Research on the Mechanism of Digital Productivity Promoting the Development of Manufacturing Enterprises: Evidence from Tai'an City

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Abstract: Digital productivity refers to digital technology as the core. The rapid development of digital economy has brought new production methods and business models to manufacturing enterprises. In this context, exploring how digital productivity drives the high-quality development of manufacturing enterprises is of great significance for deepening the theoretical innovation of digital productivity, grasping the development law of the digital era, and promoting economic transformation and upgrading. This paper takes the manufacturing enterprises in Tai'an City from 2011 to 2022 as the research sample, constructs the digital productivity index and the high-quality development level of manufacturing enterprises through the entropy method, and uses the two-way fixed effect model and the mediating effect model to empirically study the channel mechanism of digital productivity on the high-quality development of manufacturing enterprises. The research finds that digital productivity can significantly improve the high-quality development level of manufacturing industry. Technological innovation and human capital are important mechanisms for digital productivity to promote the high-quality development process of manufacturing enterprises, but the conduction effect of human capital is better than that of technological innovation. Finally, according to the above research results, this paper puts forward some policy suggestions, such as constructing 'data-industry' collaborative innovation ecology, strengthening technology penetration, and innovating 'education-industry' human capital value-added model, in order to provide reference for promoting high-quality development of enterprises.

Keywords: Digital Productivity; Digital Economy; Tai'an City; Implementation Path; High-Quality Development

1. Introduction

Digital productivity refers to the ability to promote production efficiency and economic structure optimization through the efficient allocation of data elements and technological innovation with digital technology as the core. The rapid development of digital economy has brought new production methods and business models to manufacturing enterprises. Its core features include high innovation, strong permeability, wide coverage and cross-border integration [1,2]. These characteristics enable digital productivity to break through the limitations of traditional production factors and achieve a leap in production efficiency.

At the moment when the global industrial competition paradigm is accelerating, the value creation logic of the manufacturing industry is undergoing a paradigm shift from "mechanical materialism" to "digital symbiosis." This process presents a unique "dual-track" feature in China: it not only needs to complete the digital make-up of traditional production methods, but also faces the strategic opportunity of formulating new rules in the intelligent era. According to the latest calculation of the China National Industrial Information Security Development Center in 2024, the digital productivity index of China 's manufacturing industry reached 67.3 (out of 100), but the dispersion of subdivision areas was as high as 41.8, revealing the structural contradictions in the process of transformation. The core paradox facing China's manufacturing industry is that there is a significant elastic gap between the input intensity of digital infrastructure (average annual growth of 19.2%) and the growth rate of total factor productivity (average annual growth of 3.8%). This phenomenon of "digital input-output attenuation "exposes three deep-seated problems: First, the intelligent transformation of equipment has not been effectively transformed into process knowledge precipitation, and the digitization rate of process knowledge in a provincial intelligent manufacturing demonstration project is only 28.4%. Second, the market-oriented allocation of data elements has institutional damage, and the actual conversion rate of industrial data transactions is less than 1/5 of the theoretical expectation. Thirdly, the application of digital technology shows a tendency of 'excess instrumental rationality and insufficient value rationality', and the average utilization rate of digital system function of a leading enterprise is only 37%. These phenomena have prompted us to rethink: through what transmission channels can digital productivity truly become a 'converter' rather than a 'decorator' for high-quality development? Based on the above background, this paper focuses on the mechanism of digital productivity enabling the high-quality development of manufacturing enterprises, and uses the enterprise data of Tai'an City to study the channel mechanism and heterogeneity performance of digital productivity promoting the high-quality development of manufacturing enterprises in Tai'an City.

The existing literature has obtained rich conclusions in this regard. First, accelerate technological innovation. The deep penetration of digital technology has significantly reconstructed the innovation paradigm of manufacturing industry. Different from the traditional linear innovation model, the technological progress in the digital era presents the characteristics of "collaborative co-creation" [3]. On the one hand, industrial big data analysis enables enterprises to identify technology evolution trends in real time and shorten the R&D cycle by about 30%-50%[4]. For example, an automobile manufacturing enterprise uses AI simulation technology to reduce the development cycle of new models from 36 months to 18 months, while reducing trial and error costs by up to 40%. On the other hand, open digital innovation platforms (such as Huawei Shengteng AI Ecology) promote cross-enterprise technology sharing, enabling SMEs to access advanced technology resources at a lower cost, forming an 'innovation long tail effect' [5]. Secondly, by reconstructing the management paradigm, digital transformation not only optimizes the traditional management process, but also gives birth to the new governance model of 'data-driven organization' [6]. Compared with hierarchical management, digital enterprises show three typical characteristics: decentralized decision-making, and blockchain-based smart contracts increase production scheduling efficiency by more than 60% [7]; In terms of operation adaptability, a home appliance enterprise realizes dynamic adjustment of production line through digital twin technology, and the idle rate of equipment decreases by 28%; The upgrading of talent structure and human-machine collaborative decision-making have increased the demand for high-skilled labor by 45%, and promoted the transition of organizational ability to 'cognitive' [8]. Finally, the intelligent allocation of resources. Digital productivity reshapes the logic of factor allocation through 'virtual-entity integration'. The practice of industrial Internet platforms (such as root interconnection) shows that cloud collaborative design improves cross-regional R&D efficiency by 3.2 times by breaking through spatial constraints [9]; Through flexible resource restructuring, an equipment manufacturing enterprise increased the equipment utilization rate from 55% to 82% by sharing the capacity platform; Significantly reduce carbon emissions, AI-driven energy management system reduces energy consumption per unit output value by 19%, which verifies the enabling effect of digital technology on green manufacturing [10].

2. Theoretical Mechanisms

As a new paradigm of production factor combination, the essence of digital productivity is to reconstruct the value creation logic of manufacturing industry through the liquidity of data elements. First of all, digital productivity breaks the hierarchical structure of traditional innovation systems and promotes the evolution of manufacturing innovation networks from the 'center-periphery' model to a distributed topology. The core of this transformation lies in the dual movement of 'decentralization-recentralization' of data elements: On the one hand, the industrial Internet platform deconstructs the power center of the original innovation system; on the other hand, the algorithmic governance mechanism has formed a new coordination center in the higher dimension. This structural transformation has fundamentally changed the way of connection between innovation subjects, and has spawned an innovation ecosystem with small-world network characteristics. Secondly, digital productivity promotes profound changes in the production and dissemination of technical knowledge. The application of digital technology makes tacit knowledge explicit and standardized, and realizes the sharing and reuse across time and space through the industrial Internet platform. The improvement of knowledge coding reduces the cost of technology transfer and accelerates the diffusion of innovation achievements. At the same time, the application of artificial intelligence and other technologies has expanded the boundary of human cognition and made a qualitative leap in the efficiency of solving complex technical problems. Finally, digital productivity reconstructs the production function of manufacturing industry. On the basis of traditional production factors, the addition of data elements has changed the allocation efficiency of capital, labor and other factors. The penetration of digital technology enables the production system to have the ability of self-perception, self-decision and self-execution, and realizes the expansion from economies of scale to economies of scope. The evolution of this production function promotes manufacturing enterprises to break through the constraints of traditional production possibility boundaries. Based on this, Hypothesis 1 is proposed: digital productivity enables high-quality development of manufacturing industry by promoting technological innovation.

As a new paradigm of production factor allocation, the core of digital productivity is to reshape the value creation path of manufacturing industry through technology-human synergy effect. First of all, digital productivity breaks the linear accumulation mode of traditional human capital and promotes the transformation of manufacturing skill system from 'ladder' development to 'network' distribution. This reconstruction is manifested in the dual process of 'decoupling-restructuring' of skill elements: the industrial Internet platform deconstructs the rigid structure of the original skill combination, and the intelligent algorithm system realizes the flexible configuration of skill elements in a higher dimension. This kind of skill network reconstruction makes the human capital accumulation path show typical scale-free network characteristics. Secondly, digital productivity promotes the transformation of manufacturing human capital development from 'experience-dependent' to 'data-driven'. This transition includes three dimensions: industrial big data platform accelerates the coding process of tacit knowledge, augmented reality technology expands the space-time boundary of skill acquisition, and intelligent auxiliary system reconstructs the feedback mechanism of knowledge verification. The new knowledge acquisition paradigm significantly improves the efficiency of human capital accumulation and forms an enhanced loop of continuous self-optimization. Finally, the development of human capital in the manufacturing industry driven by digital productivity presents the characteristics of 'fluidization': the learning boundary is permeable, the knowledge flow is networked, and the ability evolution is adaptive. This evolution enables manufacturing enterprises to respond more quickly to technological changes, integrate knowledge resources more efficiently, and continuously improve organizational capabilities. Based on this, Hypothesis 2 is proposed: digital productivity empowers the high-quality development of manufacturing industry by improving human capital.

3. Research Design

3.1 Variable Selection and Data Source

3.1.1 Explained Variables

High-quality development of manufacturing enterprises (Mdh). Based on the connotation of high-quality development of manufacturing industry and the previous theoretical analysis, an index system including three dimensions of product quality, ecological environment and economic benefits is constructed. The specific index selection and index description are shown in Table 1. Based on this, the Mdh index is calculated by the entropy method.

Table 1. Evaluation Index System of High-Quality Development of Manufacturing Enterprises

First Index	Second Index	Indicator Description
Product Quality	R&D investment intensity	Industrial enterprises above Designated size expenditure of R & D funds in industrial enterprises / Main business income (+)
	Number of patents per capita	Number of invention patent applications of industrial enterprises above designated size / Number of R & D personnel (+)
	R&D personnel occupation rate	The number of R & D personnel in industrial enterprises above designated size / Number of employees (+)
	Rate of qualified products	Number of qualified products of manufacturing quality / Total number of products (+)
Ecological Environment	Sulfur dioxide emission intensity	Industrial carbon dioxide emissions / The added value of industry (-)
	Ammonia nitrogen emission intensity	Industrial ammonia nitrogen emissions / The added value of industry (-)
	Solid waste utilization rate	Utilization rate of industrial solid waste / Industrial solid waste production (+)
	Energy consumption intensity	Energy consumption / The added value of industry (-)
Economic Benefit	Input-output ratio of new products	New product sales revenue of industrial enterprises above designated size / New product development expenditure (+)
	Operating profit margin	Manufacturing operating profit / Main business income of manufacturing industry (+)
	Labor productivity	Industrial added value / Number of manufacturing employees (+)
	Average wage	Total wages of employees in manufacturing urban units / Number of employees (+)

Note: The positive and negative symbols in brackets represent the attribute of the index.

3.1.2 Explanatory Variables

Tai'an digital productivity index (De). This paper focuses on the representative fields of the digital economy from the three dimensions of digital technology, digital talents and digital platforms, constructs a digital productivity measurement index system, and completes the index measurement from 2011 to 2022 through the global entropy method and the main factor analysis method, as shown in Table 2.

Table 2. Indicators of Digital Productivity in Tai'an City

First Index	Second Index	Third Index
Digital Technique	Digital technology products	Main business income of communication equipment, computer and other electronic equipment manufacturing industry
		Imports of communications equipment, computers and other electronic equipment manufacturing industry
		Exports of communications equipment, computers and other electronic equipment manufacturing industry
		Software and information technology services business income
	Fundamentals of digital technology	Number of enterprise digital technology patents
		The proportion of enterprise digital technology development investment
		Enterprise digitalization
Digital Talent	Total number of digital talent	Number of artificial intelligence talents
		The number of talents engaged in big data
		From the Internet of things, the number of industrial Internet talents
	Digital talent structure	Proportion of talents receiving higher education
		Proportion of female digital talents
		The proportion of talents in private enterprises
		The proportion of traditional manufacturing talents
		The proportion of emerging manufacturing talents
Digital Platforms	Platform economy	The proportion of international e-commerce platform activity enterprises
		The proportion of domestic e-commerce platform activity enterprises
		Enterprises have the number of self-built websites
		E-commerce sales
	Platform foundation	The proportion of the main business income of the new product sales income of the enterprise
		Enterprise technical transformation expenditure
		Enterprise technology introduction expenditure

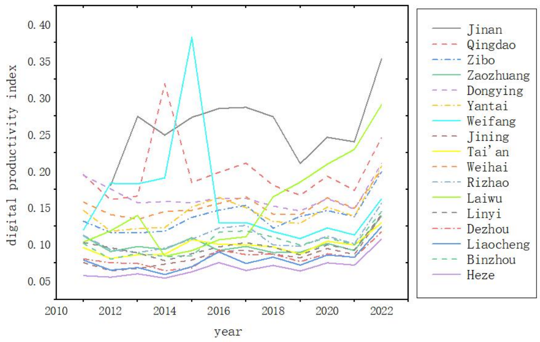

Figure 1. The Change Trend of Digital Productivity Index of Prefecture-level Cities in Shandong Province from 2011 to 2022

According to the above index system, the digital productivity index of 17 prefecture-level cities in Shandong Province is calculated. The trend of 2011-2022 is shown in Figure 1. It is not difficult to find that Tai'an City is in the back part and the level is low.

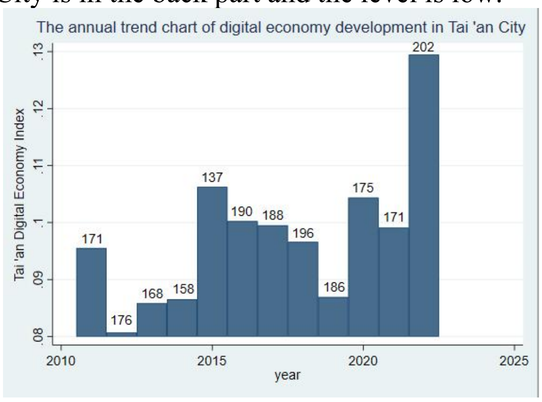

Figure 2. The Change Trend of Digital Productivity Index in Tai'an City from 2011 to 2022

A separate analysis of the changes in the digital productivity index of Tai'an City is shown in Figure 2. The number above the column indicates the national ranking of digital productivity in Tai'an City in that year. Obviously, Tai'an City has experienced volatility growth in absolute values, but the ranking position is not consistent with the value. For example, in 2011, the digital productivity index of Tai'an City was nearly 0.13, which achieved a significant improvement, but the national ranking was only 202. It shows that although the development of digital economy in Tai'an has made obvious progress, it still lags behind the progress of other cities.

3.1.3 Mediating Variables

The mediating variables are technological innovation (Ti) and human capital (Hum). Use the number of invention patent applications to characterize technological innovation; this paper uses the scientific research and technology service industry plus the information transmission, software and information technology service industry as the proportion of the total employment of urban units to the total employment of urban units to characterize human capital.

3.1.4 Control Variables

The city-level control variables selected by the project are urbanization rate (Ul), government support (Gov), and consumption level (Cs). The enterprise-level control variable set D set by mainly includes: enterprise age (Age), enterprise scale (Lnscale), profit margin (Profitrate), debt ratio (Debtrade), leverage ratio (Levrate), capital output ratio (Kyrate). Descriptive statistics of the main variables are shown in Table 3.

Table 3. Descriptive Statistics of Main Variables

Variable	Number of Samples	Mean Value	Standard Deviation	Minimum Value	Maximum Value
Mdh	1705	0.35	0.11	0.16	0.84
De	1705	0.12	0.13	0.01	0.77
Ti	1705	8.42	1.40	4.51	11.53
Hum	1705	0.04	0.03	0.01	0.21
Age	1705	10.39	7.86	0	126
Lnscale	1705	10.97	11.02	0	19.31
Profitrate	1705	0.23	0.25	-0.69	0.90
Debtrade	1705	0.57	0.41	0	3.10
Levrate	1705	2.67	3.76	0	23.70
Kyrate	1705	1.34	1.69	0	10.69

3.1.5 Data Source

The manufacturing enterprises in Tai'an City from 2011 to 2022 were selected as research samples. The data mainly comes from 'China Science and Technology Statistical Yearbook', 'City Statistical Yearbook', 'Shandong Statistical Yearbook', 'Tai'an Statistical Yearbook', CSMAR Database, Specialized New Enterprise Database, China Industrial Enterprise Database, etc. The missing data are supplemented by linear interpolation.

3.2 Model Construction

Based on the previous theoretical analysis, this paper uses panel data to construct the following benchmark regression model Hausman test results show that the fixed effect model is better than the random effect model. This paper uses the individual and time two-way fixed effect model for empirical test. The following joint model group was constructed:

$$Mdh_{it} = \alpha_1 + \alpha_2 De_{it} + \sum_{j=1}^{9} \theta_{jt} D_{jt} + \sigma_{it} + \mu_{it} + \varepsilon_{it} \quad (1)$$

$$Mdh_{it} = \alpha_1 + \alpha_2 De_{it} + \sum_{k=1}^{2} \alpha_{kt} M_{it} + \sum_{j=1}^{9} \alpha_{jt} D_{jt} + \sigma_{it} + \mu_{it} + \varepsilon_{it} \quad (2)$$

Among them, i represents the individual enterprise, t represents the year, the variable being explained is the high-quality development index of manufacturing enterprises, the explanatory variable is the digital productivity index, D represents the set of control variables, σ represents the individual fixed effect of the enterprise, μ reflects the fixed time effect of the year, and ε refers to the random disturbance term. M is a set of intermediary variables that digital productivity affects the high-quality development of manufacturing enterprises, including technological innovation (Ti) and human capital (Hum). α_k (k=1,2,3…9) are the influence coefficients of technological innovation and human capital on the high-quality development of manufacturing enterprises.

4.Empirical Results Analysis

Verify the significance of regression coefficients α_2 and α_k in Model (1) and Model (2). If both are significant at the same time, the mechanism effect exists. The test results are shown in Table 4. The results show that both the coefficient of digital productivity and the coefficient of mediating variables are significantly positive, and the goodness of fit of the model is high. Therefore, technological innovation (Ti) and human capital (Hum) do play a significant role in the high-quality development of manufacturing enterprises empowered by the digital economy. When technological innovation is the mediating variable, the transmission effect is 0.0412, accounting for 11.66% of the total effect. When human capital is the mediating variable, the transmission effect is 0.0472, accounting for 15.64% of the total effect, and the transmission effect is stronger than that of technological innovation. The regression results show that the digital economy can significantly enhance the innovation vitality of enterprises, stimulate the shift of human capital demand to high-tech and high-knowledge talents, promote the manufacturing industry to further change the growth mode, improve production efficiency, optimize the industrial structure, and improve the ability to obtain value, so as to achieve high-quality development. Therefore, the hypothesis 1 and hypothesis 2 of this topic are verified.

Table 4. Test of Mechanism of Action

	Baseline Regression	Technological Innovation	Human Capital	Joint Mediating Effect
De	0.0792*** (0.0836)	0.0412*** (0.0811)	0.0472*** (0.0129)	0.4432*** (0.0217)
Ti				0.2142* (0.7001)
Hum				0.0013** (0.4324)
Control Variable	Yes	Yes	Yes	Yes
Individual Fixed Effect	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes
N	1705	1271	1290	1193
R2	0.485	0.466	0.005	0.003

Note: * * *, * *, * are significant at the statistical level of 1%, 5% and 10% respectively, and the p value is reported in the circular brackets

5.Conclusions and Policy Recommendations

This paper theoretically analyzes the direct and indirect empowerment mechanism of digital economy on the high-quality development of manufacturing industry. Taking the manufacturing enterprises in Tai'an City from 2011 to 2022 as samples, the evaluation system of digital productivity and high-quality development index of manufacturing industry is constructed respectively, and the theoretical mechanism is empirically tested by the intermediary effect model. It is proposed that the digital economy promotes the high-quality development of manufacturing industry through two indirect paths of technological innovation and human capital, but the conduction effect of human capital is better than that of technological innovation. In view of the above research results, this paper puts forward the following policy recommendations.

First, build a 'data-industry' collaborative innovation ecology and strengthen technology penetration. Build a regional industrial data hub: relying on Tai’an equipment manufacturing, new materials and other advantageous industries, build an industry-level industrial Internet platform, and promote enterprise data sharing and collaborative research and development. Establish a 'data factor circulation pilot area', explore the data property rights separation mechanism, and encourage enterprises to release the value of production data. Targeted support for "neck" technology research: set up a special fund for Tai’an intelligent manufacturing, focus on supporting local enterprises in digital process breakthroughs in CNC machine tools, high-end building materials and other fields, and give 150% additional deduction for R&D expenses for projects that have successfully achieved domestic substitution.

Second, innovate the 'education-industry' human capital appreciation model. Create a 'digital craftsman' training system: unite Shandong University of Science and Technology, Taishan University and other universities to set up intelligent manufacturing micro-majors, implement the 'credit bank' system, and allow enterprise technical backbones to exchange academic credits through project practice. Establish 'Taishan Digital Skills Certification Center' and formulate local digital skills standards. Implement the "blue-collar elite" plan: give housing subsidies + technical equity incentives to technicians who have won national-level skills competition awards, and promote the exchange of professional titles between senior technicians and engineers to break the "ceiling" of career development.

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