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Mechanisms of Digital Economy Empowering High-Quality Development in Manufacturing: A Case Study of Hebei Province, a Traditional Manufacturing Powerhouse in China

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Abstract: The digital economy, a new economic paradigm guiding the rapid and optimal allocation of resources for high-quality economic development, has the potential to empower the high-quality advancement of the manufacturing sector. It is imperative to delve into the mechanisms underlying this empowerment. Utilizing panel data from nine cities in Hebei Province of China from 2010 to 2019, this study employs intermediary models and panel threshold models to empirically examine the mechanisms through which the digital economy enables high-quality development in Hebei's manufacturing industry across three dimensions: direct, indirect, and nonlinear. The findings are threefold: Firstly, the digital economy significantly fosters high-quality development in manufacturing. Secondly, mediation effect analyses reveal that the digital economy enhances high-quality development in manufacturing by elevating human capital levels and reducing operational costs for enterprises. Thirdly, panel threshold model analyses indicate that the efficacy of the digital economy in empowering high-quality manufacturing development varies in stages, contingent on different levels of digital infrastructure, research and development investment, and innovation. Specifically, the facilitative role of the digital economy in the high-quality development of manufacturing shows an 'increasing marginal effect' with elevated levels of research and development investment and a 'decreasing marginal effect' with the enhancement of digital infrastructure and innovation levels.

Keywords: Digital economy; High-quality development in manufacturing; Mediation effect; Threshold effect

1. Introduction

The digital economy, characterized by the identification, selection, filtering, storage, and utilization of digital knowledge and information, leads to the rapid and optimal allocation of resources, thereby fostering high-quality economic development (Mirolyubova et al., 2020). As a traditional manufacturing stronghold in China, Hebei Province's manufacturing sector is distinguished by its substantial weight, high employment, and strong driving force for the national economy. Predominantly based on the real economy, the development of manufacturing in Hebei Province is critical for the national economic layout. Despite significant achievements attributable to its resource endowment, geographical location, and developmental opportunities, Hebei's traditional manufacturing industry faces increasing downward pressures under the new economic norm and the emergence of "Internet+" and "Intelligent Manufacturing." Issues such as insufficient information technology application, overcapacity, low industrial concentration, and severe pollution challenge the sector. High-level digital economy can address these issues, thereby empowering high-quality development in Hebei's manufacturing industry. Thus, under the new era's backdrop, examining the intrinsic mechanisms of how the digital economy empowers high-quality manufacturing development, particularly in Hebei, a major manufacturing province in China, is necessary.

Existing literatures primarily explore the impact of the digital economy on manufacturing in three aspects: Firstly, regarding digitalization in enterprise management, some scholars argue that the digital economy promotes various aspects of enterprise management. Jia et al. (2022) concluded through fuzzy set qualitative comparison that autonomous innovation capability in a digital environment can facilitate transformation and upgrading in

manufacturing enterprises. Dang et al. (2021), using city-level digital economy indexes and enterprise-level patent application data from 2016-2018, confirmed that the digital economy affects cooperative innovation performance in manufacturing enterprises mainly through foreign investment and VC/PE activity, with foreign investment compelling companies to adjust R&D management and actively seek external innovative collaborations. Secondly, concerning digitalization in product production, the development of digital technologies significantly impacts product quality and production efficiency. Xie & Wang (2022), employing a new trade theory framework to analyze the digital economy and export quality, discovered that the digital economy significantly enhances the export product quality of manufacturing enterprises, with the driving effects varying across different trade modes and types of enterprises. Li & Wang (2021), by constructing a theoretical model on how the digital economy's development and data element allocation affect manufacturing productivity, found that the digital economy development has dual effects: enhancing manufacturing productivity and optimizing data element allocation. Thirdly, regarding industrial chain upgrading, manufacturing enterprises in the digital environment are more likely to transform from low-level labor-intensive to high-level digital types. Li et al. (2020) posited that as digital information becomes a standardized medium in industrial chains, manufacturing industry chains will undergo deconstruction and reconstruction, gradually achieving comprehensive digital transformation. Zhang & Yu (2021), using WIOD input-output data, concluded that domestic and foreign digital inputs have opposite effects on the global value chain division of labor for enterprises.

While these studies offer valuable insights, they lack targeted research on high-quality development in provincial and municipal manufacturing industries, especially for a traditional industrial province like Hebei. Therefore, this study combines mediation effect models and panel threshold models to delve into the mechanisms by which the digital economy influences high-quality development in manufacturing from direct, indirect, and nonlinear perspectives, offering strategies for Hebei Province to maximize the enabling role of the digital economy and implement suitable development strategies. Compared to existing literature, this study contributes marginally in two aspects: theoretically, it analyzes from multiple angles how the digital economy empowers high-quality development in Hebei's manufacturing industry, focusing on digitalization's role in optimizing industrial structure, driving innovation, and facilitating transformation. It also pays attention to two intermediary mechanisms - human capital level and enterprise operational costs - demonstrating how the digital economy indirectly promotes high-quality manufacturing development. Empirically, recognizing the importance of innovation in high-quality manufacturing development, the study incorporates innovation potential into the evaluation system for high-quality manufacturing development and measures it from five aspects, including innovation potential. Moreover, by combining mediation models and panel threshold models, the study deeply explores the nonlinear impacts of the digital economy on manufacturing, providing effective approaches for Hebei Province to explore suitable high-quality manufacturing development paths.

2. The Impact Mechanism of Digital Economy on High-Quality Development in Hebei Province's Manufacturing Industry

2.1 Direct Impact of Digital Economy on High-Quality Development in Manufacturing

The digital economy, grounded in digital information technology, encompasses both the digital industrialization and industrial digitalization (Chinoracky & Corejova, 2021). It guides the manufacturing industry towards quality enhancement, benefit innovation, and a dynamic transformation.

Firstly, the digital economy facilitates the optimization and adjustment of manufacturing structures (Fan et al., 2022). Enhanced levels of digital infrastructure and digital research capabilities significantly promote industrial digitalization, thereby significantly boosting the structural optimization of the manufacturing industry. Jaakkola et al. (1991) posits that the use of information technology for knowledge management and sharing can render various segments of production more scientific and intelligent, thus elevating output efficiency and propelling high-quality development in manufacturing.

Secondly, the digital economy drives innovation in the manufacturing sector. Initially, the competitive intensity among manufacturing enterprises, exacerbated by the development of the digital economy, compels innovation within manufacturing companies. The rapid evolution of the digital economy, particularly the platform economy, moves markets towards openness and transparency. This symmetry of information intensifies competition among enterprises, necessitating continual product innovation and increased investment in research and development to secure market share. Furthermore, the development of the digital economy provides a conducive platform for research and development collaboration in manufacturing. With the swift advancement of modern information technology in areas such as e-commerce, mobile payments, and the sharing economy, a vast digital industrial chain emerges from the convergence of diverse elements and numerous enterprises in the digital economy chain plays a crucial role in market transactions and resource allocation, enhancing the efficiency of horizontal cooperation and innovation among manufacturing enterprises (Zhu, 2022). Finally, the digital economy accelerates the dissemination and spillover of knowledge, laying a foundation for technological innovation in manufacturing by

providing knowledge support for innovation activities. The digital era broadens the avenues for knowledge acquisition, expedites its dissemination, and augments society's collective knowledge, thereby offering a substantial knowledge base for enterprise innovation (Kleiner, 2020). Based on these observations, the following hypothesis is proposed:

H1: The digital economy directly promotes high-quality development in the manufacturing industry.

2.2 Indirect Impact of the Digital Economy on High-Quality Development in Manufacturing

2.2.1 Digital economy drives high-quality manufacturing development by enhancing human capital in manufacturing

As the digital economy propels the shift from labor-intensive to technology-intensive processes in manufacturing, a disruptive change in the employment structure within the industry is observed. This shift is characterized by an increased demand for highly skilled, technology-intensive personnel and a decreased demand for labor-intensive and medium-skilled workers. The positive impact of the digital economy on employment is mainly manifested through broadening effects, deepening effects, and job creation effects (Zhao & Said, 2023). Concurrently, the demand for higher-end talents implies higher labor compensation (Hayakawa & Venieris, 2019). The increased remuneration for highly skilled professionals elevates the income levels of the entire labor group, leading to an expanded demand for higher quality of life and products. This, in turn, further drives the high-quality development of the manufacturing industry. Consequently, the following hypothesis is posited:

H2: The digital economy can enhance the human capital level in the manufacturing industry, thereby driving its high-quality development.

2.2.2 Digital economy drives high-quality manufacturing development by reducing operational costs for enterprises

The operational costs of manufacturing enterprises, constituting a part of their non-productive expenditures, are significant. Lower operational costs reduce the total resource consumption of enterprises, enabling a more efficient breakthrough in the core production capabilities of the manufacturing industry, thereby driving its high-quality development. In the process of continuous refinement of the manufacturing industry's value chain, the digital economy can leverage the advantage of rapid information transmission to effectively reduce the costs of information exchange. This reduction simplifies sales and transaction processes, enabling enterprises to purchase required raw materials and process them for sale at a lower cost (Zhang et al., 2022), thereby comprehensively reducing the operational costs that are reliant on transaction processes (Wu et al., 2023). Consequently, when enterprises reduce operational costs, the decrease in non-productive expenditures allows for more efficient allocation of their resources, channeling these resources towards core research and development departments, thereby strengthening the positive impact between the digital economy and high-quality development in manufacturing. Based on these considerations, the following hypothesis is proposed:

H3: The development of the digital economy can reduce the operational costs of enterprises, thereby driving high-quality development in the manufacturing industry.

2.3 Nonlinear Impact of Digital Economy on High-Quality Development in Manufacturing

The influence of the digital economy on the high-quality development of the manufacturing industry exhibits nonlinear dynamic characteristics. On one hand, with the increasing levels of digital infrastructure construction and innovation, the impact of the digital economy on high-quality development in manufacturing exhibits a pattern of "diminishing marginal effects." In the initial stages of digital economy development, when the level of development is relatively low and the marginal cost of acquiring digital information for innovative entities is high, the resulting spillover effect of innovation is not pronounced. The scenario of high investment and low return leads to only a limited number of enterprises willing to make investments. On the other hand, the advent of the digital economy disrupts the traditional economic model’s characteristic of "diminishing marginal returns" of input factors. As the dividends of the digital economy continue to grow, numerous enterprises recognize the inevitability of development in the digital domain, subsequently increasing their research and development investments in digital technologies. Therefore, the facilitative role of the digital economy is found to increase marginally with the escalation in research and development investments. Based on these observations, the following hypothesis is proposed:

H4: The digital economy has a nonlinear impact on the high-quality development of the manufacturing industry.

3. Modeling

3.1 Model Selection

In alignment with the research objectives of this study, the following models are selected:

Model 1: In accordance with Hypothesis 1, to verify the direct impact mechanism between the digital economy and high-quality development in manufacturing, the following baseline regression model is established:

$$\ln\left(\text{manu}_{i,t}\right)=\alpha_0+\alpha_1\,\text{dig}_{i,t}+\alpha_2 Z_{i,t}+\varepsilon_{i,t} \tag{1}$$

where, i represents the region, and t denotes time; $manu_{i,t}$ is the dependent variable, indicating the level of high-quality development in manufacturing; $dig_{i,t}$ is the core explanatory variable, representing the level of the digital economy; $Z_{i,t}$ denotes a series of selected control variables; α_0 is the intercept term; and $\varepsilon_{i,t}$ is the random disturbance term.

Model 2: In line with Hypotheses 2 and 3, to further verify the indirect impact mechanism of the digital economy in empowering high-quality manufacturing development and to test whether human capital level and enterprise operational cost are mediating variables, the following mediation effect models are constructed in accordance with relevant testing principles for mediating variables:

$$t^{tmp}p_{i,t}=\beta_0+\beta_1\,\text{dig}_{i,t}+\beta_2 Z_{i,t}+\varepsilon_{i,t} \tag{2}$$

$$\ln\left(\text{ manu }_{i,t}\right)=\gamma_0+\gamma_1 M_{i,t}+\gamma_2\,\text{dig}_{i,t}+\gamma_3 Z_{i,t}+\varepsilon_{i,t} \tag{3}$$

where, $M_{i,t}$ represents the mediating variable, i.e., human capital level (tmp) and enterprise operational cost (enc); γ_2 signifies the direct impact effect of the digital economy on high-quality manufacturing development, and the product of γ_1 and β_1 indicates the mediating effect of the digital economy on high-quality manufacturing development. If both γ_1 and β_1 pass the significance test, then partial mediation is established.

Model 3: In accordance with Hypothesis 4, to verify the nonlinear effect of the digital economy on high-quality manufacturing development, this study utilizes the panel threshold model, as referenced from Hansen, for testing (Hansen, 1999). If only the single threshold test is passed, the following single threshold regression model is constructed:

$$\ln\left(\text{manu}_{i,t}\right)=\psi_0+\psi_1\,\text{Core}_{it}\times I\left(\text{Adj}_{it}\le Th1\right)+\psi_2\,\text{Core}_{it}\times I\left(\text{Adj}_{it}>\text{Th}1\right)+\psi_i Z_{i,t}+\varepsilon_{i,t} \tag{4}$$

If both the single and double threshold tests are passed but not the triple threshold test, the following double threshold regression model is constructed:

$$\begin{aligned}\ln\left(\text{ manu }_{i,t}\right)&=\psi_0+\psi_1\,\text{Core}_{i,t}\times I\left(\text{Adj}_{i,t}\le\ \text{Th}1\ \right)+\psi_2\,\text{Core}_{i,t}\times I\left(\text{Th}1<\text{Adj}_{i,t}\le Th2\right)\\&+\psi_3\,\text{Core}_{i,t}\times I\left(\text{Adj}_{i,t}>\text{Th}\,2\right)+\psi_i Z_{i,t}++\varepsilon_{i,t}\end{aligned} \tag{5}$$

where, $Core_{i,t}$ is the core explanatory variable; $I(*)$ is an indicator function that takes the value of 1 or 0, where 1 is assigned if the condition within the brackets is satisfied, otherwise 0; $Adj_{i,t}$ is the threshold variable; $Th1$ and $Th2$ are the estimated threshold values; and the coefficients ψ_1, ψ_2, and ψ_3 vary across different intervals.

3.2 Selection of Variables

3.2.1 Dependent variable

This study selects the level of high-quality development in manufacturing as the dependent variable. Presently, domestic research on the evaluation system for high-quality development in manufacturing is quite extensive. Duan & Yu (2021) established a comprehensive evaluation index system from three major aspects: economy, ecology, and society. This system encompasses eight dimensions, including industrial structure, industrial organization, speed and efficiency, industrial innovation, openness, trade competitiveness, ecological benefits, and social contribution. Yang et al. (2021) evaluated high-quality manufacturing development from four aspects: economic creation, technological innovation, openness, and green environmental protection. Furthermore, based on the guidelines issued by the Ministry of Industry and Information Technology of China on accelerating the cultivation and development of high-quality enterprises in the manufacturing sector, this study evaluates the high-quality development of Hebei Province's manufacturing industry from five dimensions: innovation potential, economic benefits, green development, energy development, and public benefit, as detailed in Table 1.

Table 1. Evaluation indicator system for high-quality development of manufacturing industry in Hebei Province

Objective	Primary Indicator	Secondary Indicator	Measure of Indicator	Attribute of Indicator	Weight
High-Quality Development of Manufacturing Industry in Hebei Province	Innovation Potential	Technological Human Resources Input Level	Full-Time Equivalent of R&D Personnel (Person-Years)	+	0.117
		Scientific and Technological Input Level	R&D Expenditure (100-million-yuan Yuan)	+	0.138
		Level of Patent Technology	Number of Patent Applications Granted (Items)	+	0.100
		Level of Industrial Structure Optimization	Investment in Manufacturing Construction Projects (100 million Yuan)	+	0.088
	Economic Benefits	Industrial Contribution Rate	Added Value of Secondary Industry / Regional GDP (%)	+	0.033
		Level of Labor Productivity	Profit / Operating Income of Industrial Enterprises above Designated Size (%)	+	0.030
	Green Development	Water Environment Quality Level	Industrial Wastewater Discharge (Ten Thousand Tons)	-	0.007
		Level of Toxic Gas Emissions	Industrial Sulfur Dioxide Emissions (Tons)	-	0.014
		Air Quality Level	Industrial Dust Emissions (Tons)	-	0.004
		Water Consumption Level	Water Consumption of Enterprises above Designated Size (Ten Thousand Cubic Meters)	-	0.012
	Energy Development	Energy Consumption Level	Industrial Energy Consumption (Ten Thousand Tons of Standard Coal)	-	0.029
		Level of Energy Investment	Investment in Energy Industry (Ten Thousand Yuan)	+	0.080
		Electricity Consumption Level	Industrial Electricity Consumption (Ten Thousand Kilowatt Hours)	+	0.165
	Public Benefit	Employment Level	Number of Employees in Manufacturing (Ten Thousand People)	+	0.088
		Living Standard of Residents	Per Capita Consumption / Per Capita Disposable Income of Residents (%)	+	0.095

3.2.2 Core explanatory variable

This study selects the digital economy as the core explanatory variable. Regarding the measurement of the digital economy level, there is yet to be a unified standard in the academic community, and most often, a composite indicator system is constructed in combination with the research objective. This paper uses panel data from various cities in Hebei Province from 2010 to 2019. Considering the characteristics of data availability, comparability, and comprehensiveness, the study mainly references the 2021 edition of the *China Digital Economy Development White Paper*. A city-level digital economy development indicator assessment system is designed, using three dimensions as primary indicators of the digital economy index system: the infrastructure of the digital economy in Hebei Province, the application of the digital economy in Hebei Province, and the development of the digital industry in Hebei Province. Among them, the secondary indicator for the infrastructure of Hebei Province's digital economy is the number of internet broadband access users; for the application of Hebei Province's digital economy, the secondary indicators are telecommunications business revenue and postal business revenue; and for the development of the digital industry in Hebei Province, the secondary indicator is the number of employees in the computer and information services industry.

3.2.3 Control variables

In this study, employment level, economic development level, industrial contribution level, and foreign investment are selected as control variables. (1) Employment Level (ele): This study selects the number of employees in the production and supply of electricity, gas, and water to represent the employment level. As sources of energy for manufacturing production, the supply of electricity, gas, and water directly impacts the development level of the manufacturing industry, and the employment level reflects the prosperity of this sector to a certain extent. (2) Economic Development Level (eco): Per capita GDP is used to represent the level of economic development. A higher level of economic development indicates more funds available for investing in talent recruitment, equipment upgrades, and expansion of production scale, which are beneficial for the development of

local manufacturing. (3) Industrial Contribution Level (gdp): This paper uses the GDP of the secondary industry to represent the level of industrial contribution. The secondary industry primarily refers to the processing and manufacturing industry, and the higher the output of this industry, the more it can directly drive the development of manufacturing. (4) Foreign Investment (inv): foreign direct investment is used to represent foreign investment. A higher level of foreign investment leads to more capital inflow into the domestic market. Moreover, advanced management models and technologies brought by foreign investors can help enterprises improve production efficiency and increase output value.

3.3 Data Sources

This study utilizes panel data from various cities in Hebei Province for the years 2010 to 2019. The data were sourced from the *Hebei Provincial Statistical Yearbook*, the *China Statistical Yearbook*, the *Hebei Provincial Science and Technology Expenditure Statistics Bulletin*, the *Hebei Provincial Information and Communications Industry and Internet Development Report*, the *China Science and Technology Statistical Yearbook*, the *Hebei Provincial Internet Development Report*, and the *Statistical Bulletin of National Economic and Social Development* from various cities.

4. Empirical Analysis Results

4.1 Baseline Regression Results

The digital economy has a positive impact on the high-quality development of the manufacturing industry in Hebei Province. The study encompasses a total of nine subjects over a span of ten years. To examine whether the addition of control variables alters the direction and magnitude of the impact of the core explanatory variable on the dependent variable, this study incrementally added control variables in its analysis. Table 2 presents the overall influence of Hebei Province's digital economy on the development of the manufacturing industry.

Table 2. Baseline regression results

	(1)	(2)	(3)	(4)	(5)
Variables	ln_manu	ln_manu	ln_manu	ln_manu	ln_manu
dig	2.935***	2.001***	1.233***	1.189***	1.096***
	(0.277)	(0.223)	(0.123)	(0.124)	(0.124)
ele		0.254***	0.252***	0.272***	0.170***
		(0.0410)	(0.0283)	(0.0316)	(0.0507)
eco			0.866***	0.910***	0.516**
			(0.0746)	(0.0831)	(0.197)
inv				-0.0416	-0.0526
				(0.0473)	(0.0456)
gdp					0.134***
					(0.0491)
Constant	-1.697***	-2.004***	-2.256***	-2.276***	-2.085***
	(0.0356)	(0.0544)	(0.0484)	(0.0475)	(0.0948)
Observations	87	87	87	87	87
R-squared	0.636	0.760	0.867	0.868	0.881

Note: ***, **, and * respectively indicate significance at the 1%, 5%, and 10% levels in a two-tailed t-test.

Firstly, regarding the overall situation of the core explanatory variable, the digital economy's level of development, empowering the high-quality development of Hebei Province's manufacturing industry, it is evident from Table 2 that the core explanatory variable in models (1) through (5) is significantly positive at the 1% level. Additionally, the number of control variables does not affect the role of the digital economy in promoting high-quality development. As can be seen from column (5) in Table 2, for every one percentage point increase in the development level of Hebei Province's manufacturing industry, there is a 1.906% increase in its manufacturing development level.

Secondly, regarding the impact mechanism of control variables on the high-quality development of Hebei Province's manufacturing industry, columns (2) to (5) indicate that with the sequential addition of control variables, except for foreign investment (inv), which did not pass the significance test, the remaining three control variables maintain the same direction and level of significance in their impact on the dependent variable. Therefore, this paper primarily focuses on the analysis of the impact mechanism of control variables on the dependent variable in column (5).

i. The regression coefficient of employment level (ele) is significantly positive at the 1% level, indicating that the employment level has a positive impact on the high-quality development of Hebei Province's

manufacturing industry. Increasing employment levels can provide more human resources for the manufacturing industry while also enhancing the overall consumption level in Hebei Province, thereby expanding the domestic consumer market.

ii. The regression coefficient of the economic development level (eco) is significantly positive at the 5% level, indicating that the higher the per capita GDP of the cities in Hebei Province, the more income residents have for consumption. This can stimulate market investment and development, thus promoting high-quality development in Hebei Province's manufacturing industry.

iii. Foreign investment (inv) has a negative impact on high-quality development but did not pass the significance test. A possible reason is that most of the capital flowing into Hebei Province from abroad is not invested in the manufacturing industry, thus failing to stimulate its intended effect.

iv. The regression coefficient of the industrial contribution level (gdp) is significantly positive at the 1% level, indicating that the industrial contribution level has played a positive role in the high-quality development of Hebei Province's manufacturing industry. The higher the output value of the secondary industry, the greater its promoting effect on the high-quality development of manufacturing.

Finally, through the analysis of $R^2$and the five regression models, it is observed that the core explanatory variable effectively explains the dependent variable, the high-quality development of the manufacturing industry in Hebei Province. With the incremental addition of control variables, the value of R^2also gradually increases, indicating that adding control variables can enhance the explanatory power of the core explanatory variable. Therefore, the method of incrementally adding control variables is appropriate.

4.2 Robustness Tests

To ensure the validity of the conclusions, the following three methods were employed for robustness testing:

i. Substitution of the core dependent variable. The high-quality development evaluation system of Hebei Province's manufacturing industry was reconstructed using the principal component analysis method. Column (1) of Table 3 shows that the regression coefficient of dig is significantly positive at the 1% significance level, indicating that the digital economy positively drives the high-quality development of the manufacturing industry in Hebei Province.

Table 3. Results of robustness test

	(1)	(2)
Variables	ln_manu2	ln_manu
dig	0.567***	
	(0.0661)	
dig’		0.147**
		(0.0562)
Control variable	yes	yes
Constant	-0.427***	-2.022***
	(0.0505)	(0.118)
Observations	87	87
R-squared	0.740	0.847

Note: ***, **, and * respectively indicate significance at the 1%, 5%, and 10% levels in a two-tailed t-test.

Table 4. Test for endogeneity issues

	(1)	(2)	(3)
Variables	dig	ln_manu	ln_manu
L1.dig	1.076***		
	(0.0507)		
dighat		1.006***	
		(0.158)	
dig			1.006***
			(0.141)
Constant	0.0129	-2.108***	-2.108***
	(0.0173)	(0.114)	(0.111)
F-statistic	449.79***		
Control variable	yes	yes	yes
Observations	87	87	87
R-squared	0.955	0.875	0.883

Note: ***, **, and * respectively indicate significance at the 1%, 5%, and 10% levels in a two-tailed t-test.

ii. Substitution of the core explanatory variable. The level of the digital economy was re-measured using the

principal component analysis method, with results presented in column (2) of Table 3. It is observed that the development of Hebei Province's manufacturing industry is influenced by the digital economy, indicating the robustness of the model's conclusions.

iii. Utilization of the instrumental variable method to address potential endogeneity issues in the model. In this study, the first-order lag of the core explanatory variable was used as an instrumental variable, and the two-stage regression results are shown in Table 4. Column (1) of Table 4 indicates that the regression coefficient of the first-order lag of the digital economy (L1.dig) is significantly positive at the 1% significance level, and the F-statistic in the first stage is greater than 10, suggesting that the instrumental variable is correlated with the endogenous variable. In summary, considering endogeneity factors, the facilitative role of the digital economy remains significant, suggesting a certain robustness in the conclusions.

4.3 Mediation Effect Test

To examine the indirect transmission mechanism by which the digital economy impacts high-quality manufacturing development through human capital levels and enterprise operational costs, this study conducted empirical testing using mediation effect models based on the baseline regression. The test results are shown in Table 5.

As shown in the baseline regression results in column (1), the regression coefficient of the digital economy (dig) is significantly positive at the 1% significance level, indicating that the digital economy effectively promotes high-quality development in manufacturing.

Columns (2) and (3) test whether the digital economy can impact high-quality manufacturing development through the level of human capital. Column (2) shows that the regression coefficient of the digital economy (dig) is significantly positive at the 1% level, indicating that the digital economy plays a positive role in enhancing human capital levels. Column (3) shows that both the digital economy (dig) and human capital level (emp) have regression coefficients that are significantly positive at the 1% level, suggesting that the digital economy can enhance manufacturing development by improving human capital levels, with a partial mediation effect size of 0.165.

Columns (4) and (5) test whether the digital economy impacts high-quality manufacturing development through enterprise operational costs. In both columns (4) and (5), the regression coefficients of the digital economy (dig) are significantly positive at the 1% level, while in column (5), the regression coefficient of enterprise operational cost (enc) is significantly negative at the 1% level. This indicates that the digital economy can promote high-quality manufacturing development by reducing production and operational costs, with a partial mediation effect size of 0.083.

Table 5. Regression results of mediating variables

	(1)	(2)	(3)	(4)	(5)
Variables	ln_manu	emp	ln_manu	enc	ln_manu
dig	1.096***	0.185***	0.931***	0.455***	0.873***
	(0.124)	(0.0438)	(0.147)	(0.0592)	(0.173)
emp			0.891***		
			(0.333)		
enc					-0.182***
					(0.0625)
Constant	-2.085***	0.00264	-2.087***	-0.0109	-2.087***
	(0.0948)	(0.0417)	(0.0939)	(0.0654)	(0.0970)
Control variable	yes	yes	yes	yes	yes
Observations	87	87	87	87	87
R-squared	0.881	0.811	0.887	0.821	0.878

Note: ***, **, and * respectively indicate significance at the 1%, 5%, and 10% levels in a two-tailed t-test.

4.4 Nonlinear Effect Analysis

The threshold model was used to analyze the nonlinear effects of the digital economy on the high-quality development of manufacturing. The analysis examined the impact mechanism of the digital economy on high-quality manufacturing development under different levels of digital infrastructure construction (A1), research and development investment (A2), and innovation (A3). The Bootstrap resampling method was employed to sample the dataset 500 times repeatedly. In each threshold variable, the model passed the existence test for single or double threshold effects, with results shown in Table 6.

Table 6. Regression results of the threshold model

	(1)	(2)	(3)
Variables	ln_manu	ln_manu	ln_manu
Core		*dig*	
Adj	*A1*	*A2*	*A3*
Th1	0.0439	0.0233	2.5699
Th2		0.5092	
Core×*I*(*Adj*≤*Th1*)	4.474***	-2.388***	3.011***
	(0.000)	(0.025)	(0.006)
Core×*I*(*Th1*<*Adj*≤*Th2*) or	0.24475	0.42860	0.38246
Core×*I*(*Adj*>*Th1*)	(0.321)	(0.085)	(0.145)
Core×*I*(*Adj*>*Th2*)		1.371***	
		(0.001)	
Control variable	yes	yes	yes
Observations	90	90	90

Note: ***, **, and * respectively indicate significance at the 1%, 5%, and 10% levels in a two-tailed t-test.

Columns (1) to (3) of Table 6 display the estimated results of the panel threshold regression model with digital infrastructure construction level (A1), research and development investment level (A2), and innovation level (A3) as threshold variables, and the level of digital economy development as the core explanatory variable.

i. Digital Infrastructure Construction Level. As shown in column (1) of Table 6, with the improvement of the digital infrastructure construction level, the direct impact of the digital economy on the high-quality development of manufacturing gradually strengthens. Furthermore, when the digital infrastructure construction level (A1) is below 0.0439, the direct impact effect of the digital economy (dig) on high-quality manufacturing development is significantly positive at the 1% level. However, when the digital infrastructure construction level (A1) exceeds 0.0439, the regression coefficient of dig does not pass the significance test, indicating that the promoting effect of the digital economy is not apparent. This suggests that the development of the digital economy is inseparable from the support of digital infrastructure and that in the early stages of digital economy development, its infrastructure construction must align with the development level of manufacturing to ensure more sustainable and efficient development of the digital economy.
ii. Research and Development Investment Level. The estimated results in column (2) of Table 6 show that when the scale of research and development investment (A2) is below 0.0233, the regression coefficient of the digital economy (dig) is significantly negative at the 1% level. When the scale of research and development investment (A2) exceeds 0.0233 but is less than 0.5092, the regression coefficient of the digital economy (dig) increases. When the scale of research and development investment (A2) is higher than 0.5092, the regression coefficient of the digital economy (dig) is significantly positive at the 1% level, indicating that with the increase in research and development investment level, the promoting role of the digital economy shows nonlinear growth. The level of research and development investment in technological innovation directly affects the digital economy's role in promoting high-quality development. Therefore, increased funding for technological innovation should be encouraged to enhance the sustainability and efficiency of the digital economy's development.
iii. Innovation Level. The estimated results in column (3) of Table 6 show that when the innovation level (A3) is below 2.5699, the regression coefficient of the digital economy (dig) is significantly positive at the 1% level, indicating that the positive effect of the digital economy on high-quality manufacturing development gradually strengthens with the enhancement of the innovation level. When the innovation level (A3) exceeds 2.5699, the regression coefficient of the digital economy (dig) is only 0.38246. This suggests that within a certain range, the innovation level positively influences the promotion of the digital economy. However, excessively high levels of innovation can burden the development of the digital economy and hinder high-quality manufacturing development in Hebei Province to some extent.

5. Conclusions and Policy Recommendations

Based on panel data from 2010-2019 for nine prefecture-level cities in Hebei Province, encompassing the digital economy and manufacturing, this study-built mediation models and panel threshold models to explore the intrinsic impact mechanisms of digital economy development on high-quality manufacturing development from direct, indirect, and nonlinear perspectives. The main conclusions are as follows: (1) The digital economy significantly promotes the rapid growth of Hebei Province's manufacturing industry. (2) Mediation model results indicate that the digital economy promotes rapid development in manufacturing by enhancing human capital levels and reducing enterprise operational costs. (3) Results from the threshold panel model show that at different levels of digital infrastructure construction, research and development investment, and innovation, the impact of the digital

economy on high-quality manufacturing development in Hebei Province exhibits stepwise differences, with varying effects. Excessive levels of digital infrastructure construction and innovation weaken the promoting role of the digital economy, whereas increased research and development investment strengthens the promoting effect of the digital economy on manufacturing.

Based on these conclusions, the following policy recommendations are proposed:

First, it's suggested to vigorously support the development of the digital economy in Hebei Province by improving new-generation digital infrastructures such as cloud computing, the Internet of Things, and data centers, and accelerating the application of new technologies like AI, big data, and 5G in traditional manufacturing in Hebei Province. At the same time, focus should be laid on breaking through core technologies, speeding up the digital transformation of traditional industries, fully utilizing the advantages of the digital economy, promoting employment and economic development in Hebei Province, and enhancing the contribution rate of the secondary industry to more effectively promote the enabling mechanism of the digital economy.

Second, it's suggested to accelerate the establishment and improvement of the human capital system, providing a solid talent foundation for the development of the digital economy in Hebei Province. One approach is to utilize the strategic advantages of the integration of Beijing, Tianjin, and Hebei, attracting external resources through cooperation with key universities in Beijing and Tianjin to enhance the quality of talent cultivation. In addition, the government should innovate teaching methods through digital technologies while popularizing basic education, and advance vocational education. Furthermore, to respond to the demand of China's labor market, emphasis should be laid on cultivating high-quality, high-skilled talents, establishing a comprehensive talent service system, effectively utilize human resources, and laying a solid talent foundation for high-quality manufacturing development driven by the digital economy.

Third, it's suggested to enhance the operational efficiency of manufacturing enterprises in Hebei Province by utilizing the information transmission advantages of the digital economy to improve the operational efficiency of Hebei's manufacturing industry, effectively reducing operational costs in manufacturing, an important component of Hebei's industry, and exerting a positive impact on promoting high-quality development in manufacturing. For small and medium-sized enterprises with limited data collection and application capabilities, it's suggested to encourage large enterprises and state-owned enterprises to open and share data interfaces, strengthen information resource circulation among enterprises, and improve business efficiency.

Fourth, it's suggested to stimulate the innovative vitality of Hebei Province's manufacturing industry in the digital economy. Innovation-driven is the key focus and difficulty in the transformation of the manufacturing industry. On the one hand, based on the strategic needs of the digital transformation of Hebei Province's manufacturing industry, it's suggested to strengthen digital basic scientific research funding, promote cooperation and innovation in production, education, and research, allocate more investment in research and development, and reduce the proportion of investment in digital infrastructure construction and innovation levels. On the other hand, enterprises should also establish research platforms in areas such as industrial Internet, big data, artificial intelligence, and network security according to their actual situations and specific needs, break through core technologies, and strive for independent innovation at the technological and product levels.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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