The Impact of Digital Economy on Technological Innovation of Manufacturing Enterprises from the Perspective of Virtual Agglomeration: Evidence from China

Qing ZHANG*, Shaofeng RU and Zhengnan ZHAO

School of Economics and Management, Northwest University, Xi'an, China; zq05271995@163.com; rsf00@163.com; zenonzhao@126.com

* Corresponding author: zq05271995@163.com

Abstract: As China enters the era of digital economy, it is of great significance to study the influence of digital economy on technological innovation of manufacturing enterprises. This paper measures the level of digital economy and virtual agglomeration of industry in about 30 provinces (municipalities and autonomous regions) in China except for Tibet and makes an empirical study with the data of listed manufacturing companies from 2012 to 2020. The results show that digital economy can improve the output and efficiency of technological innovation of manufacturing enterprises, but this promoting effect is only significant in the eastern and central regions, non-large manufacturing enterprises, and non-state-owned enterprises. The testing results of the mechanism show that the digital economy merely promotes the technological innovation output of manufacturing enterprises by accelerating the virtual agglomeration of industrial specialization and diversification, but does not improve the efficiency of technological innovation of manufacturing enterprises. In the future, China should accelerate the development of the digital economy. Manufacturing enterprises should accelerate the pace of digital transformation. And the government and manufacturing enterprises should jointly accelerate the construction of industrial Internet platforms for enhancing the spillover effect of technological innovation resources.

Keywords: digital economy; virtual agglomeration; technological innovation of manufacturing enterprises

JEL Classification: L60; O14; O32

1. Introduction

80% of China's technological innovation is generated by manufacturing enterprises. Therefore, accelerating the technological innovation of manufacturing enterprises is an important way to enhance the scientific and technological strength of the nation. In 2021, the added value of China's manufacturing industry reached 31.4 trillion yuan, ranking first in the world for 12 consecutive years, but manufacturing enterprises are still facing problems such as weak technological innovation and "stuck neck" technology being controlled by others, so it is urgent to find new momentum for technological innovation of manufacturing enterprises. The development of the digital economy not only accelerates the digital

transformation of technological innovation which includes methods, models, management, processes, and results, but also enables manufacturing enterprises to achieve cross-regional and cross-organizational communication, reduces the cost of information search and acquisition, enhances the spillover effect of knowledge and technology, and enhances the allocating efficiency of technological innovation resources. This new pattern of shifting manufacturing enterprises from geographical agglomeration to network agglomeration is called a new organizational form of virtual agglomeration, including specialized and diversified virtual agglomeration. Compared with the form of geographic agglomeration, virtual agglomeration not only changes the resource allocation mode and efficiency of economic activities by accelerating knowledge spill, but also avoids the problems of land scarcity, traffic congestion, and environmental pollution caused by geographical agglomeration, and reduces the congestion effect of agglomeration.

So, will the digital economy promote technological innovation of manufacturing enterprises, and is there heterogeneity in this promotion? Does the digital economy promote technological innovation of manufacturing enterprises through virtual agglomeration? Clarifying the above issues is of great significance to enhance the technological innovation capabilities of manufacturing enterprises in the context of the digital economy.

Therefore, this paper integrates the digital economy, virtual agglomeration, and technological innovation of manufacturing enterprises into the same framework, and uses the listed company data of manufacturing enterprises and provincial panel data in China from 2012 to 2020 to carry out research. Based on measuring the level of specialized and diversified virtual agglomeration, the two-way fixed model is used to test the impact effect of digital economy on the technological innovation of manufacturing enterprises, and the heterogeneity analysis of manufacturing enterprise samples of different industries, regions, enterprise sizes and equity types is carried out. Then, the mediation effect model is used to test the influence mechanism of specialized and diversified virtual agglomeration.

2. Literature Review

2.1. The Impact of the Digital Economy on the Technological Innovation of Manufacturing Enterprises

Some scholars studied the impact of the digital economy on the technological innovation of manufacturing enterprises. The digital economy brought new digital technologies to manufacturing enterprises, accelerated the flowing and sharing of knowledge and technological resources, and contributed to technological innovation among manufacturing enterprises (Tommaso et al., 2021; Christian et al.,2022). The digital economy created a favorable institutional environment for the technological innovation of manufacturing enterprises, realized the transparency of market information, and expanded the main body of enterprise technological innovation into a diversified innovation organization composed of the government, enterprises, universities, and users. In addition, there was heterogeneity in the role of the digital economy in promoting technological innovation of manufacturing enterprises, and the role of digital economy in promoting technological innovation of

knowledge- and technology-intensive manufacturing enterprises were more significant (Zheng et al., 2022). The above literature analyzed the impact of the digital economy on the technological innovation of manufacturing enterprises from the perspective of the external environment and internal technological innovation subjects of enterprises, however, the analysis of other factors affecting the technological innovation of manufacturing enterprises needs to be supplemented.

2.2. Virtual Agglomeration

At present, the literature on virtual agglomeration mainly includes three categories. The first is to define the connotation of virtual agglomeration. Considering virtual agglomeration is a new organizational form, in which multiple enterprises in or between industries gather on the network platform for information interchange and cooperation, and there were no time and space constraints on the platform (Brown & Lockett, 2001). The second is to summarize the advantages of virtual agglomeration. The network platform supporting virtual agglomeration was operated in a community-based mode, shortening the psychological distance between enterprises through formal and informal systems in digitally networked communities, and promoting enterprise exchanges (Muzzi & Albertini, 2015). The third is to measure the level of virtual agglomeration. By using the method of sharing movement, Zhao et al. (2022) calculated the penetration of digital services as a measurement indicator of the virtual agglomeration level of manufacturing, which the data required for the calculation include the input-output data of OECD and the first census of industrial enterprises in China. The existing literature only measured the level of virtual agglomeration of manufacturing specialization. In fact, in addition to specialized virtual agglomeration, the diversified virtual agglomeration of manufacturing enterprises and productive service industries will also have an important impact on technological innovation.

2.3. The Impact of the Digital economy on the Technological Innovation of Manufacturing Enterprises through Virtual Agglomeration

A small number of scholars conducted their studies by combining digital economy, virtual agglomeration, and technological innovation of manufacturing enterprises. The development of a new generation of information technology provided support for a technical platform for the virtual agglomeration of manufacturing enterprises and accelerated the aggregation of decentralized capabilities of innovation. Manufacturing enterprises accelerated the transfer of knowledge through acquisition, absorption, and integration of technological innovation resources, to improve the level of technological innovation (Alsharo et Al., 2017; Zhang and Ren, 2018; Feng, 2018). Chen et al. (2022) constructed an analysis framework including intelligent services, factor agglomeration, and regional innovation, and concludes that intelligent services can improve regional innovation performance by enhancing the spillover effect of virtual agglomeration elements. However, how the digital economy affects the technological innovation of manufacturing enterprises through virtual agglomeration needs further research.

3. Methodology

3.1. Theoretic Mechanism

The impact of the digital economy on the technological innovation of manufacturing enterprises includes three aspects. First, the method of technological innovation is combinatory. The technological innovation methods in the era of digital economy are no longer limited to the joint effect of theoretical foundation, professional technology, and market goals, but the recombination of a new generation of information technology and information to achieve collaborative innovation through multiple technologies; Second, the pattern of technological innovation is shared. The original research and development personnel come from manufacturing enterprises, but the digital economy breaks the restrictions on research and development personnel, promotes cooperative innovation in multiple organizations and fields, and accelerates the construction of innovation ecosystems. Third, the management of technological innovation is a breakthrough. In the era of digital economy, digital knowledge and information become an important factor of production, when it is difficult for enterprises to manage non-standardized and unstructured data, they only need to search, obtain and analyze data on the cloud platform where data is stored according to their demand, which reduces the cost of acquiring and managing technological innovation resources of manufacturing enterprises, thereby promoting technological innovation output and efficiency improvement. Fourth, the technological innovation process is non-linear. In the era of digital economy, manufacturing enterprises break linear thinking and realize the nonlinear transformation of technological innovation in time and space, which enables manufacturing enterprises to carry out the production of the product, research, and development at the same time. Fifth, the results of technological innovation are universal. As a new factor of production in the era of digital economy, compared with traditional factors of production such as labor and land, data can be copied infinitely. Therefore, the technological innovation results generated by the use of data elements can also be reused as new elements, thereby accelerating the generation of new technological innovation results.

Furthermore, the digital economy also promotes technological innovation of manufacturing enterprises through specialized and diversified virtual agglomeration. First, the digital economy reduced the thinking dependence of manufacturing enterprises by accelerating specialized and diversified virtual agglomeration, making communication between enterprises more convenient. Through the integration of specialized and diversified knowledge, the technological innovation process is promoted to open and inclusive, and there are many innovation patterns such as networked research and development and e-innovation community, which in turn promotes the technological innovation output and efficiency improvement of manufacturing enterprises (Andrea et al., 2020; Jun et al.,2020). Second, the digital economy reduced the cost of enterprise information search and matching and saved the cost of technological innovation by aggregating manufacturing enterprises and productive service enterprises on the network platform (Maria et al., 2004). Third, through specialized and diversified virtual agglomeration, the digital economy accelerated the

generation of economies of scale and the competitiveness of manufacturing enterprises, thereby helping enterprises improve the efficiency of technological innovation.

Based on theoretical analysis, the following hypotheses are proposed:

- H1. The digital economy can accelerate the technological innovation output and efficiency improvement of manufacturing enterprises.
- H2. The digital economy can accelerate the technological innovation output and efficiency improvement of manufacturing enterprises through specialization and diversified virtual agglomeration.

3.2. Model Establishment

Firstly, in order to test whether the digital economy can directly accelerate the technological innovation output and efficiency improvement of manufacturing enterprises, this paper constructs a benchmark regression model, as shown in (1):

$$Inn_{it}=\beta_0+\beta_1 De_{jt}+\beta_2 Controls+\theta_t+\mu_n+\varepsilon_{jt} \quad (1)$$

In model (1), the subscript i, j, n, and t represent the enterprise, province, industry, and year, The Inn indicates the level of technological innovation of manufacturing enterprises, including the level of technological innovation output (*Innout*) and the efficiency of technological innovation (*Inneff*). The *De* represents the level of the digital economy, the *Controls* represents the control variables at the enterprise level and regional level, and. To control the impact of year and industry factors on the technological innovation of manufacturing enterprises, θ represents the year-fixed effect, and μ represents the industry-fixed effect.

If the β_1 in the first model is significant, it is further tested whether the digital economy can accelerate the technological innovation output and efficiency improvement of manufacturing enterprises through specialization and diversified virtual agglomeration, specifically referring to the mediation effect test proposed by Wen Zhonglin and Ye Baojuan in 2014. As shown in models (2) and (3).

$$Med_{jt}=\beta_0+\beta_1 De_{jt}+\beta_2 Controls+\theta_t+\mu_n+\varepsilon_{jt} \quad (2)$$

$$Inn_{it}=\beta_0+\beta_1^{'} De_{jt}+\delta Med_{jt}+\beta_3 Controls+\theta_t+\mu_n+\varepsilon_{jt} \quad (3)$$

In models (2) and (3), the *Med* represents the level of virtual agglomeration, the remaining subscripts have the same meaning as model (1).

3.3. Data Source and Variable Selection

The data in this paper are derived from the Statistical Yearbook of China, the Wind database, and the Guotai'an database. This paper takes China's A-share manufacturing listed companies as the research object, matches the provincial digital economy and virtual agglomeration of industry, and finally constructs the panel dataset from 2012 to 2020.

The explained variables in this paper are the technological innovation output and the efficiency of manufacturing enterprises. Referring to the research results of Qing and Huang

(2021), the number of patent applications is used to measure the technological innovation output of enterprises. At the same time, during data processing, it is found that the number of patent applications of manufacturing enterprises in individual years is 0, so adding 1 to the number of patent applications and then taking the logarithm. ensuring the validity of the sample on the one hand, and reducing the standard error of the variable on the other hand. Drawing on Chang's (2020) measuring method of technological innovation efficiency, this paper uses an SBM model containing undesired output to calculate the technological innovation efficiency of manufacturing enterprises. The input elements in the model include capital and human capital, which are respectively measured by research and development funding and the number of personnel. The expected output is the number of enterprise patents, measured by the number of invention patents authorized by the manufacturing enterprise in the current year. Non-expected output refers to the innovation loss that occurs in the process of innovation output of manufacturing enterprises, measured by the average number of invention patent applications in the past three years minus the number of invention patents granted in the current year. The reason for choosing the average number of invention patent applications in the past three years is that the period from application to grant of invention patents is generally 1-3 years. In the robustness test, the ratio of the log of the patent application to the amount of research and development investment is used to measure the technological innovation efficiency of manufacturing enterprises (Chen et al., 2021).

The core explanatory variable in this paper is the level of the digital economy. An important prerequisite for the development of the digital economy in China is the support of the government's industrial policies, and the digital economy presents a complex and systematic nature that is constantly evolving (Chen, 2022). Therefore, this paper defines the digital economy as a new form of economic structure and operation mode changes caused by the continuous penetration of digital technology groups into various fields under the guidance of industrial policies, supported by the digital technology industry and connecting the Internet. Based on the connotation of the digital economy and the availability of data, this paper constructs a digital economy level index system from four dimensions, including digital economy policy environment, digital technology industry scale, Internet connection, and digital technology application, with a total of 9 subdivided indicators. Furthermore, the "Entropy-WASPS method" was used to measure the digital economy level of 30 provinces (municipalities and autonomous regions) in China except for Tibet from 2012 to 2020.

The mediating variable in this paper is the level of virtual agglomeration, including specialization and diversification. In this paper, the location entropy formula is used for measurement (Zhang et al., 2017), as shown in equations (4) and (5).

$$Medspe_{ijt} = \frac{D_{ijt} \Big/ D_{it}}{D_{jt} \Big/ D_{t}} \tag{4}$$

$$Meddiv_{it} = \left(1 - \frac{\left|Medspe_{ijt} - Medspe_{ipt}\right|}{Medspe_{ijt} + Medspe_{ipt}}\right) + Medspe_{ijt} + Medspe_{ipt} \tag{5}$$

In equations (4) and (5), *i*, *j*, *p*, and *t* respectively represent the region, manufacturing, productive service industry, and year, $Medspe_{ijt}$, $Meddiv_{it}$ represent the specialized and diversified virtual agglomeration level of regional manufacturing enterprises, $Medspe_{ipt}$ represents the specialized virtual agglomeration level of regional productive service enterprises, and D_{ijt} represents the level of digital technology application of regional manufacturing industry, D_{it} represents the level of digital technology application in all industries in the region, D_{jt} represents the national manufacturing digital technology application level, and D_t represents the level of digital technology application in all industries in the country.

The descriptive statistics of variables are shown in Table 1.

Table 1. Descriptive statistics of variables

Variables	Mean	St.d	Min	Max	N
Innout	4.951	1.427	0	11.09	11,538
Inneff	0.726	0.237	0.0008	1.001	11,538
De	0.384	0.266	0.0005	0.909	11,538
Rdt	17.905	1.496	5.094	23.491	11,538
Asset	23.132	1.175	17.806	27.547	11,538
As	0.414	0.365	0.008	31.467	11,538
Grow	0.649	17.438	-28.589	1,294.219	11,531
Roa	0.029	0.102	-3.2	1.408	11,538
Lnocf	19.205	1.584	10.506	24.668	11,538
Hc	0.175	0.024	0.099	0.222	11,538
Struc	1.376	0.847	0.611	5.244	11,538
Medspe	1.16	0.856	0	6.605	11,538
Meddiv	2.879	2.343	0.512	19.986	11,538

Notes: The data in the table is derived from the results of the operation in Stata.

Table 2. Basic results

Variables	Innout			Inneff		
	(1)	(2)	(3)	(4)	(5)	(6)
De	0.935***	0.531*	0.694***	0.065*	0.071*	0.087*
	(0.307)	(0.282)	(0.275)	(0.036)	(0.043)	(0.045)
Controls	NO	YES	YES	NO	YES	YES
Fix Industry	NO	NO	YES	NO	NO	YES
Fix Year	NO	NO	YES	NO	NO	YES
Observations	11,538	11,531	11,531	11,538	11,531	11,531
R^2	0.006	0.394	0.492	0.006	0.03	0.107

Notes: The data in the table is derived from the results of the operation in Stata. The superscripts ***, **, * are significant at the level of 1%, 5%, and 10%, respectively. The standard errors are in parentheses.

4. Results

4.1. Preliminary Regression

The regression results of the digital economy affecting the technological innovation of manufacturing enterprises are shown in Table 2. Among them, the explanatory variables in columns 1 to 3 are the technological innovation output of manufacturing enterprises, and the explanatory variables in columns 4 to 6 are the efficiency of technological innovation of manufacturing enterprises. It can be seen that regardless of whether control variables, industry-fixed effects, and time-fixed effects are added, the digital economy has a significant

positive impact on the technological innovation output and efficiency of manufacturing enterprises, indicating that the development of the digital economy promotes the technological innovation of manufacturing enterprises.

4.2. Test of Robustness

First, this paper tests robustness by substituting the explanatory variables. To test the robustness of the impact of the digital economy on the technological innovation output and efficiency of manufacturing enterprises, the number of applications of the invention patent is used as a measurement index for the technological innovation output of manufacturing enterprises. The ratio of the number of patent applications to the logarithmic amount of research and development investment is used as a measure of the efficiency of technological innovation of manufacturing enterprises. Second, this paper tests robustness by substituting explanatory variables. The early form of the digital economy was mainly based on electronic commerce. Therefore, this paper uses the logarithmic values of electronic commerce transaction volume in 30 provinces (municipalities and autonomous regions) in China except for Tibet as the core explanatory variable to replace the original digital economy index. The regression results of replacing the explained variables and core explanatory variables show that the digital economy does have a significant positive impact on the output and efficiency of technological innovation of manufacturing enterprises.

4.3. Analysis of Heterogeneous

(1) Heterogeneity of the industry to which the enterprise belongs. High-tech manufacturing includes pharmaceutical manufacturing, aviation, spacecraft and equipment manufacturing, electronic and communicating equipment manufacturing, computer and office equipment manufacturing, medical equipment manufacturing, instrumentation manufacturing, and information chemical manufacturing, and the rest of the manufacturing industries are medium and low-tech manufacturing. Therefore, this paper regresses the samples of high-tech manufacturing enterprises and medium- and low-tech manufacturing enterprises respectively, and the results are shown in Table 3. It can be seen that in the sample of high-tech manufacturing enterprises, the digital economy has promoted technological innovation efficiency, but has not promoted technological innovation output. In the sample of medium and low-tech manufacturing enterprises, the digital economy promoted the technological innovation output but did not have a significant positive impact on technological innovation efficiency. The possible reason is that the applied level of digital technology of high-tech manufacturing enterprises is relatively high, and the technological innovation output of enterprises depends more on human capital and capital investment within the enterprise, which is weakly affected by the development level of the digital economy, but the digital economy helps to accelerate the spillover of knowledge and technology, and enterprises can reduce the loss of technological innovation by obtaining technological innovation information, thereby having a significant positive impact on the technological innovation efficiency. For medium and low-tech manufacturing enterprises, the technological innovation output depends more on external human and financial support,

the digital economy is to accelerate the circulation of technological innovation factors for medium and low-tech manufacturing enterprises to provide resource-oriented support of technological innovation, accelerate technological innovation output, but due to the relatively low level of digital technology application of medium and low-tech manufacturing enterprises, high innovation losses may occur in the process of technological innovation, so the digital economy is difficult to have a significant positive impact on the technological innovation efficiency.

Table 3. Heterogeneous results of industry

Variables	High technology		Medium and low technology	
	Innout	Inneff	Innout	Inneff
De	0.572	0.154**	0.756**	0.046
	(0.402)	(0.064)	(0.371)	(0.065)
Controls	YES	YES	YES	YES
Fix Industry	YES	YES	YES	YES
Fix Year	YES	YES	YES	YES
Observations	5,155	5,155	6,376	6,376
R^2	0.505	0.114	0.476	0.727

Notes: The superscripts ***, **, * are significant at the level of 1%, 5%, and 10%, respectively. The standard errors are in parentheses.

(2) Heterogeneity of the region to which the enterprise belongs. In this paper, the sample of manufacturing enterprises is divided into four categories, eastern region, central region, western region, and northeast region. Among them, the eastern region includes 10 regions, the central region includes 6 regions, the western region includes 11 regions, and the northeast region includes 3 regions. The results of the regression are shown in Table 4. The digital economy has had a significant positive impact on the technological innovation output and efficiency of manufacturing enterprises in the eastern and central regions, while the western region and the northeast region have failed the test. This may be due to the greater policy support of the governments in the eastern and central regions for the digital economy, and the stronger development of the digital technology industry, which has improved the level of the digital economy, which in turn has promoted the technological innovation of manufacturing enterprises. However, the digital economy industrial policies in the western region and northeast region need to be improved, and the level of digital infrastructure is low, which makes it difficult to promote the technological innovation of manufacturing enterprises.

Table 4. Heterogeneous results of the region

Variables	Eastern region		Central region		Western region		Northeast region	
	Innout	Inneff	Innout	Inneff	Innout	Inneff	Innout	Inneff
De	1.12***	0.132**	0.166*	1.286***	-0.529	-0.692	2.507	0.072
	(0.354)	(0.066)	(0.085)	(0.407)	(1.384)	(0.294)	(1.945)	(0.47)
Controls	YES	YES	YES	YES	YES	YES	YES	YES
Fix Industry	YES	YES	YES	YES	YES	YES	YES	YES
Fix Year	YES	YES	YES	YES	YES	YES	YES	YES
Observations	7,656	7,656	1,906	1,906	1,439	1,439	530	530
R^2	0.501	0.121	0.532	0.51	0.51	0.131	0.607	0.396

Notes: The superscripts ***, **, * are significant at the level of 1%, 5%, and 10%, respectively. The standard errors are in parentheses.

(3) Heterogeneity of enterprise scale. According to the "Statistical Classification of Large, Medium, Small and Micro Enterprises (2017)" issued by the China Bureau of Statistics, manufacturing enterprises with operating income greater than or equal to 400 million yuan in this paper are classified as large manufacturing enterprises, and enterprises with less than 400 million yuan are classified as non-large manufacturing enterprise samples and returned separately. It can be seen from the results of Table 5 that the digital economy did not have a significant positive impact on the technological innovation output and efficiency of manufacturing enterprises in the sample of large manufacturing enterprises, and in the sample of non-large manufacturing enterprises, the digital economy had a significant positive impact on the technological innovation output and efficiency of manufacturing enterprises, possibly because the overflowing effects of technology and knowledge of the digital economy in non-large manufacturing enterprises were more obvious.

(4) Heterogeneity of enterprise equity. In this paper, the sample of manufacturing enterprises is divided into state-owned manufacturing enterprises and non-state-owned manufacturing enterprises, and regression is carried out separately. The regression results on the sample of enterprise equity heterogeneity in Table 5 show that the digital economy does not have a significant positive impact on the technological innovation output and efficiency of state-owned manufacturing enterprises, but has a significant positive impact on the technological innovation output and efficiency of non-state-owned manufacturing enterprises. This may be because the digital transformation goals and processes of state-owned enterprises are conservative and backward compared with non-state-owned enterprises, so it is difficult for the digital economy to promote the technological innovation of state-owned manufacturing enterprises, which is also the same as the research conclusion of Bo et al. (2022).

Table 5. Heterogeneous results of scale and equity of manufacturing enterprises

Variables	Heterogeneity of scale				Heterogeneity of equity			
	Large		Non-large		State-owned		Non-state-owned	
	Innout	Inneff	Innout	Inneff	Innout	Inneff	Innout	Inneff
De	0.413	0.078	2.529***	0.239**	0.78	0.082	0.84**	0.063**
	(0.297)	(0.05)	(0.753)	(0.098)	(0.492)	(0.076)	(0.348)	(0.038)
Controls	YES	YES	YES	YES	YES	YES	YES	YES
Fix Industry	YES	YES	YES	YES	YES	YES	YES	YES
Fix Year	YES	YES	YES	YES	YES	YES	YES	YES
Observations	10110	10110	1421	1421	4131	4131	7400	7400
R^2	0.488	0.093	0.587	0.398	0.547	0.079	0.467	0.141

Notes: The superscripts ***, **, * are significant at the level of 1%, 5%, and 10%, respectively. The standard errors are in parentheses.

4.4. Test of Mechanism

In this paper, the mediating effects of specialized and diversified virtual agglomeration are tested separately, and the results are shown in Table 6. The regression results of columns (1) and (4) show that the digital economy has a significant positive impact on specialized and diversified virtual agglomeration, indicating that the digital economy accelerates the construction of regional informatization, networking, and intelligence, thereby promoting

the virtual agglomeration of manufacturing enterprises in cyberspace. With the rapid development of the digital economy, the level of specialized and diversified virtual agglomeration will continue to increase. The regression results of columns (2) and (5) show that the digital economy promotes the technological innovation output of manufacturing enterprises by accelerating respectively specialized and diversified virtual agglomeration. It shows that the digital economy enhances the spillover effect of knowledge of technological innovation through the exchange and cooperation of manufacturing enterprises within and between industries, accelerates the flow and sharing of resources of manufacturing enterprises, and thus promotes the technological innovation output of manufacturing enterprises. The regression results in columns (3) and (6) show that the digital economy does not improve the technological innovation efficiency of manufacturing enterprises by promoting specialized and diversified virtual agglomeration. The efficient measurement of technological innovation of manufacturing enterprises in this paper includes both the requirement of maximizing the expected output and the requirement of minimizing the non-desired output when given capital and manpower input, but the digital economy has not improved the technological innovation efficiency of manufacturing enterprises by accelerating specialized and diversified virtual agglomeration, which may be because although the digital economy has realized the rapid flow of various innovative resources through specialized and diversified virtual agglomeration, the utilization effect of manufacturing enterprises on technological innovation resources needs to be improved. Manufacturing enterprises may waste the resources of technological innovation in the process of technological innovation, resulting in the spillover effect of innovative resources brought about by specialized and diversified virtual agglomeration.

Table 6. Testing results of the mechanism

Variables	The mediating effect of specialized virtual agglomeration			The mediating effect of diversified virtual agglomeration		
		Innout	Inneff		Innout	Inneff
De	1.253***	0.537**	0.096**	1.487***	0.755***	0.088*
	(0.04)	(0.274)	(0.049)	(0.242)	(0.272)	(0.046)
Medspe		0.132*	-0.008			
		(0.075)	(0.019)			
Meddiv					0.018***	0.0005
					(0.007)	(0.001)
Controls	YES	YES	YES	YES	YES	YES
Fix Industry	YES	YES	YES	YES	YES	YES
Fix Year	YES	YES	YES	YES	YES	YES
Observations	11,538	11,538	11,531	11,538	11,538	11,531
R2	0.296	0.724	0.109	0.036	0.724	0.109

Notes: The superscripts ***, **, * are significant at the level of 1%, 5%, and 10%, respectively. The standard errors are in parentheses.

5. Discussion

This paper expands on existing research from the following three aspects: first, current scholars pay more attention to the impact of digital technology on the technological innovation of manufacturing enterprises (Tommaso et al., 2021; Christian et al., 2022),

ignoring the transformation of the digital economy to the organizational structure of manufacturing enterprises, and in the era of digital economy, accelerating knowledge spillover and reducing transaction costs through virtual agglomeration has become an important way for manufacturing enterprises to improve the level of output and efficiency of technological innovation. Second, the existing literature mostly measures the level of virtual agglomeration in an industry (Zhao et al., 2022), but virtual agglomeration includes both specialized virtual agglomeration within the industry and diversified virtual agglomeration between industries, and the measurement methods should be different. Third, the impact of digital economy on technological innovation of manufacturing enterprises varies among samples of different manufacturing industries, enterprise scales, regions, and equity types, and the existing literature is slightly insufficient in this regard (Zheng et al., 2022).

6. Conclusions and Recommendations

This paper concludes the following: First, the digital economy promotes the technological innovation output and efficiency of manufacturing enterprises, and hypothesis 1 of this paper is verified. Second, the role of digital economy in promoting the technological innovation output and efficiency of manufacturing enterprises is affected by the industry type, geographical location, enterprise scale, and equity nature of manufacturing enterprises. Third, the testing results of the mechanism show that the digital economy has a significant positive impact on specialized and diversified virtual agglomeration, and the digital economy promotes technological innovation output of manufacturing enterprises by accelerating specialized and diversified virtual agglomeration but does not improve the technological innovation efficiency of manufacturing enterprises, hypothesis 2 in this paper has not been fully validated.

This paper puts forward the following three policy implications: First, local governments should formulate strategies and plans for the digital economy that are in line with the actual development of regions, introduce diversified and incentive policies for the digital economy, and improve the constructing level of new digital infrastructure, to accelerate the development of the digital economy. Second, manufacturing enterprises should accelerate digital construction, and for state-owned manufacturing enterprises, senior managers should reach a consensus among them to accelerate the digital transformation of enterprises, establish the leading position of digital transformation on technological innovation of enterprise, and focus the digital transformation of enterprises on technological innovation of products and services; Non-state-owned manufacturing enterprises should do a good job in the training and management of digital technology talents, reduce the loss rate of digital technology talents, and make the digital economy better promote the technological innovation of manufacturing enterprises. Third, accelerate the construction of the industrial Internet platform, promote the specialized and diversified virtual agglomeration of manufacturing enterprises and productive service enterprises on the platform, realize the efficient flow of resources of technological innovation such as technology, talents, and capital in manufacturing and productive service industries, and improve the resource allocating of

technological innovation efficiency, to promote technological innovation of manufacturing enterprises; At the same time, the regulatory department of the platform should supervise the legality of the behavior of entities on the platform in real-time, and open multiple channels of supervision to ensure the healthy and sustainable development of the platform.

Conflict of interest: none

References

Adrian, Y., Christina, S., & Rina, H. (2018). Aligning with new digital strategy: a dynamic capabilities approach. *Journal of Strategic Information Systems, 27*(1), 43–58. https://doi.org/10.1016/j.jsis.2017.09.001

Alsharo, M., Gregg, D., & Ramirez, R. (2017). Virtual team effectiveness: the role of knowledge sharing and trust. *Information& Management, 54*(4), 479–490. https://doi.org/10.1016/j.im.2016.10.005

Andrea, L. B., Laura, R., & Pierre, A. B. (2020). Global networks, local specialization, and regional patterns of innovation. *Research Policy, 49*(8), 104031. https://doi.org/10.1016/j.respol.2020.104031

Bo, X. Y., Xing, G. L., & Kou, K. (2022). Research on the influence of network embeddedness on innovation performance: evidence from China's listed firms. *Journal of Innovation & Knowledge, 7*(3), 100210. https://doi.org/10.1016/j.jik.2022.100210

Brown, D. H., & Lockett, N. J. (2001). Engaging SMEs in e-commerce: the role of intermediaries within e-cluster. *Electronic Markets, 11*(1), 52–58. https://doi.org/10.1080/10196780121767

Chang, Q. Q. (2020). Differential effects of tax incentives on innovation efficiency of high-tech enterprises. *Finance & Economics, 8,* 83–92.

Chen, D. Q., Sun, Y., & Wang D. (2021). Relational network embedding, joint venture capital, and enterprise innovation efficiency. *Economic Research, 56*(11), 67–83.

Chen, X. H., Li, Y. Y., Song, W. J., & Wang, Y. J. (2022). Theoretical system and research prospect of the digital economy. *Management World, 38*(2), 208–224+13–16.

Chen, Y., Zhang, L. Y. Z., & Song, W. B. (2022). Research on the construction path of intelligent service enabling innovative urban agglomeration – from the perspective of entity and virtual industry agglomeration. *Scientific and Technological Progress & Countermeasures, 39*(09), 33–41.

Christian, R., Gastón, P., & Fernández, D. C. (2022). Artificial intelligence and industrial innovation: evidence from German firm-level data. *Research Policy, 51*(7), 104555. https://doi.org/10.1016/j.respol

David, H. B., & Nigel J. L. (2001). Engaging SMEs in E-commerce: the role of intermediaries within eclusters. *Electronic Markets, 11*(1), 52–58. https://doi.org/10.1080/10196780121767

Feng, P. C. (2018). Research on organizational evolution in the era of big data. *Journal of Economist, 3,* 57–62.

Hoornaert, S., Ballings, M., Malthouse, E. C., & Van den Poel, D. (2017). Identifying new product ideas: waiting for the wisdom of the crowd or screening ideas in real time. *Journal of Product Innovation Management, 34*, 580–597. https://doi.org/10.1111/jpim.12396

Jun, L., Hui, H. C., Yi, L. F., & Bao, H. Y. (2020). Influence of artificial intelligence on technological innovation: Evidence from the panel data of China's manufacturing sectors. *Technological Forecasting and Social Change, 158,* 120–142. https://doi.org/10.1016/j.techfore.2020.120142

Maria, C., Eleonora, D. M., & Stefano, M. (2004). From local networks of SMEs to virtual districts? Evidence from recent trends in Italy. *Research Policy, 33*(10), 1509–1528. https://doi.org/10.1016/j.respol.2004.08.009

Muzzi, C., & Albertini, S. (2015). Management competencies in an innovation community. *R&D Management, 45,* 196–211. https://doi.org/10.3846/bme.2014.240

Qing, T., & Huang, X. H. (2021). Domestic market segmentation, dual market incentive, and enterprise innovation. *Chinese Industrial Economy, 12,* 88–106.

Ru, S. F., Li, J. L., & Du, J. L. (2015). The path transformation of technological innovation in China's new normal economic growth in the era of big data. *Journal of Humanities, 4,* 36–40.

Tang, H. X., Zhang, X. Z., & Wang, L. X. (2020). Spatio-temporal evolution and influencing mechanism of China's land-sea economic integration. *China Soft Science, 12,* 130–144.

Tommaso, C., Martin, K., Silvia, M., & Lucia, P. (2021). Digital technologies, innovation, and skills: Emerging trajectories and challenges. *Research Policy, 50*(7), 104289. https://doi.org/10.1016/j.respol

Wen, Z. L., Fang, J., Xie, J. Y., & Ouyang, J. Y. (2021). Methodological research on domestic mediating effect. *Advances in Psychological Science, 30*(8), 1692–1702.

Zhang, B. C., & Ren, H. (2018). Research on the mechanism of knowledge resource acquisition in virtual organization on sustainable innovation ability. *Journal of Management, 15*(7), 1009–1018.

Zhang, H., Han, A. H., & Yang, Q. L. (2017). Analysis on the spatial effect of Collaborative agglomeration of manufacturing and producer services in China. *Quantitative & technical economics, 34*(2), 3–20.

Zhao, C. M., Ban, Y. H., Li, H. B., & Liu, Y. (2022). Whether virtual agglomeration can promote the quality upgrade of urban export products. *Economic & Management, 44*(7), 23–41.

Zheng, Y. X., & Yang, R. (2022). Digital economy and enterprise innovation: a perspective based on the need for innovation. *Science and Technology Management Research, 10*, 11–19.