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Research on the Digital Economy, Technological Innovation, and Transformation and Upgrading of the Manufacturing Industry in Shandong Province

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Abstract: Based on panel data from 16 cities in Shandong Province from 2013 to 2022, and grounded in theoretical analysis, this paper constructs a benchmark regression model, a mediating effect model, and a heterogeneity test for empirical analysis. The results show that: (1) the digital economy has a significant positive effect on promoting the transformation and upgrading of the manufacturing industry in Shandong Province; (2) the digital economy can drive the transformation and upgrading of the manufacturing industry through technological innovation; and (3) the impact of the digital economy on the transformation and upgrading of the manufacturing industry in Shandong Province is evidently heterogeneous.

Keywords: Digital economy; Technological innovation; Transformation and upgrading of manufacturing industry; Mediating effect

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1. Introduction

The manufacturing industry represents the core competitiveness of a country or region [1], and technological innovation provides the impetus and foundation for the transformation and upgrading of the manufacturing industry. The digital economy is the key path for the transformation and upgrading of the manufacturing industry [2] and is also the core element of new quality productivity, which represents the direction and trend of the country's future development. The coming period will be a critical time for the development of the digital economy and the transformation and upgrading of the manufacturing industry in Shandong Province, presenting a historic opportunity to win a new round of development competition.

How to fully leverage Shandong's vast potential in the digital economy, combined with the province's comprehensive manufacturing sectors, to further unlock development potential in both the digital economy and manufacturing and create new quality productivity has become crucial to Shandong Province's high-quality development. While the existing literature is abundant, few studies have focused on the impact of the digital

economy, technological innovation, and the transformation and upgrading of the manufacturing industry in Shandong Province. Additionally, limited research has been done on the impact of the digital economy on the transformation and upgrading of the manufacturing industry in Shandong Province through technological innovation.

2. Research hypothesis

The development of the digital economy has fundamentally transformed the industrial chain structure, enabling more flexible production and orderly cooperation in the manufacturing industry, thereby significantly enhancing its overall competitiveness [3]. The manufacturing industry is experiencing unprecedented changes, and optimizing the allocation of resource factors is essential to promoting its high-quality development. High-end, intelligent, and green manufacturing are the only viable paths for the transformation and upgrading of the manufacturing industry in the new era [4], and these characteristics are key indicators of successful industrial transformation and upgrading.

The development of the digital economy is influenced by regional policies, spatial advantages, and economic development, leading to the flow of resources toward areas with higher returns and efficiency [5]. The transformation and upgrading of the manufacturing industry also require the support of economic development. In regions with favorable policies and strong economic and social development, the digital economy can attract talent and capital inflows, creating optimal conditions for the transformation and upgrading of the manufacturing industry [6]. Therefore:

Hypothesis 1: The digital economy has a significant positive effect on the transformation and upgrading of the manufacturing industry.

Hypothesis 2: The impact of the digital economy on the transformation and upgrading of the manufacturing industry exhibits regional heterogeneity.

The digital economy is an innovation-driven economy, with its primary focus shifting from producers to the concentration of resources on knowledge and technological innovation [7]. As such, the digital economy itself is a form of technological innovation [8]. The digital economy has a strong technological innovation effect on the development of the manufacturing industry. The integration of digital technologies into manufacturing fosters the co-development of the digital and manufacturing sectors. The high level of penetration by the digital economy facilitates the rapid application of technological innovations in manufacturing, thereby driving industrial and technological advancements [9].

The development of the digital economy has overcome the limitations of time and space on technological innovation, increased its flexibility, improved efficiency, and reduced costs for enterprises. First, the advancement of digital technologies accelerates the flow of knowledge resources, enhances knowledge innovation capabilities, improves the structure of human capital, and empowers enterprises with knowledge for innovation and reform [10]. Second, the digital economy provides a favorable environment for technological innovation, better meeting the data transmission, storage, and processing needs of enterprises, optimizing the digital economy's infrastructure, accelerating the transformation of manufacturing production, and promoting the transformation and upgrading of the manufacturing industry. Therefore:

Hypothesis 3: The digital economy promotes technological innovation.

Hypothesis 4: The digital economy influences the transformation and upgrading of the manufacturing industry through technological innovation.

3. Research design

3.1. Model specification

3.1.1. Construction of benchmark regression model

Wherein, i represents various cities, t represents years, a is the estimated parameter, ε is the residual, M is the control variable, and n = 2, 3, 4, 5.

3.1.2. Construction of mediation effect model

Wherein, i represents various cities, t represents years, β and γ are estimated parameters, λ and μ are residuals, M is the control variable, and n = 2, 3, 4, 5.

3.2. Variable selection

3.2.1. Explained variables

The level of transformation and upgrading of the manufacturing industry (Ug): measured across three dimensions—high-end, intelligent, and green manufacturing.

3.2.2. Core explanatory variables

The development level of the digital economy (De): measured through two dimensions—digital industrialization and industrial digitalization [11].

Based on existing research, further consideration is given to data availability, completeness, and significance, as shown in **Table 1**.

Table 1. Building an indicator system

First level indicators	Second level indicators	Third level indicators
Manufacturing transformation and upgrading	High-end	Expenditure on R&D in industrial enterprises above the designated size as a proportion of business income
		Equivalent full-time R&D personnel in industrial enterprises above the designated size
	Intelligent	Business income from computer, communication, and other electronic equipment manufacturing in industrial enterprises above the designated size as a proportion of total business income
		Value of high-tech industry as a proportion of industrial enterprises above the designated size
	Green	Total discharge of industrial wastewater / Value-added of industry
		Comprehensive utilization of general industrial solid waste / General industrial solid waste generation
Digital economy	Digital industrialization	Number of mobile phone users
		Number of fixed broadband internet subscribers
		Per capita telecommunication service volume
		The average salary of urban private sector employees in the transmission of information, software, and information technology services above the designated size
	Industrial digitization	Number of computers used per hundred people
		Number of websites per hundred enterprises
		E-commerce sales volume
		The proportion of enterprises engaged in e-commerce transactions

3.2.3. Intermediary variables

Technological innovation (Ti): The number of domestic invention patents granted per capita in each city is used to measure the level of technological innovation, and the data is processed logarithmically.

3.2.4. Control variables and instrumental variables

The urbanization rate is used to characterize the level of urbanization (cl). The proportion of general budget expenditure in GDP represents the level of government participation. The proportion of total deposits and loans of financial institutions in GDP represents the level of financial development (fl), and the data is also logarithmically processed. The proportion of financial expenditure on science and education in the general budget expenditure is used to represent the level of education investment (edl).

The first-order lag term $De_{(i, t-1)}$ of the development level of the digital economy is selected as the instrumental variable.

4. Empirical analysis

4.1. Baseline regression analysis

This paper uses the entropy method to estimate the comprehensive scores of digital economy development and manufacturing transformation and upgrading in cities in Shandong Province from 2013 to 2022. It calculates the mean values of these comprehensive scores for the three economic circles, respectively.

According to the regression results in **Table 2**, for every 1 unit increase in the development level of the digital economy, the level of transformation and upgrading of the manufacturing industry increases by an average of 0.2092 units. This demonstrates that the digital economy has a stable driving effect on the transformation and upgrading of the manufacturing industry. Promoting the further development of the digital economy is conducive to the transformation and upgrading of the manufacturing industry in Shandong Province. Thus, **Hypothesis 1** is valid.

Table 2. Benchmark regression analysis

Variable	Model (1)
De	0.2092*** (3.69)
fl	0.3167** (2.42)
cl	0.1507 (0.27)
gl	-0.4364 (-0.46)
edl	-0.5842 (-0.9)
Constant term	-1.3886* (-2.08)
Individual and time-fixed	YES
R-squared	0.6606

Note: *, **, *** represent 10%, 5%, and 1% significance levels respectively, and values in parentheses refer to *t*-values.

4.2. Robustness test

Instrumental variables were used for regression analysis, and the results were consistent with the benchmark regression trend. The regression coefficient remained nearly identical to that of the benchmark regression

model, further verifying **Hypothesis 1**. This also demonstrates that the conclusion that the digital economy promotes the transformation and upgrading of the manufacturing industry is robust.

Table 3. Robustness tests

Variable	Model (2)
$D_{e(i, t-1)}$	0.1619** (2.23)
fl	0.3423** (2.20)
cl	0.1131 (0.19)
gl	-0.1615 (-0.17)
edl	-0.8048 (-0.97)
Constant term	-1.4924* (-1.76)
Individual and time-fixed	YES
R-squared	0.6547

4.3. Analysis of intermediary effect

Technological innovation is used as an intermediary variable, and the digital economy and the transformation and upgrading of the manufacturing industry are analyzed within the same framework. According to the results of model (3), the coefficient is significant at the 1% level, indicating that the digital economy has a significant positive effect on technological innovation, thus supporting **Hypothesis 3**.

Model (4) incorporates technological innovation indicators into the model: both the digital economy and technological innovation significantly promote the transformation and upgrading of the manufacturing industry in Shandong Province. Compared with the benchmark regression model, the regression coefficient for the digital economy decreased, but the positive significance of its impact remained unchanged. The overall fit of the model increased after including technological innovation indicators, which further enhances the interpretation of the role of the digital economy in driving the transformation and upgrading of the manufacturing industry in Shandong Province. Therefore, technological innovation acts as a mediating factor in this process, supporting **Hypothesis 4**. See **Table 4** for further details.

Table 4. Results of intermediary effect analysis

Variable	Model (3)	Model (4)
De	0.7246*** (4.80)	0.1432* (2.00)
Ti	-	0.0910* (2.04)
fl	-1.0626*** (-3.48)	0.4134*** (2.98)
cl	0.0703 (0.05)	0.1443 (0.27)
gl	-0.1282 (-0.1)	-0.4247 (-0.46)
edl	0.6024 (0.38)	-0.6390 (-1.11)
Constant term	5.9875*** (3.15)	-1.9335 (-2.69)
Individual and time-fixed	YES	YES
R-squared	0.8728	0.6817

4.4. Heterogeneity analysis

Further heterogeneity analysis of the three economic circles reveals significant regional differences in the effect of the digital economy on promoting the transformation and upgrading of the manufacturing industry in Shandong Province (**Table 5**). The regression coefficient for the Jiaodong economic circle is significant at the 5% level, with a coefficient of 0.2212, which is higher than the provincial average. However, the regression coefficient for the provincial capital economic circle is not significant, while the southern economic circle experiences a negative impact.

Table 5. Results of heterogeneity analysis

Variable	Model (5)	Model (6)	Model (7)
	Provincial Capital Economic Circle	Jiaodong Economic Circle	Lunan Economic Circle
De	0.2449 (1.77)	0.2212** (3.19)	-0.1493 (-0.98)
fl	0.1980** (3.35)	0.8808** (3.57)	-0.3142* (-2.69)
cl	-1.7473** (-3.19)	-1.1501 (-0.55)	-0.0702 (-0.25)
gl	0.5452 (0.89)	1.7382 (0.03)	1.8132 (1.78)
edl	0.7515 (2.88)	-0.7205 (-1.24)	1.1193 (1.37)
Constant term	-0.1852** (-0.47)	-3.8302 (-4.03)	1.2792 (1.41)
Individual and time-fixed	YES	YES	YES
R-squared	0.7939	0.8881	0.9387

5. Policy recommendations

5.1. Improve institutions and mechanisms to ensure the healthy and orderly development of the digital economy

Adhering to the principles of trust, control, and traceability, strict regulatory rules and standards should be formulated, and the supply of digital transformation services strengthened [12]. Enhancing market supervision, macro-control, and policy and regulatory systems that align with the development of the digital economy is essential. This will promote the efficient circulation and use of compliant digital resources. Efforts should be focused on strengthening early warning, prevention, and control mechanisms, as well as capacity building for security risks in the digital economy. Data types should be classified, and protection should be implemented accordingly.

5.2. Strengthen policy guidance and fully leverage the leading role of technological innovation

Technological innovation resources should be integrated, with efforts focused on key core technologies, constantly improving the role of technological innovation as the source of leadership and its ability to allocate factors [13]. An innovation consortium, led by leading enterprises and supported by universities and institutions, should be established. This consortium would coordinate the participation of various innovation entities to promote the intelligent and digital transformation of the manufacturing industry [14]. The goal is to encourage more enterprises to embrace cloud technology and leverage its benefits, to drive the transformation and application of technological achievements, and to promote the implementation of technological innovation in

industrial practices [15].

5.3. Optimize the industrial layout and further promote the integration of digital and physical practices

Comprehensive planning for traditional, emerging, and future large industries should be undertaken to optimize the upstream and downstream layout of the industrial chain. Local conditions must be adapted to build a modern industrial system that reflects local characteristics and advantages. Emerging technologies, such as big data, cloud computing, and the Internet of Things, should be used to transform and upgrade business models, products, and services. Intelligence, platformization, and branding should be comprehensively improved to promote the seamless integration of industrial production and sales "online + offline." This will enable industries to respond more effectively to market changes and customer needs, creating the optimal combination of product chains.

Disclosure statement

The author declares no conflict of interest.

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