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INDUSTRIAL DIGITALIZATION AND REGIONAL INNOVATION EFFICIENCY: EVIDENCE FROM 30 PROVINCES AND CITIES IN CHINA[1]

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***ABSTRACT**. With the rapid progress of the digital technology revolution, industrial digitalization has brought new opportunities for improving regional innovation efficiency. To explore whether industrial digitalization can effectively improve regional innovation efficiency, using the panel data of 30 provinces and cities in China during 2013-2020, based on the techno-economic paradigm theory*

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and appropriate technology theory, the influencing mechanism of industrial digitalization on regional innovation efficiency was probed into through the Super-SBM model of unexpected output, the entropy method, and the econometric analysis method. Results reveal that (1) industrial digitalization has a significantly positive impact on regional innovation efficiency in China, i.e., industrial digitalization provides a new idea for solving the dilemma of regional "innovation efficiency". (2) Industrial digitalization indirectly improves regional innovation efficiency by optimizing the industrial structure effect and human capital effect and promoting the tendency of industrial structure and talent structure to reasonable and advanced development. (3) The innovation spillover of industrial digitalization exhibits double threshold effects. The threshold value in Central China is the minimum and the highest growth rate is observed in Western China, providing an opportunity window for the central and western regions to realize corner overtaking. In this study, the influencing process and action conditions of industrial digitalization on regional innovation efficiency were revealed and the application scenarios of digital technological innovation were expanded, providing a reference for China to implement digital transformation and formulate innovation strategies.

KEYWORDS: industrial digitalization, regional innovation efficiency, industrial structure, human capital.

JEL classification: O12, L78, C12, M21.

Introduction

As the leading forces of the world's scientific and technological revolution and industrial transformation, digital technologies such as artificial intelligence, big data, and cloud computing are becoming new engines to promote global economic recovery (Wang *et al.*, 2017). Industrial digitalization refers to the process of digitally upgrading and rebuilding the total factors in the upstream and downstream links of the industrial chain under the guidance of a new generation of digital technologies to improve industrial efficiency, that is, the process of digitally and intelligently transforming traditional industries through digital technologies (Pan *et al.*, 2022). Based on the collaborative requirements of innovation and the advantages of digital technologies in reducing the cost of cross-border and cross-regional linkage, digital technologies can improve the efficiency of industrial R&D activities and are expected to become the "new kinetic energy" to enhance regional innovative vitality and economic growth.

The literature focuses on many aspects. The first is the influence of the Internet and information technology on innovation efficiency. For instance, innovation spillover is promoted by the popularization of digital technologies (Varian, 2010) and the regional innovation level is markedly elevated by the application of information technologies (Forés and Camisón, 2016). Theoretical and empirical research has also been conducted on the influence of the digital economy on economic (high-quality) development (Zhang *et al.*, 2021; Limna *et al.*, 2022; Chen *et al.*, 2023). The influence of the digital economy on industrial (structure) upgrading has been studied (Liu *et al.*, 2022; Sturgeon, 2022). For example, the upgrading of the industrial structure is positively promoted by the development of the digital economy and scientific and technological innovation, as evidenced by the data of provinces in China (Su *et al.*, 2021). Researchers have also focused on the influence of the digital economy on innovation output and innovation performance (Brynjolfsson, Kahin, 2003; Teece, 2018; Ning *et al.*, 2022). To sum up, the literature provides beneficial enlightenment for the present study, but the digitalization, ecological, and networking trends of regional innovation activities in the new era have been neglected, and whether industrial digitalization will affect regional innovation efficiency has not been clearly answered.

The techno-economic paradigm theory provides a useful theoretical framework for studying these problems. The techno-economic paradigm, which is a theoretical framework, describes the different influencing degrees of four technological innovation types-incremental innovation, basic innovation, new technology system reform, and techno-economic model innovation-on the transition of the economic pattern. Because of the unique diffusivity and boundaryless nature, digitalization can effectively break through the geographical limitations of innovation, improve innovation knowledge dissemination efficiency, promote the generation and collision of innovative thinking, and release the spillover effect of innovation to enhance the innovation knowledge stock and stimulate the stock effect of innovation. The progress of digital economic development and industrial digitalization is continuously accelerated; meanwhile, the sustaining innovation of traditional industries is stimulated and a new industrial ecology featured with longitudinal interconnection and transverse interworking is formed through data values, network carriers, and digital technology empowerment, thereby hastening the generation of cross-boundary fused new industries and new models (Teece, 2018).

Industrial digitalization is therefore clearly correlated with innovation efficiency to some extent. Then, can the new technologies, new models, and new business forms hastened by industrial digitalization drive the improvement of regional innovation efficiency? What are the mechanisms and conduction paths behind this? Can this become the key for China to break through the plight of "innovation efficiency"? Does it aggravate or narrow regional gaps? Answering such questions will be of great realistic significance. On this basis, whether digital technologies could become the "new kinetic energy" for the regional innovation efficiency of China in the new era was judged from the innovation-driven perspective.

The contributions of this study are as follows. First, it adopts the techno-economic paradigm theory as the theoretical framework to explore the impact of industrial digitalization on regional innovation efficiency, which expands the research perspective of regional innovation. Second, by optimizing the effect of industrial structure and human capital, industrial digitalization promotes the rationalization and advanced development of industrial structure and talent structure, and indirectly improves the efficiency of regional innovation. Third, the innovation spillover of industrial digitalization has a double threshold effect, and it is necessary to adopt industrial digitalization strategies according to local conditions. This discovery not only expands the application scenarios of digital technology innovation, but also provides a reference for China to effectively implement digital transformation.

The remainder of this study was organized as follows. In Section 1, the influencing mechanism and conduction path of industrial digitalization on regional innovation efficiency were theoretically analyzed. In Section 2, the empirical models and variables were set. In Section 3, an empirical analysis was performed, and the direct, indirect, and nonlinear conduction mechanisms of industrial digitalization for regional innovation efficiency were tested. In Section 4, the discussion was presented, and the robustness test was implemented. In Section 5, the conclusions and managerial implications of this study were introduced.

1. Theoretical Analysis and Hypothesis Development

1.1 Direct Conduction Mechanism

Based on the techno-economic paradigm theory, digitalization is a systematic transformation process that changes the production mode, business model, and industrial organization mode via digital technologies. Digitalization contributes to new value growth, efficiency improvement, and agility by transforming the innovation paradigm and optimizing the industrial resource allocation method, thereby boosting total-factor productivity.

Based on the economic growth model $Y = \alpha.F(K, L)$, innovation efficiency is improved by industrial digitalization through three paths. (1) The factor input is increased or the factor allocation (K, L) is optimized, and the output is elevated. By digitizing production factors, digital technologies fully release the vitality of such factors as talents and capital, break through the constraint brought by the limited supply of traditional production factors to innovation, enhance the information flow of innovation subjects and factors, improve the circulation speed of factors, and realize more collaborative innovation and integrated innovation. Under the scale effect, digital technologies not only increase the quantity and quality of input factors but also analyze and adjust the proportion of factors input based on real-time data and accurately allocate the factors into regional innovation subjects (Wang and Cen, 2022). (2) The combination mode of factors is changed or new factors ($F(\cdot)$) are added to improve the allocation efficiency. In digital transformation, data has gradually evolved into the core factor ($F(D, K, L)$) of regional innovation, and the factors belonging to the attribute of "data" therefore become the new variables driving innovative development and the new weights achieving competitive advantages. Data interaction, sharing, and transfer facilitate the information interaction between producers and consumers, which not only eliminates the supplier–demander information barriers, reduces the supplier–demander information asymmetry, substantially improves information search efficiency, and enhances the supply–demand matching efficiency of innovation factors but also effectively bridges the information gap between developers and demanders, improves the matching efficiency between innovation activities and realistic demands, and helps reduce innovation risks. In this process, digital technologies change the form of growth functions by considerably increasing the marginal output and service efficiency of data (Wang *et al.*, 2022). (3) Technological progress (α) is accelerated and total-factor productivity is improved. Digital technologies have continuously penetrated into different industries and links, promoting the reform of innovative development efficiency, quality, and impetus, accelerating technological development, and improving total-factor productivity. Industrial digitalization changes the attributes and combination modes of traditional factors (Mukhopadhyay and Kekre, 2002), hastens the formation of new models such as the sharing economy and platform economy and new business forms like digital finance, crowdfunding, and crowdsourcing, creates new demands and new industries, and boosts the improvement of total-factor productivity (Basu and Fernald, 2022).

H1: Industrial digitalization can significantly improve the regional innovation efficiency of China.

2.2 Indirect Conduction Mechanism

2.2.1 Industrial Structure Effect

Digital transformation has become an important way of industrial upgrading. If widely applied, digital technologies can achieve the upgrading of the production mode, the reconstruction of the industrial structure, and the optimization of the value chain, to boost the upgrading of the global industrial structure. As stated by techno-economic paradigm theory, digital transformation can effectively enhance enterprise productivity, reduce production costs, optimize business models, and create more value. In addition, the digital economy has also brought emerging industries and business forms, such as cloud computing, the Internet of Things, big data, and artificial intelligence, which will further promote the upgrading of the industrial structure (Su *et al.*, 2021). The indirect influence of the industrial structure on regional innovation efficiency is described as follows. First, the digital industrialization process optimizes the industrial structure (Trippl, 2020) and promotes the rationalization and advancement of the industrial structure. Specifically, digital technologies have a more efficient market-oriented configuration, which will solve the mismatching and shackles of factors to a certain extent, realize the digital and intelligent transformation of products, product production processes, organizational forms, and business models, promote the digital upgrading of traditional industries, improve production efficiency and factor allocation efficiency, and accelerate the optimization and upgrading of traditional industries. Second, industrial digitalization can cultivate new high-end factors, boost industrial development toward the direction of digitalization, further boost industrial re-layout and factor reallocation, and release new structural bonuses. Digital technologies will facilitate the continuous integration and mutual penetration of the real economy and emerging services, and the bounds between industries are increasingly obscure. The continuous development of digital technologies will expedite the formation of new forms of modern services, including networking and digitalization, to elevate the proportion of the digital industry and drive the upgrading of the industrial structure.

With the upgrading of the industrial structure, the industrial layout tends to be reasonable, providing a better environment and basis for innovation activities and improving innovation efficiency (O'Mahony, Vecchi, 2005). Knowledge and technologies will be densely applied to relevant products and technologies based on the development needs of the industry itself, production factors have gradually flowed from low-efficiency departments to high-efficiency ones, and innovation efficiency is enhanced in the reallocation process of innovation resources (Wu, Shao, 2022).

2.2.2 Human Capital Effect

According to the theory of appropriate technology, the emergence of advanced technologies needs human capital to match with them (Trenev, 2018). Industrial digitalization leads to great changes in the traditional production mode and working mode, requiring the labor market to provide professional senior human capital adapting to the industrial development. With the deep integration of digital technologies with traditional industries, digital talents should possess skills that can be applied to other fields in an integrated fashion in addition to the corresponding professional skills (Lewis *et al.*, 2004). The market demand for interdisciplinary talents is increasing rapidly. To meet the talent demands of the labor market, the human capital input will be enlarged in various regions and their human capital level will be improved accordingly (Kelchevskaya, Shirinkina, 2019). Human capital contributes to digest, absorb, and apply new technologies. It can enhance efficiency of regional knowledge spillover and technology diffusion, so as to help regional innovation efficiency optimization (Grigorescu *et al.*, 2020).

H2: Industrial digitalization indirectly drives regional innovation efficiency through the industrial structure effect and human capital effect.

2.3 Nonlinear Conduction Mechanism

The economic operation mode under industrial digitalization presents the data-driven, Internet of Things, and innovative iteration characteristics. As pointed out by techno-economic paradigm theory, the nonlinear characteristic influence of industrial digitalization on regional innovation is specifically manifested as follows.

Network externality: Restricted by the digital network scale, the acquisition cost of innovation subjects was high in the initial stage of industrial digitalization. As industrial digitalization was continuously deepened, the multiplication effect of network linking points started appearing (Ding *et al.*, 2021), the marginal acquisition cost of innovation subjects declined gradually, and initial innovation benefits were acquired. With the digitalization of industrial development to a specific level, the positive feedback and strong externality of networks will be triggered and the network value of industrial digitalization will present explosive growth so that innovation subjects can achieve scale economies.

Data self-growth: Data has gradually become the core factor of innovative development. With its non-competitive and reproducible properties, data show self-growth and convergence, i.e., the more data are used, the higher the utilization rate, and the process of data sharing and transfer is a knowledge diffusion process characterized by "marginal progressive increase" (Zahra, George, 2002; Sorescu, Schreier, 2021).

Industry relevancy: With the deep integration of industrial digitalization into traditional industries, traditional facilities have realized intelligent and digital transformation so that digital technologies exhibit a more marked enabling effect in traditional fields, accelerating industrial innovation and contributing to the nonlinear growth of innovation output. From the angle of carrier platforms, innovation platforms have prevented the spatial–temporal constraints between innovation subjects (Gorodnichenko, Talavera, 2017), realizing knowledge sharing and diffusion at nearly zero cost, continuously reducing innovative R&D costs, expanding the scale of innovation groups, and leading to the dynamic evolution of the spillover effect of innovation (Neves, Sequeira, 2018). On the basis of this analysis, the following hypothesis was put forward.

H3: Industrial digitalization improves regional innovation efficiency in a nonlinear way, presenting regional differences.

3. Methodology

3.1 Modeling

To explore the influence and action mechanism of industrial digitalization on regional innovation efficiency, direct effects were tested first, and a two-way fixed effect model including individual effect and time effect was constructed.

$$Te_{it} = \alpha_0 + \alpha_1 Id_{it} + \alpha_2 Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

In Formula (1), Te_{it} represents the innovation efficiency of province i in period t, Id_{it} is the industrial digitalization level of province i in period t, $Control_{it}$ reflects other control variables that may affect innovation efficiency from the interprovincial level μ_i is the individual fixed effect that does not change with time, λ_t is the time effect, and ε_{it} is a stochastic disturbance term.

After the direct conduction mechanism was tested, the indirect conduction mechanism was tested with "industrial structure level" (Str) and "human capital level" (Edu) as the mediator variables, aiming to explore whether industrial digitalization influenced the regional innovation efficiency in China through indirect paths. With the human capital level as an example, a mediating effect model was established.

$$Edu_{it} = \beta_0 + \beta_1 Id_{it} + \beta_2 Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{2}$$

$$Te_{it} = \delta_0 + \delta_1 Id_{it} + \delta_2 Edu_{it} + \delta_3 Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{3}$$

Further, a threshold regression model was constructed by reference to the Hansen panel threshold model estimation method (Hansen, 1999) to investigate the nonlinear spillover effect of industrial digitalization on regional innovation efficiency:

$$\begin{aligned} Te_{it} &= \varphi_0 + \varphi_1\ Id_{it} \cdot I\left(Id,, \gamma_1\right) + \varphi_2 Id_{it} \cdot I\left(Id_{it} > \gamma_1\right) + \cdots \\ &+ \varphi_n Id_{it} \cdot I\left(Id_{it},, \gamma_n\right) + \varphi_{n+1} Id_{it} \cdot I\left(Id_{it} > \gamma_n\right) + \varphi_c Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \end{aligned} \tag{4}$$

In Formula (4), Id_{it} is both a threshold variable and a core explanatory variable; γ is the threshold value to be estimated. $I(\cdot)$ represents an indicator function, which is taken as 1 if the condition in the bracket is met, or otherwise, $I(\cdot)$ is taken as 0.

3.2 Variables

3.2.1 Explained Variable

The explained variable is regional innovation efficiency. Regional innovation efficiency not only needs to examine the input-output relationship of innovation but also needs to highlight the coordinated development of innovation and ecology. Given this, for regional innovation efficiency investigated in this study, the technological achievements brought by innovation input and the ecological cost triggered by energy consumption were taken into account. In addition, energy consumption was added to represent environmental input in the aspect of innovation input, and in terms of innovation output, the discharge of industrial "three wastes" (wastewater, waste gas, and solid waste) in each region was additionally set as unexpected output (environment output), specifically as listed in *Table* 1.

Table 1. Measuring indexes for regional green innovation efficiency

Classification				Index	Unit
Regional innovation efficiency (*Te*)	Input factor	Innovation input	Human input	Full-time equivalence of R&D personnel	Persons/year
			Financial input	Internal R&D expenditure	RMB 100 million
			Material input	Fixed assets investment in scientific research and technical services	RMB 100 million
		Environmental input		Energy consumption	10,000t of standard coal
	Output factor	Expected innovation output	Direct output	Number of patents applied for	PCS
				Trading volume of technology market	RMB 100 million
			Indirect output	Sales revenue of new products	RMB 100 million
		Unexpected output	Environmental output	Sulfur dioxide emission	10,000t of standard coal
				Total wastewater discharge	10,000t of standard coal
				General industrial solid waste output	10,000t of standard coal

Source: author's own results.

For effective measurement, the innovation efficiency in various regions of China was measured using the Super-SBM model of unexpected output in MaxDEA 8 Ultra software, as seen in the following formula (5).

$$\min \varphi = \frac{\frac{1}{k}\sum_{i=1}^{k}\frac{\overline{x_i}}{x_{i0}}}{\frac{1}{l_1+l_2}\left(\sum_{q=1}^{l_1}\frac{\overline{y^w}}{y^w_{q0}}+\sum_{q=1}^{l_2}\frac{\overline{y^b}}{y^b_{q0}}\right)}$$

$$s.t.\begin{cases} \overline{x} \ge \sum_{j=1,j\ne 0}^{n} x_{ij}\lambda_j, \quad i=1,2,\ldots,k \\ \overline{y^w} \le \sum_{j=1,j\ne 0}^{n} y^w_{qj}\lambda_j, \quad q=1,2,\ldots,l_1 \\ \overline{y^b} \ge \sum_{j=1,j\ne 0}^{n} y^b_{qj}\lambda_j, \quad q=1,2,\ldots,l_2 \\ \lambda_j \ge 0, \quad j=1,2,\ldots,n;\ j\ne 0 \\ \overline{x}\ge x_0, \quad \overline{y^w}\le y^w_0, \quad \overline{y^b}\ge y^b_0 \quad \lambda_j \ge 0 \end{cases} \tag{5}$$

In Formula 5, φ is the target efficiency, $x_0 = X\lambda + s^-, y_0^w = Y^w\lambda - s^{w+}, y_0^b = Y^b\lambda + s^{b-}$; x, y^w, and y^b represent the factors in the input, expected output, and unexpected output matrices, respectively; i and q stand for the number of input and output indexes, respectively. k, l_1, and l_2 denote the expected input, expected output, and unexpected output contained in each decision-making unit, s^-. s^{w+}, and s^{b-} are slack variables. λ_j is a weight vector.

3.2.2 Explanatory Variable

The explanatory variable is industrial digitalization. Considering the absence of officially disclosed comprehensive indexes and the insufficient comprehensiveness and objectivity of single indexes, a comprehensive evaluation system for the industrial digitalization level was established by adhering to comprehensive, scientific, and effective orientations according to the theoretical connotation of industrial digitalization in combination with its development situation. The index design is exhibited in *Table* 2, where the comprehensive score of industrial digitalization was measured through the entropy method.

Table 2. Evaluation index system for the industrial digitalization level

Classification		Index		Unit
Industrial digitalization (*Id*)	Digitalization foundation	Internet penetration rate		%
		Mobile phone penetration rate		EA/one hundred persons
		Length of optical cable lines		Kilometer
	Digitalization capability	Digital Inclusive Finance index		%
		Digital convergence scale	Proportion of e-commerce trading volume in GDP	%
			Proportion of enterprises with e-commerce trading activities	

Source: author's own results.

3.2.3 Mediator Variable

Mediator variables are industrial structure (*Str*) and human capital (*Edu*). By reference to the research of Zhao *et al.* (2022), and Ma and Chang (2023), the industrial structure is expressed by the proportion of the added value of the tertiary industry in that of the secondary industry. The human capital level is characterized by the per capita years of education accepted in each region. Per capita years of education= (number of people with a college education or above *16+ senior high school and secondary vocational school *12+ junior high school *9+ primary school *6+ illiteracy * 0) / total population over 6 years old.

3.2.4 Threshold Variable

The industrial digitalization level was chosen as the threshold variable to reveal whether the regional innovation effect of the industrial digitalization level presented dynamically nonlinear changes and its threshold features. Given regional heterogeneity, the interregional difference in threshold effect was examined from aspects of eastern, central, and western regions.

3.2.5 Control Variable

The following variables were selected as control variables to avoid the estimation deviation caused by missing variables and to reduce the interference of exogenous factors. R&D investment intensity (*RD*) is expressed by the R&D investment intensity of each region. High R&D investment is an important embodiment of the innovation level, which can significantly improve innovation efficiency (Dai *et al*., 2022). Government intervention (*Gov*) is expressed by the proportion of local general public budget expenditure in GDP. Considering the public attribute of some innovation activities, their innovation results cannot be exclusively enjoyed. To enhance the enthusiasm of investors, the government supports innovation activities through financial assistance and preferential policies, thus affecting the regional innovation efficiency (Huaping, Binhua, 2022). Infrastructure level (*Inf*) is expressed by the proportion of year-end expressway mileage in the area of each province and city. Infrastructure support is required for the prosperous development of industrial digitalization (Curran, 2018).

3.3 Data Sources

In this study, the panel data of 30 provinces and cities in China from 2013 to 2020 were selected as the research samples (considering the serious lack of data in Hong Kong, Macao, Taiwan, and Xizang Autonomous Region, they were excluded). The year 2013 was selected as the starting point because since that year, the development of the Internet in China has gradually deepened, and it has begun to change from a consumer Internet to an industrial Internet, bringing about the leap-forward development of digital technologies and becoming an important driving force for China's economic growth.

Table 3. Descriptive statistics of variables

Variable	Sample size	Mean	Standard deviation	Minimum value	Maximum value
Industrial digitalization (*Id*)	240	0.4455	0.1682	0.1015	0.8825
Regional innovation efficiency (*Te*)	240	0.7129	0.3341	0.1082	1.5836
R&D investment intensity(*RD*)	240	1.6658	1.1304	0.4612	6.2918
Government intervention (*Gov*)	240	0.2515	0.1028	0.1180	0.6274
Infrastructure level (*Inf*)	240	0.0321	0.0264	0.0014	0.1334
Industrial structure (*Str*)	240	1.0479	0.3431	0.2300	1.8280
Human capital (*Edu*)	240	9.2310	0.9012	5.9866	11.4813

Source: author's own results.

In this study, the regional innovation efficiency and industrial digitalization level measured as well as their mediator variables and control variables all came from *China Statistical Yearbook*, *China Statistical Yearbook on Science and Technology*, *Educational Statistics Yearbook of China*, and *Information Statistics Yearbook of China* during 2014-2021 as well as the official websites of the statistics bureaus in each province and city. Individual missing data were compensated through linear interpolation, shown as *Table* 3.

4. Result Analysis

To test the direct, indirect, and nonlinear conduction mechanisms of industrial digitalization for regional innovation efficiency, an empirical analysis was performed in STATA15 software using a panel fixed model, a mediating effect model, and a threshold model.

4.1 Direct Effect Test

After the Hausman test, a fixed effect model was selected for estimation. *Table 4* reports the test results of the direct and mediating effects of industrial digitalization on regional innovation efficiency.

Table 4. Basic regression estimation results

Variable \ Model	Explained variable *TE*		
	Model 1	**Model 2**	**Model 3**
Id	0.3211*** (5.21)	0.3675*** (2.03)	0.4603*** (2.50)
RD			-0.8461*** (-3.77)
Inf			0.5311*** (2.77)
Gov			0.8027*** (2.98)
cons	-0.1853*** (-3.18)	-0.0271*** (-0.10)	3.6549*** (3.98)
Control variable	NO	NO	YES
Urban fixed effect	NO	YES	YES
Year fixed effect	NO	YES	YES
N	240	240	240

Note: *, **, and *** indicate level of significance at 10%, 5%, and 1%, respectively.

Source: author's own results.

Models 1 and 2 only consider the influence of the industrial digitalization level on regional innovation efficiency, and the regression estimation coefficient of this variable was significantly positive, preliminarily manifesting that industrial digitalization in China significantly promoted the improvement of regional innovation efficiency during 2013-2020. After the control variable (Model 3) was added, the regression coefficient of the industrial digitalization level remained significantly positive at a significance level of 1%, also reflecting that the promotion of industrial digitalization still has a significant impact on improving the regional innovation efficiency after the other factors affecting the regional innovation efficiency were controlled within the range of selected samples. The reasons are as follows. (1) Digital technologies effectively break through the spatial-temporal constraints of different innovative individuals, reduce the transmission level of original information, accelerate the diffusion and appreciation of information in regional innovation systems, and improve the information transmission efficiency (Jesemann, 2018). (2) Industrial digitalization has expanded the breadth, width, and depth of innovation activities. Under the background of industrial digitalization and driven by information technology innovation, new industries, new business forms, and new models can be constantly spawned. These include promoting industrial differentiation and fission, upgrading and deriving new industries, promoting the industrial chain to extend to high value-added links to form new business forms, implementing integration and restructuring based on innovation factors, and forming business models with unique competitiveness. (3) Industrial digitalization has optimized the innovation structure and quality. With the development of industrial digitalization, the concerns have been shifted from quantity expansion to innovation quality in innovation activities. Promoting innovation upgrading with digitalization and greening concepts and building a green, low-carbon, and ecological modern regional innovation system has become a universal consensus and future development trend (Lu *et al*., 2020).

4.2 Mediating Effect Test

According to the stepwise regression method, Model 4 tested the influence of the industrial digitalization level on the industrial structure level, shown in *Table* 5. The industrial structure level was significantly positively affected by digital industrialization, i.e., the industrial digitalization level could promote the rationalization and advancement of the industrial structure. Model 5 tested whether digital industrialization indirectly influenced the regional innovation efficiency via the industrial structure. The results revealed that the industrial structure played a significant partial mediating role, i.e., it indirectly influenced the regional innovation efficiency. This reflected that industrial structural upgrading facilitates the digital and intelligent transformation of traditional industries, and innovation factors have gradually transferred from low-efficiency industrial sectors to high-efficiency industrial sectors, thus positively influencing the regional innovation efficiency.

Table 5. Mediating effect estimation results

Variable \ Model	Mediator variable *Str*	Explained variable *TE*	Mediator variable *Edu*	Explained variable *TE*
	Model 4	**Model 5**	**Model 6**	**Model 7**
Id	0.5512*** (2.90)	0. 4139** (2.28)	0.5512*** (2.90)	0. 4619*** (2.53)
Str		2.7758*** (2.94)		
Edu				2.2962** (2.09)
cons	2.2165*** (32.06)	-2.6511 (-1.14)	2.2314*** (36.87)	8.6999*** (3.37)
Control variable	YES	YES	YES	YES
City fixed effect	YES	YES	YES	YES
Year fixed effect	YES	YES	YES	YES
N	240	240	240	240

Note: *, **, and *** indicate level of significance at 10%, 5%, and 1%, respectively.

Source: author's own results.

Similarly, Model 6 tested the influence of the industrial digitalization level on the human capital level. Model 7 tested whether industrial digitalization indirectly affected the regional innovation efficiency through the human capital level. According to the test results, the partial mediating effect of human capital was marked, and the human capital level indirectly influenced the regional innovation efficiency.

To sum up, the mediating effect test revealed that industrial digitalization indirectly affects the regional innovation efficiency through the industrial structure and human capital, so Hypothesis 2 is supported by empirical tests.

4.3 Nonlinear Threshold Effect Test

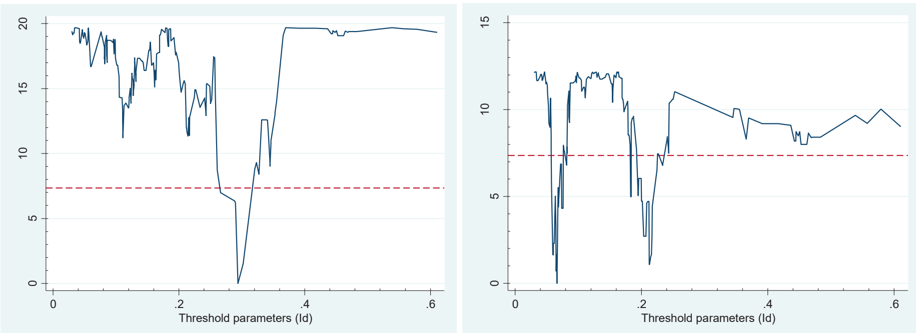
The threshold test was carried out with the industrial digitalization level as the core explanatory variable. Before the threshold model estimation, the panel threshold existence test was performed through the bootstrap method (*Table* 6). The industrial digitalization passed the single- and double-threshold tests and failed the three-threshold test at the significance level of 5%, and the estimated value of the double-threshold test passed the reality check (*Figure* 1). The threshold effect test results of Model 8 indicated that the industrial digitalization level exerts a nonlinear influence on the regional innovation efficiency, with double thresholds, so Hypothesis 3 is verified by the empirical test.

Table 6. Threshold effect estimation results

Model	Threshold model	F value	P value	Critical value 1%	5%	10%	Threshold value	Confidence interval
Model 8	Single-threshold	27.330***	0.004	17.708	8.879	6.874	0.1333	[0.057, 0.234]
	Double-threshold	8.165**	0.012	9.074	5.242	5.748	3.956	[0.266, 0.302]

Note: Note: *, **, and *** indicate level of significance at 10%, 5%, and 1%, respectively. The results are acquired through 500 times of repeated sampling based on the bootstrap method.

Source: authors' own results.



Source: created by the authors.

Figure 1. **Threshold Effect Authenticity Test**

The dynamically nonlinear characteristics of different regions were further investigated. Models (9)-(11) in *Table* 7 reflect the threshold test results regarding the industrial digitalization level in eastern, central, and western regions, respectively. The dynamic influence on the innovation efficiency in the three major regions showed a "marginal progressive increase" trend, specifically manifested as follows. In the eastern region, the innovation efficiency improvement in the eastern region has a relatively low Internet threshold constraint, enabling this region to drive innovation efficiency via digital technologies. With congenital regional advantages and talent resources, the eastern region can accelerate technology innovation and innovation orientation, exert "first-mover" advantages, actively mine "new blue oceans," deploy the new ecology, develop new industries, create new models, and enhance the resilience of industrial digitalization. Central region displays a lower threshold constraint in comparison with the eastern and western regions, further enabling the central region to improve the regional innovation efficiency via industrial digitalization. Therefore, the primary task of improving the innovation efficiency in the central region in the current phase lies in actively extending the application scenarios of digitalization, improving the digital transformation efficiency of traditional industries, and promoting the deep integration of industrial digitalization with the real economy. The industrial digitalization level in the western region has a threshold value higher than the national average level, indicating that the western region possesses a high access threshold due to the restriction of spatial location and economic development level. Once the first threshold value is exceeded, however, the influence of industrial digitalization on the regional innovation efficiency will grow at a doubled speed. Hence, the western region should give full play to the network effect and "Metcalfe's law" power of industrial digitalization, continue to accelerate the infrastructure construction for industrial digitalization, and actively realize corner overtaking through the new "racing track" of industrial digitalization. Thereby, Hypothesis 3 is further proved by the threshold effect tests of the eastern, central, and western regions.

Table 7. Threshold effect test

Variable		Nationwide	Te (eastern region)	Te (central region)	Te (western region)
		Model 8	Model 9	Model 10	Model 11
Threshold value	γ_1	0.066	0.086	0.039	0.216
	γ_2	0.294	0.204	0.225	0.294
$Id \cdot I(Id \leq \gamma_1)$		0.3733*** (4.46)	0.3412*** (3.39)	1.2338*** (4.43)	0.5296*** (4.25)
$Id \cdot I(\gamma_1 < Id < \gamma_2)$		0.7053*** (3.05)	0.5226*** (4.66)	1.6602*** (5.32)	1.3437*** (3.52)
$Id \cdot I(Id \geq \gamma_2)$		1.2889*** (3.47)	0.8339*** (3.87)	1.8856*** (3.40)	1.8909*** (3.44)
Control variable		YES	YES	YES	YES
Number of cities		30	12	9	9
N		240	96	72	72

Note: *, **, and *** indicate level of significance at 10%, 5%, and 1%, respectively.

Source: authors' own results.

The robustness test was performed through the instrumental variable method using the explained variable and adding control variables, aiming to perform the robustness analysis of test results, shown in *Table* 8.

First, the explanatory variable was replaced. Specifically, the regional innovation efficiency (output orientation) measured by the Super-SBM model of DEA unexpected output was replaced by the regional innovation efficiency (non-oriented) index, which passed the significance level test of 1%. The symbols and significance of other control variables did not change evidently.

Second, the core explanatory variable lagged by one period. To be specific, the core explanatory variable, namely industrial digitalization level, was subjected to regression after lagging for one period. The regression results of Model 13 showed that the regional innovation efficiency is significantly positively influenced by industrial digitalization lagging for one period.

Table 8. Robustness test

Index \ Model	Model 12	Model 13	Model 14
	Regional innovation efficiency (non-oriented)	Regional innovation efficiency	Regional innovation efficiency (mean value of industrial digitalization level of bordering cities)
Industrial digitalization (*Id*)	0.5387** (1.98)		0.2174*** (3.51)
Industrial digitalization lagging for one period (*LId*)		0.3956** (2.03)	
cons	5.7741*** (4.25)	2.5870*** (2.69)	0.5238*** (8.31)
Control variable	YES	YES	YES
City fixed effect	YES	YES	YES
Year fixed effect	YES	YES	YES
N	240	240	240

Note: *, **, and *** indicate level of significance at 10%, 5%, and 1%, respectively.

Source: author's own results

Third, endogeneity correction was implemented. Considering that the regression bias might be caused by measuring errors or missing variables, which would result in endogeneity, the endogeneity problem would be effectively handled through the instrumental variable method. By reference to Chong *et al.* (2013), the mean value of the industrial digitalization level of bordering cities in the same year was taken as the instrumental variable. Model 14 displays the regression results after adding the instrumental variable, i.e., the industrial digitalization level remains significantly positive on the premise of considering the endogeneity problem of industrial digitalization and regional innovation efficiency, completely consistent with the previous regression.

5. Discussion

In this study, whether regional innovation efficiency was affected by industrial digitalization was focused on, and the influencing mechanism of industrial digitalization on regional innovation efficiency was deeply analyzed. Then, the conduction process of the influence of industrial digitalization on regional innovation efficiency was figured out through the Super-SBM model of unexpected output and the econometric analysis method. Next, the mediating effects of the industrial structure and human capital were discussed, followed by regional threshold tests with the industrial digitalization level as the core explanatory variable. Three research findings were obtained, as detailed below.

First, the promotion of industrial digitalization still has a significantly positive impact on improving the regional innovation efficiency, becoming an important force for China to improve regional innovation efficiency in the new era. The current research with regard to the improvement of regional innovation efficiency by digitalization focuses on digitalization and total-factor productivity (Pan *et al.*, 2022), green economic efficiency (Li *et al.*, 2022), risk (Curran, 2018), and high-quality economic development (Ding *et al.*, 2021). The conclusions of this study supplement the literature, enrich the literature foundation for the research on regional innovation, and provide a new explanation for regional innovation efficiency from the digital economy perspective, i.e., industrial digitalization can effectively relieve information asymmetry and enhance factor allocation efficiency. Data factors such as big data and cloud computing, if reasonably utilized, can help accurately identify market demands, reasonably configure innovation resources, and improve regional innovation efficiency. Furthermore, the fusion and collaboration of data with traditional factors like capital and technology will be convenient for the aggregation, transfer, and application of factor resources and promote the market-oriented allocation of factors to improve regional innovation efficiency.

Second, in the aspect of the indirect effect test, this study proved that industrial digitalization facilitates the industrial structure and talent structure to develop toward rationalization and advancement and indirectly improve the regional innovation efficiency by optimizing the industrial structure effect and human capital effect. The digital economy can accelerate the transformation of traditional industries and the formation of emerging industries through the infiltration and integration of digital technologies, digital factors, digital platforms, and traditional industries, and realize the upgrading of the industrial structure. Industrial digitalization has greatly changed the traditional production mode and working mode, which requires the labor market to provide digital talents suitable for industrial development, and the demand for interdisciplinary talents in the market is increasing rapidly. To meet the talent demand in the labor market, various regions will increase the investment in human capital and improve the level of human capital accordingly, thus promoting the improvement of regional innovation efficiency. Therefore, it is necessary to transform traditional industries and accelerate the upgrading of traditional industries and the conversion of old and new kinetic energy (Su *et al*., 2021). From the aspect of talent cultivation, it is necessary to improve the personnel training mechanism and strengthen the training of professionals by focusing on R&D innovation, fundamental research, and industrial development of the digital economy.

Finally, from the threshold test and heterogeneity test, the whole innovation system will be affected by the long-term permeability and wide coverage of the digital economy. Regional innovation activities will become increasingly efficient with the scale expansion of the digital economy and the deepening of its development, and Metcalfe's Law and network effect are observed between the development of the digital economy and regional innovation efficiency. Therefore, the opening and sharing of data sources should be energetically promoted. Data factors, which constitute the core engine for the development of the digital economy, not only help produce new products and services but also can be applied to R&D and knowledge creation, to improve production efficiency and innovation efficiency. Measures should also be adjusted to regional conditions, and industrial digitalization is beneficial to the coordinated development of different regions (Li *et al.*, 2022). In the central and western regions, digital technologies can be adopted and pertinent measures can be taken to narrow the interregional "digital gap" and gaps in innovation efficiency.

Conclusions and Management Implications

Main Findings

In this study, the internal influencing mechanism of industrial digitalization on regional innovation and its conduction paths were expounded on from aspects of direct, indirect, and nonlinear conduction mechanisms. Based on provincial-level panel data of China during 2013–2020, the industrial digitalization level and regional innovation efficiency were measured. On this basis, the innovation spillover effect of industrial digitalization was empirically analyzed from nationwide and regional levels using the panel fixed model, mediating effect model, and threshold model. The following conclusions were drawn.

(1) industrial digitalization is helpful to improve innovation efficiency, developing into an important engine driving the innovation efficiency improvement in China in the new period.

(2) The development of digital industry will not only directly improve innovation efficiency but also indirectly improve it through the upgrading effect of human capital and industrial structure.

(3) The innovation spillover of industrial digitalization has a double-threshold effect. The tests region by region manifest that the three regions show regional differences and the "marginal progressive increase" of innovation spillover, with their threshold values ranked as western region>eastern region>central region. The promoting effect in the central and western regions is better than that in the eastern region. This is because the bonus in the eastern region has released, and this "new blue ocean" needs to be actively mined. The minimum threshold in the central region helps to rapidly exert the promoting effect of industrial digitalization, and the promoting effect in the western region is the best, providing an opportunity window for corner overtaking.

Managerial Implications

Considering that regional innovation is significantly influenced by the industrial digitalization level, government intervention, and infrastructure level, the following policy suggestions were put forward based on the research conclusions.

(1) Every effort should be made to create an industrial digital development environment. For the soft environment, it is necessary to strengthen the top-level design; increase support for the core fields of industrial digitalization such as artificial intelligence, cloud computing, big data, 5G, and blockchain; and create a good digital application scenario and digital ecology. For the hard environment, efforts should be made to improve the construction of industrial digital infrastructure, promote 5G construction, establish the new generation of information networks, and boost the infrastructure construction for such applications as digital centers, supercomputing centers, and cloud platforms.

(2) The deep integration of industrial digitalization with the traditional economy should be accelerated. In terms of stock, it is necessary to further longitudinally promote the intelligent, platform-based, and ecological transformation of traditional industries, and horizontally promote the upstream and downstream innovative development of the digital empowerment industry chain. At the increment level, efforts should be made to strengthen the cultivation of emerging industries, new technologies, new business forms, and new models and accelerate the clustered and large-scale development of emerging industries.

(3) Differentiated regional innovation strategies should be implemented. Certain regional differences are found in the influence of industrial digitalization on the regional innovation efficiency of China, requiring pertinent implementation of dynamic and differentiated innovation strategies. The promoting effect in the eastern region is weaker than that in the central and western regions because the bonus is already released, making it necessary for the provinces in the eastern region to actively deploy new ecology, develop new industries, longitudinally promote the development of digital life and digital services, accelerate the application of digital society, and strengthen the resilience and radiative driving effect of industrial digitalization. The central region exhibits a relatively low threshold for industrial digitalization. Here, the emphasis should be laid on accelerating application scenario cultivation and innovation platform construction, deeply implementing key and core technology R&D, creating new advantages in the deep integration of industrial digitalization

with the real economy, and continuously narrowing the gap with the developed eastern region. Restricted by the spatial location and economic development level, the access threshold in the western region is relatively high, requiring western provinces to persist in the long-term goals of industrial digitalization, perfect the infrastructure construction for industrial digitalization, and promote guarantee and support for a smooth transition to the stage with a doubled growth rate.

(4) The promotion of industrial structure effect and human capital effect on regional innovation efficiency should be focused on. The industrial structure effect and human capital effect are the conduction mechanisms for the promoting effect of industrial digitalization on innovation efficiency. Therefore, traditional industries should be transformed, and their upgrading and the conversion of new and old kinetic energy should be accelerated. The talent cultivation mechanism should also be perfected. In the aspect of talent cultivation, academic research institutions should establish the related specialties in aspects of R&D innovation, fundamental research, and industrial development of digital technologies and strengthen the cultivation of professional talents and applied talents. Enterprises should also actively introduce high-end digital talents and regularly conduct skill training of employees to boost the digital transformation and development of industries.

Research Limitations and Future Directions

Influenced by the research emphasis, the digitalization degree from the “economic level” was selected as the emphasis to comprehensively evaluate the development level of the digital economy, while such indexes as digital governance from the “social level” were neglected. The estimation bias may be caused to some extent by the limitation of panel data and the spatial effect of surrounding regions. In follow-up research, the digital economic index system can be further enriched, and deeper theoretical and empirical research can be carried out by combining the spatial spillover effect.

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PRAMONĖS SKAITMENINIMAS IR REGIONINIS INOVACIJŲ EFEKTYVUMAS: ĮRODYMAI IŠ 30 KINIJOS PROVINCIJŲ IR MIESTŲ

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SANTRAUKA

Sparčiai progresuojant skaitmeninių technologijų revoliucijai, pramonės skaitmeninimas suteikė naujų galimybių gerinti regionų inovacijų efektyvumą. Siekiama ištirti, ar pramonės skaitmenizavimas gali veiksmingai pagerinti regionų inovacijų efektyvumą. Naudoti 30 Kinijos provincijų ir miestų skydiniai duomenys 2013–2020 m. Remtasi technoekonominės paradigmos teorija ir atitinkama technologijų teorija, pramonės skaitmenizavimo įtakos regionų inovacijoms mechanizmu. Efektyvumas buvo tiriamas naudojant netikėtos išeigos Super-SBM modelį, entropijos metodą ir ekonometrinės analizės metodą. Rezultatai atskleidžia, kad, pirma, pramonės skaitmenizacija reikšmingai teigiamai veikia regioninį inovacijų efektyvumą Kinijoje. Antra, pramonės skaitmeninimas netiesiogiai pagerina regionų inovacijų efektyvumą optimizuodamas pramonės struktūros poveikį ir žmogiškojo kapitalo poveikį bei skatindamas pramonės struktūros ir talentų struktūros tendenciją į pagrįstą ir pažangų vystymąsi. Trečia, pramonės skaitmeninimo naujovių plitimas turi dvigubą slenkstinį poveikį. Slenkstinė vertė Centrinėje Kinijoje yra minimali, o didžiausias augimo tempas stebimas Vakarų Kinijoje, todėl centriniams ir vakariniams regionams suteikiama galimybė lenkti posūkius. Šiame tyrime buvo atskleistas pramonės skaitmenizacijos procesas ir veiksmų sąlygos, turinčios įtakos regionų inovacijų efektyvumui, išplėsti skaitmeninių technologinių inovacijų taikymo scenarijai, suteikiantys pagrindą Kinijai įgyvendinti skaitmeninę transformaciją ir formuluoti inovacijų strategijas.

REIKŠMINIAI ŽODŽIAI: pramonės skaitmeninimas; regionų inovacijų efektyvumas; pramonės struktūra; žmogiškasis kapitalas.