaped relationship between digital technology innovation and lowering costs, suggesting non-state firms, small and medium firms and firms located in central and western China will amplify the nonlinear relationship. That is, the negative effect of digital technology innovation on lowering costs at low levels of digital technology innovation and the positive effect of digital technology innovation on lowering costs at high levels of digital technology innovation will both be weaker for state-owned firms, large scale firms, and firms located in eastern China. Similarly, columns (4) to (6) in Table 8 show that state ownership, firm size, and location feature do negatively moderate the U-shaped relationship between digital technology innovation and upgrading efficiency, suggesting non-state firms, small and medium firms and firms located in central and western China will amplify the U-shaped relationship. That is, the negative effect of digital technology innovation on upgrading efficiency at low levels of digital technology innovation and the positive effect of digital technology

innovation on upgrading efficiency at high levels of digital technology innovation will both be weaker for state-owned firms, large scale firms, and firms located in eastern China. furthermore, to facilitate these two interpretations, we plot the nonlinear relationships in Figures 3 and 4.

Table 8. Heterogeneity regression results (nonlinear relationship)

	Costs			*Efficiency*		
	(1)	(2)	(3)	(4)	(5)	(6)
Digital_tech_inn	-0.013**	-0.007***	-0.023***	0.007***	0.010***	0.002**
	(-2.29)	(-3.21)	(-4.00)	(3.51)	(4.12)	(2.40)
Digital_tech_inn^2	-0.009***	-0.011*		0.012***	0.009**	0.020**
	(-2.91)	(-1.82)		(3.00)	(2.70)	(2.35)
Ownership	-0.026*			-0.006**		
	(-1.77)			(2.11)		
Digital_tech_inn^2*	0.016**			-0.004***		
Ownership	(2.45)			(-3.09)		
Size		0.002*			0.000	
		(1.87)			(1.01)	
Digital_tech_inn^2*		0.009**			-0.017*	
Size		(2.51)			(-1.79)	
Location			-0.050***			0.004
			(-4.23)			(0.87)
Digital_tech_inn^2*			0.014***			-0.019***
Location			(2.91)			(-3.31)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed	Yes	Yes	Yes	Yes	Yes	Yes
Regional-fixed	Yes	Yes	No	Yes	Yes	No
Observations	16,937	16,937	16,937	16,937	16,937	16,937

R^2	0.311	0.361	0.401	0.356	0.413	0.400

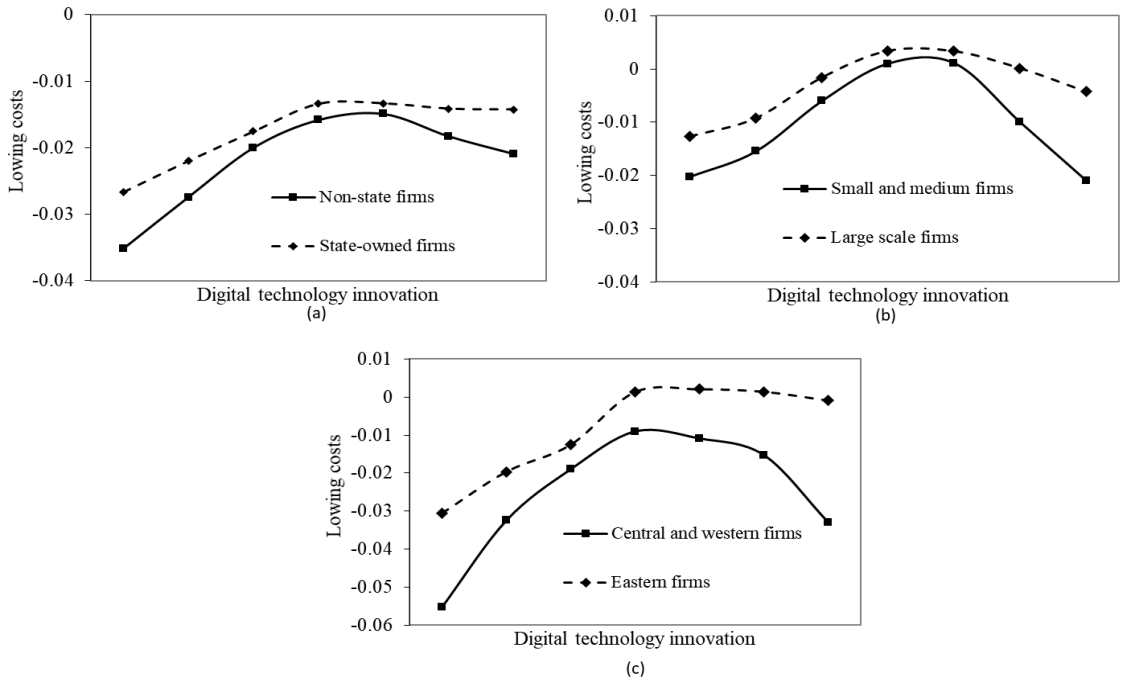

Figure 3. The inverted U-shaped relationship between digital technology innovation and lowering costs.

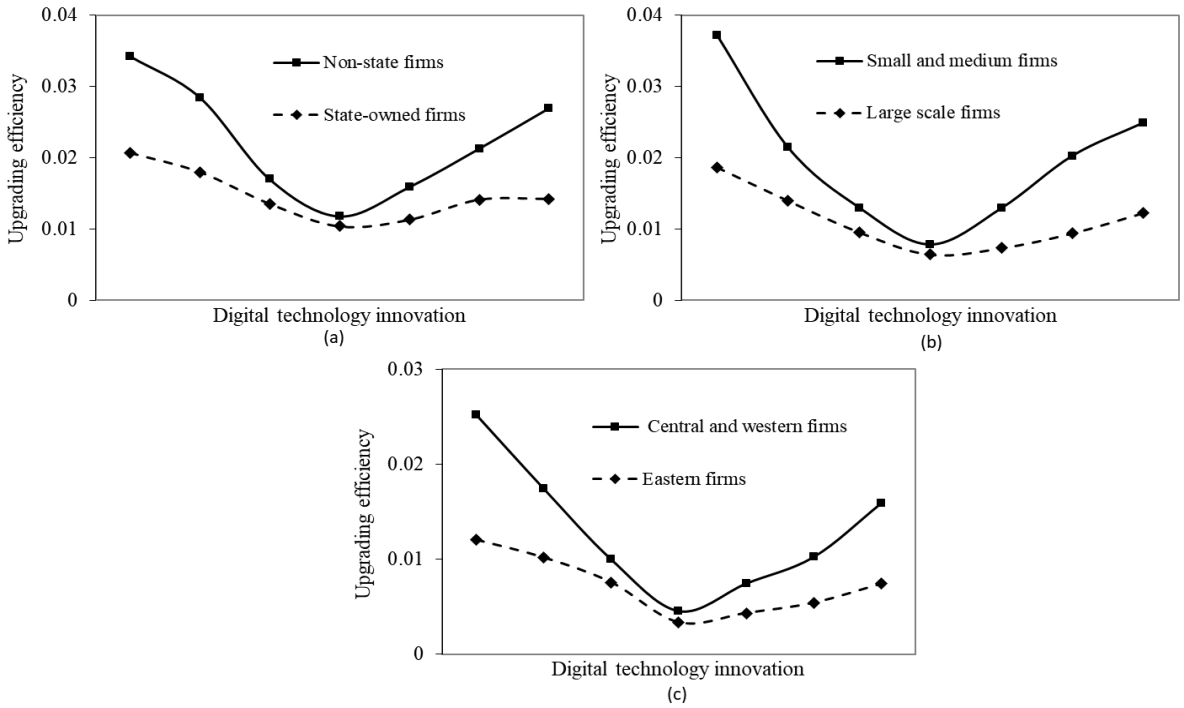

Figure 4. The U-shaped relationship between digital technology innovation and

upgrading efficiency.

6. Discussion

6.1 Main findings

This paper explores the effect of digital technology innovation on firm value. Research on digital innovation has mostly discussed it from theoretical and broadly perspective (Kohli and Melville, 2019), while there is lacks of empirical study. Compared to digital innovation, digital technology innovation is originality-oriented and foundation-oriented in the digital era, firm can enhance its value with the help of digital technology innovation. Constructing a multi-source sample data, including patent document and annual report from listed manufacturing firms in China, we demonstrate the positive effect of digital technology innovation on firm value enhancement and further explores its internal mechanism. The following findings as found:

First, we find that digital technology innovation enhances firm value. By leveraging digital technology, firms collect and analyze vast amounts of data that can inform decision-making (Modgil et al., 2021). Thus, digital technology innovation provides various opportunities to boost productivity, streamline operations, and enhance customer experiences. Firms can gain a competitive edge by conducting digital technology innovation to make informed decisions, automate processes, identify areas for improvement, and ultimately enhance their value. In addition, this study also finds that the varying degree of firm size, firm ownership, and regional characteristics can result in differences in the role of digital technology innovation in firm value. In detail, compared with state-owned firms, digital technology innovation has a greater enhancing effect on the value of non-state firms. Meanwhile, this difference is equally applicable to large scale firms as well as small and medium-sized firms.

Second, digital technology innovation is found to exert nonlinear effect on lowering costs and upgrading efficiency. Previous studies have suggested that the

development of digital technology can lower firms' costs and improve their efficiency from a linear perspective (Björkdahl, 2020; Zhai et al., 2022). Our finding is inconsistent with existing literature, and confirms that the effect of digital technology innovation on lowering costs and upgrading efficiency typified by an inverted U-shaped pattern and a U-shaped pattern respectively. This is understandable given that digital technology innovation is a long-term process, it requires substantial investment in the initial phase, and leads to an increase in the costs for firms. However, as the innovation reaches a certain level, investment reduces gradually, resulting in a decrease in the costs. Similarly, in the initial stage, the development and application of digital technology may not be mature, which could lower the efficiency of firms to some extent. However, as it gradually matures, it will quickly upgrade the efficiency of firms. The heterogeneity results reveal that the three characteristics, including state ownership, firm size, and location, positively moderate the inverted U-shaped relationship of lowering costs and negatively moderate the U-shaped relationship of upgrading efficiency.

Third, the mechanism analysis shows that digital technology innovation can lower firm's costs and upgrade its efficiency, and indirectly improves the value of firm. The conduction of digital technology innovation can automate many repetitive and time-consuming tasks, freeing up firm to focus on more value-added activities, reducing the need for manual labor and the associated costs; ultimately enhance firm value. In addition, digital technology innovation can facilitate better and more streamlined communication, improve coordination, and also enable more precise tracking and analysis of a wide variety of business metrics, both within firms and with their customers and suppliers. This makes it easier to identify areas of inefficiency and opportunities for enhancement of firm value.

6.2 Implications for theory and practice

Our study makes three important theoretical implications. First, from a definition

perspective, we highlight there are distinct differences between digital technology innovation and digital innovation. Digital technology innovation is a fundamental innovation activity of various digital technologies, and digital innovation is mostly achieved through the application of digital technology to innovate enterprise operational processes and business models. Accordingly, this study concludes that digital technology innovation leans more toward the theoretical level, while digital innovation leans more toward the practical level. Second, this study provides empirical insights into digital technology innovation research from a patent perspective. Existing literature on digital technology innovation has mainly paid attention to conceptualization research (Ciarli et al., 2021; Si et al., 2022; Sorescu and Schreier, 2021), whereas little studies have investigated how to measure digital technology innovation. In this study, we innovatively use patents as a measure. Drawing on the IPC of patents, which is usually used to symbolize technological fields, this study defines a IPC list about digital technology fields, and then this list is applied to discriminate whether an innovation is digital-related or not. Consequently, this study provides a novel method for measuring digital technology innovation; furthermore, the patent perspective presents this method has a good generalization and it can be applied to other academic domains. In addition, we build a positive relationship between digital technology innovation and firm value, and use an unbalanced panel data of manufacturing firms in China to test this relationship. This study fills the research gap on lack of empirical study on this topic. Third, further, we perform a mechanism analysis by lowering costs and upgrading efficiency, such mediation model unpacks the black box of the impact of digital technology innovation on firm value, offering a more comprehensive understanding regarding the internal mechanism of digital technology innovation how to work. More important, this study suggests that digital technology innovation exerts nonlinear effect on lowering costs and upgrading efficiency, which provides a nuanced perspective in understanding the effect of digital technology

innovation that enhancing firm value, and indicates that there are differences in the enhancement effect.

This study offers additional practical implications. First, firms, manufacturing firms in particular, should embrace digital technology innovation. In today's world, digital technology innovation plays a crucial role for businesses. The increasing dependency on digital technology has led to the development of new business models and customer experiences. Second, increasing investment in digital technology innovation to promote the manufacturing firm's digital transformation as soon as possible. Digital technology innovation has positive spill-over effects, based on its permeability, substitutability, and synergy features, as well as its mechanisms for lowering costs and upgrading efficiency, developing digital technology can accelerate the transformation and upgrading of firms. Third, non-state firms or small- and medium-sized firms could see digital innovation as a way to enhance their competitiveness against large scale firms or stated-own firms, as varying digital technologies can streamline business processes and improve productivity.

6.3 Limitations and future aspects

This study has also several limitations that call for future research directions. First, China differs from developed countries regarding digitalization (Beier et al., 2017; Wen Zhong & Lee, 2022). Therefore, we cannot confirm the generalizability of our findings to other countries with varying levels of digitalization. Future research could attempt to explore the contingent effect of digital technology innovation in other countries. Second, due to the limited data, we did not conduct instrumental variable analysis to mitigate potential endogeneity concerns. Thus, future research could explore instrumental variables to correct for endogeneity bias. Third, regarding the classification of digital technology fields, we just use IT-related IPC codes to symbolize them, we have to acknowledge it has disadvantages. Future research could study other measurement methods.

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