Research on the Constraint Mechanism of Industrial Digitization Enabling High-quality Industrial Development

*Zecheng Lian

School of Economics and Management, Lanzhou University of Technology, Lanzhou, Gansu 730050, China
*zecheng0928@163.com

Abstract. Based on the three-sector model, a theoretical framework for industrial digitalization is constructed to facilitate high-quality industrial development, taking into account the constraints of human capital level and R&D investment intensity. The non-linear nature of high-quality industry development is attributed to these constraints; only after surpassing corresponding threshold values in human capital level and R&D investment intensity can the promotion effect of industrial digitalization on high-quality industry development be significantly enhanced. According to research findings, continuous improvement in talent cultivation, research and development investment intensity is essential for overcoming these constraints and accelerating regional industry's high-quality development enabled by industrial digitalization.

Keywords: Constraint mechanism; Industrial digitization; High quality development of industry

1 INTRODUCTION

The long-term extensive growth of China's industry has ultimately led to significant resource consumption and serious environmental pollution. In 2022, the industry, which accounts for only 33.2% of GDP, consumes 65.7% of the country's energy and emits 87.6% of sulfur dioxide and 63.2% of nitrogen oxides. Under the dual constraints of resources and environment, the growth rate of added value of large-scale industries has decreased from 6.2% in 2018 to 3.6% in 2022. This indicates that the traditional extensive industrial growth model is unsustainable, and the development of China's industry must transform towards green, intensive, and high-quality development. In the era of digital economy, data, as the most core production factor, has become a new engine driving high-quality industrial development. Based on the reality of China's industrial and digital development, it is crucial to study the constraint mechanism of industrial digitalization driving high-quality industrial development in order to empower high-quality industrial development with digitalization.

The research on the impact of digitization on the high-quality development of industry has a certain foundation, and the research conclusions are relatively consistent, that

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is, industrial digitization has a promoting effect on the high-quality development of industry. (Li Shiheng et al, 2022)[1] found that the digital economy has a significant direct empowering effect on high-quality industrial development, and can indirectly empower high-quality industrial development through the transmission effects of human capital, industrial upgrading, and innovation capabilities, with significant regional heterogeneity. The above research has laid a good foundation for this study, but these studies are all based on linear models, highlighting the driving role of digitization in the high-quality development of industry, while there is insufficient research on the constraints and mechanisms in the driving process. In fact, due to constraints such as human capital level(Hui Shupeng et al)[2] and R&D investment intensity, the process of industrial digitization empowering high-quality industrial development may be non-linear. The core of industrial digitization lies in the integration of digital technology and industry, in which the level of human capital is crucial. If the level of human capital is high and the quality of workers is high, they can master digital technology well(Cao Aijun et al) [3] and fully apply it to the production and operation process of enterprises, improve the level of industrial digitization, and better empower high-quality industrial development. The intensity of R&D investment is an important indicator of technological innovation capability(Zhou Zhenjiang et al) [4]. Regions with high R&D investment are prone to innovation in digital technology, which can accelerate the application of new technologies in enterprise production and operation, form a high level of industrial digitization, and drive high-quality industrial development.

2 THEORETICAL MODEL

Drawing on the research of (Clark et al, 1998)[5], in order to analyze and optimize the efficiency and quality of each link in the production process, and promote economic development and growth, this paper establishes a closed economic model with three departments: research and development, intermediate product, and final product. Most scholars often only examine the "expected" outputs of investment and labor based on established research models, or select a single environmental variable as the "non expected" output, lacking a comprehensive examination of resource and environmental variables. Based on this, this study takes into account the environmental pollution caused by industrial enterprises, and combines the research of (Elsadig et al. 2012)[6] to incorporate the energy consumption and industrial "three wastes" indicators in industrial production into the C-D production function, resulting in:

$$Y_{i,t} = A_{i,t} N_{i,t}^{\alpha} (C_{i,t} X)^{\beta} D_{i,t}^{\gamma} \quad (1)$$

Among them, i represents region, t represents time, A represents other exogenous shocks, such as management level, etc; C represents the advanced level of production technology for intermediate products determined by the level of industrial digitization; X represents the intermediate products required for the production of the final product; D represents the unified emission of industrial waste, N represents the function of labor input L and capital input K, $N_{i,t} = L_{i,t}^{\theta} K_{i,t}^{1-\theta}$

In the intermediate product department, if the production of intermediate products requires the consumption of energy and various raw materials, which are collectively referred to as resources in this article and represented by R, then the production of resources and intermediate products follows:

$$X_{i,t} = \delta_{i,t} R_{i,t} \tag{2}$$

Among them, δ represents resource utilization efficiency.

In the study by (Benhabib et al. 1991)[7], it was proposed that the emergence of technological innovation would lead to new production methods and products, thereby improving productivity and economic efficiency. Based on this technology diffusion model, the advanced level of production technology for intermediate products $C_{i,t}$ satisfies:

$$lnC_{i,t} - lnC_{i,0} = m_i + q_1 hc_{i,t} + q_2 rd_{i,t} + \left(e_1 hc_{i,t} + e_2 rd_{i,t}\right)\left[\frac{x_{max} - x_{i,0}}{x_{i,0}}\right] \tag{3}$$

The technological innovation effect and imitation effect of human capital level and R&D investment intensity exist in equation (3). According to (Fleisher et al, 2010)[8], considering the positive externalities generated by human capital level and R&D investment intensity in specific regions or industries, it can be inferred that the spillover effects of these two factors are as follows:

$$shc_{i,t} = \frac{di_{i,t}}{d_{i\_min}}\left[\frac{x_{max,t} - x_{i,t}}{x_{i,t}}\right], srd_{i,t} = \frac{di_{i,t}}{d_{i\_min}}\left[\frac{x_{max,t} - x_{i,t}}{x_{i,t}}\right].$$

Among them, d_i^{min} represents the shortest distance between each region and the most technologically advanced area.

Substituting equations (2) and (3) into equation (1) yields a C-D function that includes human capital level, R&D investment intensity, and high-quality industrial development level：

$$Y_{i,t} = A_{i,t} N_{i,t}^{\alpha} (C_{i,t} \delta_{i,t} R_{i,t})^{\beta} D_{i,t}^{\gamma} \tag{4}$$

Based on the level of high-quality industrial development (GTFP) and the characteristics of the C-D production function, we can obtain:

$$GTFP_{i,t} = \frac{Y_{i,t}}{N_{i,t}^{\alpha}} = A_{i,t} (C_{i,t} \delta_{i,t} R_{i,t})^{\beta} D_{i,t}^{\gamma} \tag{5}$$

According to equation (3), the constraint condition equation can be obtained:

$$s.t.\, lnC_{i,t} - lnC_{i,0} = m_i + q_1 hc_{i,t} + q_2 rd_{i,t} + \left(e_1 hc_{i,t} + e_2 rd_{i,t}\right)\left[\frac{x_{max} - x_{i,0}}{x_{i,0}}\right] \tag{6}$$

From equations (5) and (6), it can be seen that the digitization of industries in various regions has a certain impact on the level of high-quality industrial development. However, the two factors of human capital level and R&D investment intensity also constrain the degree of impact of industrial digitization on the level of high-quality industrial development.

3 CONSTRUCTION OF ECONOMETRIC MODELS AND VARIABLE DESCRIPTION

3.1 Model Building

Based on the previous analysis, the relationship between human capital level, R&D investment intensity, industrial digitization, and high-quality industrial development level has been elucidated. Therefore, this article sets the econometric model as follows:

$$GTFP_{i,t} = \beta_0 + \beta_1 idl_{i,t} + \beta_2 eo_{i,t} + \beta_3 eg_{i,t} + \beta_4 so_{i,t} + \beta_5 fdi_{i,t} + \beta_6 ti_{i,t} + \mu_i + \sigma_i + \varepsilon_i \quad (7)$$

Among them, i represents different regions, and t represents different years; GTFP represents the level of high-quality industrial development; idl represents the level of digitalization in the industry; eo represents the degree of economic openness; eg stands for environmental governance; so represents structural optimization; fdi refers to the level of foreign direct investment; ti represents technological innovation; μ_i represents the fixed effects of provinces; σ_i represents the fixed effect of the year; ε_i represents the perturbation term and follows a normal distribution.

Given that the process of industrial digitization empowering high-quality industrial development may exhibit non-linear mechanisms, this article refers to Hansen's (1999) panel threshold model to analyze the constraint mechanism of industrial digitization empowering high-quality industrial development. Based on equation (7), the following panel threshold regression model is further constructed:

$$GTFP_{i,t} = \beta_0 + \varphi_1 idl_{i,t}(\vartheta_{i,t} \le \alpha) + \varphi_2 idl_{i,t}(\vartheta_{i,t} > \alpha) + \beta_1 eo_{i,t} \quad (8)$$

$$+\beta_2 eg_{i,t} + \beta_3 so_{i,t} + \beta_4 fdi_{i,t} + \beta_6 ti_{i,t} + \beta_6 ti_{i,t} + \mu_i + \sigma_i + \varepsilon_i$$

Among them, ϑ represents the threshold variable, α represents the threshold value corresponding to the threshold variable, and the rest of the symbols have the same meaning as equation (7).

3.2 Variable Selection and Explanation

Dependent variable: Select the level of high-quality industrial development as the dependent variable. Regarding the connotation of high-quality development, there are two types: process oriented and result oriented. This article draws on the research of (Ju Hong et al, 2020)[9] and (Hui Shupeng et al, 2021)[10], and selects the result oriented green total factor productivity (GTFP) as an indicator to measure the level of industrial high-quality development. This article uses the SBM model and GML index model for unexpected output super efficiency to measure green total factor productivity.(Yuan Yijun et al, 2015)[11] The Max DEA software was used to estimate the level of industrial high-quality development considering energy consumption and CO_2 emissions.

Core explanatory variable: Select the level of industrial digitization as the explanatory variable. To comprehensively reflect the level of industrial digitization in provinces, this article draws on the research of (Dai Xinling 2022)[12] and (Lin Yan 2023)[13], selects 13 specific indicators from four dimensions: industrial digitization investment, industrial digitization application, industrial digitization foundation, and digital talent, and constructs an industrial digitization evaluation index system. The entropy method is used for calculation, as indicated in Table 1.

Table 1. Industrial digitization level evaluation index system

Level 1 indicators	Level 2 indicators
Industrial digitalization investment	Full time R&D capacity of industrial enterprises above designated size
	Completed investment in information transmission, computer services, and software industry
	R&D expenditure as a percentage of GDP
	Number of R&D projects of industrial enterprises above designated size
Industrial digitalization application	Number of computers used per 100 people in enterprises
	Number of enterprises with e-commerce transactions
	Number of websites owned by enterprises (per hundred)
Fundamentals of Industrial Digitalization	Length of optical cable line
	Number of Internet broadband access ports
	Proportion of science and technology expenditure in public finance expenditure
Digital talent	Number of personnel responsible for information transmission, computer services, and software in urban units
	Number of employed personnel in scientific research and technology services industry
	Number of employees in the information service industry

Threshold variables: Select human capital level and R&D investment intensity as threshold variables. Measure the level of human capital using the average years of education for the population aged 6 and above in each region(Zou Weiran et al, 2024)[14]. The R&D investment intensity is represented by the proportion of R&D funds invested in each region to its GDP(Fu Weizhong et al, 2021)[15]. This article combines existing research results and establishes a comprehensive and systematic index system for digital industrialization based on its connotation. Digital industrialization is divided into four dimensions: scale level, investment level, efficiency level, and innovation level.

Control variables: Select economic openness (eo), environmental governance (eg), structural optimization (so), level of foreign direct investment (fdi), and technological innovation (ti) as control variables. The degree of economic openness is expressed as the proportion of total import and export trade in each region to the region's GDP(Liu fan et al, 2021)[16]. The emission data of three wastes (industrial wastewater, industrial solid waste, and industrial sulfur dioxide) used for environmental governance is synthesized using the entropy method(Yang Wenfu, 2022)[17]. Structural optimization is measured by the proportion of added value of the tertiary industry in each region to industrial added value(Gao Yu et al, 2023)[18]. The level of foreign direct investment is expressed as the proportion of foreign direct investment in each region to the region's GDP(Tang Xin et al, 2023)[19]. Technological innovation is expressed by taking the logarithm of the number of patent applications and authorizations in each region(Yan Tao et al, 2022)[20].

4 MODEL ESTIMATION AND ANALYSIS

4.1 Benchmark Regression Results

Table 2. Regression results of basic model for panel data

	(1)	(2)	(3)
	Fixed effects model GTFP	Random effects model GTFP	Mixed effects model GTFP
idl	1.144^{**} (1.99)	1.134^{**} (2.25)	0.711^{**} (2.10)
eo	-0.631^{*} (-1.86)	-0.533^{**} (-2.25)	-0.653^{***} (-6.21)
eg	18.070^{***} (2.71)	13.300^{**} (2.42)	-11.890^{*} (-1.94)
so	0.923 (0.88)	1.102 (1.45)	1.589^{***} (5.61)
fdi	5.680^{**} (2.43)	6.257^{***} (2.61)	5.537^{***} (4.50)
ti	-0.080 (-1.09)	-0.014 (-0.30)	0.034 (1.11)
_cons	1.307 (1.06)	0.459 (0.65)	0.026 (0.07)
N	270	270	270
R^2	0.703	0.464	0.318

Note:*、**、*** indicate significant at the 10%, 5%, and 1% significance levels, respectively; values in parentheses are t-statistics;

As indicated in table 2, through B-P test, Wald, Hausman test, the fixed effects model was selected as the most suitable, and the R2 of fixed effects was the highest. The fixed effects model shows that industrial digitization has a significant positive promoting effect on high-quality industrial development. Under other constant conditions, for every 1% increase in industrial digitization, the average level of high-quality industrial development increases by 1.144%.

4.2 Threshold Effect Test

Further analyze the constraint mechanism of the impact of industrial digitization on the level of high-quality industrial development, and conduct threshold self sampling tests on each variable under the assumptions of a single threshold and a double threshold. Determine whether the threshold effects of the three threshold variables in this hypothesis exist, and determine the corresponding threshold numbers and specific threshold positions.

Table 3. Threshold effect results

Threshold variable	Threshold number	F	P	Critical value		
				1%	5%	10%
hc	Single threshold	20.620^{***}	0.003	13.511	16.317	20.431
	Double threshold	20.300	0.633	20.804	14.967	11.967
rd	Single threshold	6.500^{**}	0.023	37.789	26.946	24.992
	Double threshold	8.000	0.617	35.798	26.011	22.301

When human capital level and R&D investment intensity are used as threshold variables, a single threshold is significant at 1%. Table 3 shows that when using two variables as threshold variables for single threshold and double threshold tests, the F-statistic and P-value obtained passed the single threshold effect test, but did not pass the double threshold effect test. Therefore, a single threshold model was selected.

Table 4. Estimated threshold effect and confidence interval

Threshold variable	Threshold number	Threshold estimation value	95% confidence interval	
hc	Single threshold	10.030	9.845	10.078
rd	Single threshold	0.013	0.012	0.013

Table 4 reports the estimated threshold values for three variables, with a single threshold value of 10.030 for human capital level and 0.013 for R&D investment intensity. The single threshold estimates of these two threshold variables are within a 95% confidence interval, and the confidence interval is narrow, indicating that the threshold estimation results are significant.

The following threshold regression is conducted:

Table 5. Threshold model regression results

Variable	Threshold variable	
	hc	rd
idl（hc≤α）	1.081	
	(1.24)	
idl（hc>α）	1.944^{***}	
	(3.07)	
idl（rd≤α）		-0.849
		(-0.62)
idl（rd>α）		1.701^{***}
		(2.58)

Control variable	YES	YES
Fixed time effect	YES	YES
Regional fixed effects	YES	YES
N	270	270
R^2	0.479	0.492

As indicated in Table 5.When the level of human capital is below the threshold of 10.03, the effect of industrial digitization on empowering high-quality industrial development is not significant; When the level of human capital is greater than the threshold value of 10.03, it is significant at the 1% statistical level, indicating that in areas with higher levels of human capital, industrial digitization has a significant promoting effect on the high-quality development of industry. As the level of human capital exceeds the corresponding threshold, this promoting effect will be enhanced. This is because the higher the level of human capital and the higher the quality of workers in the region, the better they can master digital technology and apply it to the entire process of industrial enterprise production and operation to promote the digitalization process of the industry, thereby driving the high-quality development level of the industry.

When the R&D investment intensity is less than the threshold value of 0.013, the effect of industrial digitization on empowering high-quality industrial development is not significant; When the R&D investment intensity is greater than the threshold value of 0.013, it is significant at the 1% statistical level, indicating that in areas with high R&D investment intensity, industrial digitization has a significant promoting effect on the level of high-quality industrial development. As the R&D investment intensity exceeds the corresponding threshold, this promoting effect will be enhanced. This is because when R&D investment intensity is high, it is easy to innovate in digital technology, forming a higher level of industrial digitization, thus making the promotion effect of industrial digitization on the high-quality development level of industry more obvious.

5 CONCLUSION AND IMPLICATIONS

5.1 Main Conclusions

A theoretical model for the constraint mechanism of industrial digitization empowering high-quality industrial development was constructed based on the three sector model, which suggests that industrial digitization can drive high-quality industrial development, and this process is constrained by three factors: human capital level and R&D intensity.

The above theoretical model was tested using a multiple panel regression model. The digitization of industries has a significant promoting effect on the high-quality development of industries. According to the benchmark regression results, assuming all other conditions remain constant, for every 1% increase in industrial digitization, the average level of high-quality industrial development increases by 1.144%.

Further utilizing the panel threshold regression model, the constraint mechanism of industrial digitization empowering high-quality industrial development was examined.

The empowerment of high-quality industrial development through industrial digitization is constrained by both the level of human capital and the intensity of R&D investment. When the level of human capital and R&D investment intensity are below the corresponding threshold values, the effect of industrial digitization on empowering high-quality industrial development is not significant. Only after crossing the corresponding threshold constraints, the level of industrial digitization will continue to improve, and the driving effect on high-quality industrial development will be significant and show an increasing trend.

5.2 Inspiration and Prospect

The empowerment of high-quality industrial development through industrial digitization is not achieved overnight due to the constraints of human capital level and R&D investment intensity. Efforts must be made to improve human capital level and R&D investment intensity, break through their respective threshold constraints, and fully unleash the empowering effect of industrial digitization on high-quality industrial development. Therefore, the following countermeasures and suggestions are proposed:

Firstly, efforts should be made to improve the level of human capital. Breaking through the constraints of human capital level in the process of empowering high-quality industrial development through industrial digitization, and accelerating the high-quality development of industry. Digital talents are a key force in promoting the development of industrial digitalization. Technologies related to industrial digitalization play an important role in the deep integration of basic research and development with the real economy. Through digital platforms as carriers, talents from different fields can be gathered and connected to leverage the external effects of human capital.

Secondly, efforts should be made to increase the intensity of R&D investment. Different R&D investment intensities will result in significant differences in the promotion effect of industrial digitalization on industrial green total factor productivity. Therefore, we cannot blindly improve the level of industrial digitalization. We should base ourselves on reality, continuously increase R&D investment intensity, and fully unleash the empowering effect of industrial digitalization on high-quality industrial development. We should fully utilize capital market financing, improve the risk compensation mechanism for technology financing, and establish an evaluation system for research and development investment.

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