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The Driving Mechanism and Computational Analysis of Digital Transformation in the Transformation of Traditional Industrial Spatial Structure in the Yangtze River Delta Economic Belt

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ABSTRACT

The promotion of industrial digital transformation is a crucial breakthrough in the evolution of economic structures and the physical layout of spaces. It has the potential to elevate the entire industrial chain to a high-end value chain, creating more profit opportunities and enhancing the influence of domestic industries in the international cycle. This study uses the cities in the Yangtze River Delta Economic Belt as a case study to explore the spatial effects of digital transformation on the healthy transformation of traditional industrial structures. It constructs relevant spatial coupling models and empirically verifies them by testing specific assumptions. The experimental results indicate that the model is significant at a level greater than 5%, making it suitable for selecting spatial measurement models. The mean square error of its network simulation output is 0.1333, confirming the expected hypothesis and demonstrating that digital transformation has a significant spatial driving effect on industrial upgrading.

Keywords: Digital Trans, Industrial, Yangtze River, Spatial coupling models

1. Introduction

The global industrial economic landscape is undergoing profound changes. The prices of energy and raw materials are continuously rising, while the constraints on resources and the environment are intensifying. The internal and external dynamics of China's industrial competition have been

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impacted [2]. Firstly, the market space for low-end industries in the low value-added segments of the global value chain, previously secured by labor advantages, has been compressed due to low labor costs in developing countries. Secondly, faced with barriers from developed countries and global trade protectionism, China has yet to establish a strong competitive advantage in high-end industries. Thirdly, traditional industries in China lack their own momentum for development, still plagued by inherent drawbacks such as low profit margins, inefficient production models, and fierce competition [4, 5]. In the past, when some developed countries addressed these issues, they typically built low-end value chains in developing countries to achieve external expansion by consuming and exploiting the factor resources of those countries [11]. These approaches are now outdated, and it is necessary to explore a new path with Chinese characteristics.

Digital transformation represents a typical "integrated economy." Leveraging integrated development as an opportunity, it plays a supporting and leading role in the real economy, especially in industries, and has become an important starting point for mode transformation, structural adjustment, and kinetic energy change [6]. First, digital transformation will leverage the driving effect of factors, turning data into a fourth type of production factor. It will penetrate and adjust the allocation of traditional factors such as labor, land, and capital, improving the efficiency of factor allocation and easing the excessive consumption and dependence of traditional industries on tangible assets and energy [1]. Secondly, the network space created by digital transformation breaks the limitations of physical space, enabling the circulation, reorganization, and reallocation of resources across different regions, thereby reconstructing the spatial layout of the industrial chain. This can effectively smooth domestic circulation and enhance the stability and competitiveness of China's industrial and supply chains [10]. It can ease the pressure caused by the compression of international markets and serve as a crucial factor in enhancing industrial added value. Finally, the empowerment of traditional industries through digitalization and industrial digitalization promotes the full integration of industries with the digital network. By relying on digital platforms, the efficiency and collaboration of all links in the industrial chain, supply chain, and innovation chain are improved. With the aid of digital and intelligent R&D design, production, manufacturing, and logistics, personalized and flexible production is achieved, ensuring continuous renewal of competitiveness [7, 14]. In conclusion, digital transformation drives both data-driven and industry-driven effects, changing the efficiency of factor allocation, reducing energy dependence, improving production efficiency, achieving flexible production, enhancing new competitiveness, and comprehensively promoting industrial upgrading. Ultimately, this will elevate China's industries to the middle and high end of the global value chain [12].

Given this context, it is crucial to address the imbalance in the development of digital transformation, how digital transformation can better serve regional economic development, and how China can build a new model of regional economic development driven by digital transformation. These are urgent issues that require solutions [8].

This paper, therefore, takes the Yangtze River Delta Economic Belt as a case study to explore the spatial effect of digital transformation on the healthy transformation of traditional industrial structures. It aims to provide theoretical support and policy recommendations for building a new regional economic development model driven by digital transformation.

2. Spatial Effect Model of Digital Transformation on Healthy Transformation of Traditional Industrial Structure

Regional spatial systems are evolving from local to global. Commodity flows, information flows, and capital flows are being recombined globally, and spatial elements are gradually emerging with new connotations [13]. Beyond cities, the industry network actors in the production network have become important nodes. A line serves as an essential channel connecting network nodes. It represents a collection of dynamic and static concepts, including capital flow, commodity flow, labor force, information flow, and the construction of soft and hard infrastructure supporting various "flows," such as transportation and communication infrastructure, market circulation channels, etc., as shown in Table 1.

Regional Elements and Their Combinations	Spatial Subsystem	Space Combination Type
Point to Point	Capital and information node system	Regional urban system, urban internal functional area
Point Line	Capital information hub system	Financial center, information center, and knowledge innovation center
Point Face	Urban regional system	Metropolitan area
Line to Line	Network facility system	Capital network, information network, high-speed transportation network
Line Face	Industrial regional system	Specific high-tech industrial belt
Face to Face	Integrated economic system	Specific industrial zones based on division of labor and cooperation
Point Line Face	Space economic integration system	Value section labor division area

Table 1. New Combination Mode of Spatial Structure Elements in Digital Transformation

The relationship between the spillover effect of digital transformation and time T is shown in Figure 1. In the figure, the dotted line with dots represents the diffusion effect of digital transformation, the dotted line with horizontal lines and dots represents the polarization effect, and the solid line formed by combining the two effects represents the spillover effect of digital transformation.

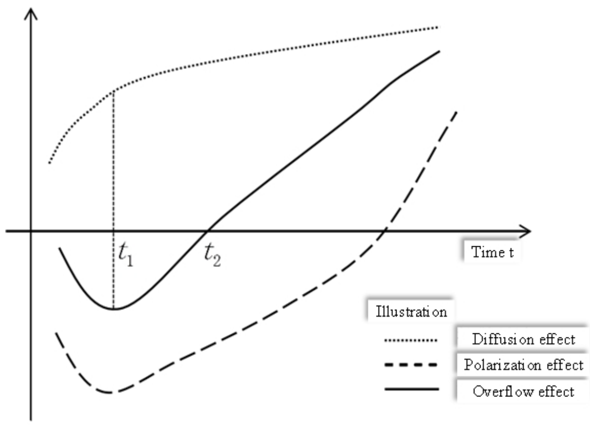

Fig. 1. Diffusion effect, polarization effect, and spillover effect of digital transformation over time

The competition partnership in the digital transformation spatial relationship network is dynamic, changing with the stages of digital transformation development [9]. Specifically:

(a) In the stage of weak regional connection, each region focuses on its development needs. Competition and cooperation intensity between regions is relatively small.

(b) As regional connections strengthen, competition becomes dominant due to increased consumption of digital resources and market rivalry.

(c) When regional connections stabilize, regions seek a win-win development model, promoting resource optimization and coordinated development.

This competitive partnership fosters rational resource distribution among regions, ultimately leading to a coordinated regional economic development pattern, as shown in Figure 2.

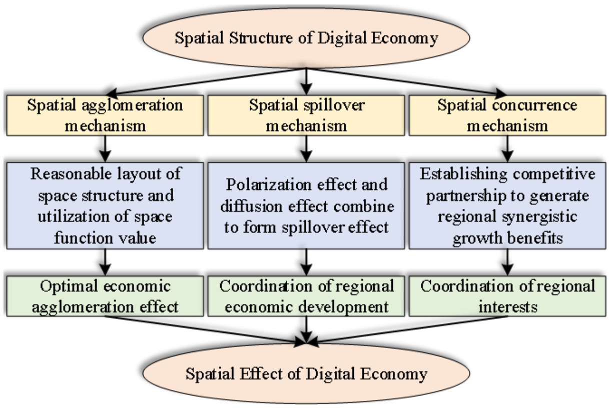

Fig. 2. Spatial effect mechanism of digital transformation

Regarding measurement methods, the entropy weight method, known for its objectivity and accuracy, is used to quantify the index weight based on the methods outlined in [13]. To facilitate comparison of the spatial effect level of industrial transformation across regions, the measured index is scaled by multiplying it by 100.

If the year span is d, n provinces, and m indicators, the j-th indicator of province i in year α is denoted as $x_{\alpha ij}$. After standardization, Eqs. (1) and (2) are obtained:

$$X'_{\alpha ij} = \frac{x_{\alpha ij}}{x_{\max}}, \tag{1}$$

$$X'_{\alpha ij} = \frac{x_{\min}}{x_{\alpha ij}}. \tag{2}$$

The index entropy is determined using Eq. (3):

$$e_j = -b \sum_{\alpha=1}^{d} \sum_{i=1}^{n} y_{\alpha ij} \ln\left(y_{\alpha ij}\right), \tag{3}$$

where $b > 0$, $b = \ln(dn)$, and $y_{\alpha ij} = X'_{\alpha ij} / \sum_{\alpha=1}^{d} \sum_{i=1}^{n} X'_{\alpha ij}$.

The utility value and weight of indicator information are shown in Eq. (4):

$$g_j = l - e_j, \quad \omega_j = \frac{g_j}{\sum_{j=1}^{m} g_j}. \tag{4}$$

The comprehensive score of spatial effect is given by Eq. (5):

$$S_{\alpha i} = \sum_{j=1}^{m} \left(\omega_j X'_{\alpha ij}\right). \tag{5}$$

The structure and function of spatial effect, as two interdependent and mutually restricted components, are indispensable in any system. In urban agglomeration spatial systems, the spatial structure exhibits specific functions. The transformation of industrial structure generally progresses through the embryonic stage, promotion stage, and stable stage, producing functions of indication, organization, regulation, and optimization in different stages, as shown in Figure 3.

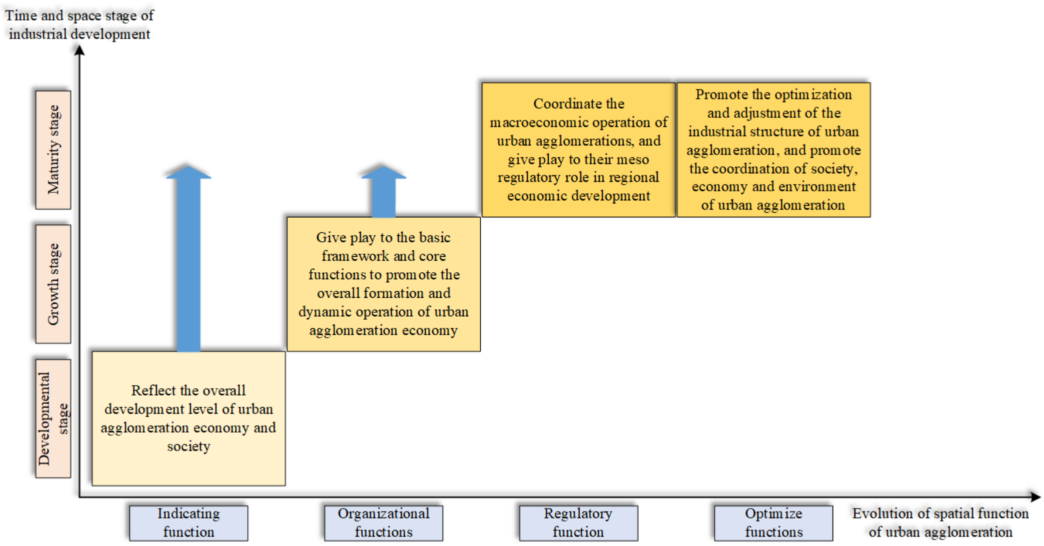

Fig. 3. Industrial structure transformation and spatial function evolution

With the strengthening of infrastructure and institutional mechanism reform brought about by digital transformation, and the continuous expansion of inter-industry and inter-regional links, the stronger the innovation ability caused by capacity accumulation, the greater the profit space for entering new products with high added value. This has improved the innovation momentum of the industry, creating a virtuous circle of interactive enhancement. The maximum benefit of the space effect can be expressed as Eqs. (6) and (7):

$$\max\ R = nf\delta - \frac{c\delta^2}{2d}, \quad n \geq 1, d \geq 1, \tag{6}$$

$$\delta = \frac{ndf}{c}. \tag{7}$$

The optimal distance for maximizing industrial income is $\delta = \frac{ndf}{c}$, and the maximum jumping distance of the industry is $\delta^* = \frac{2ndf}{c}$. If the initial capacity endowment and production capacity accumulation of the industry can support this jump distance, it will achieve leapfrog path innovation and development, obtaining high value-added benefits.

It can be seen from Figure 4 that the initial capacity endowment of the linear industrial development path can only jump by f/c. At this time, the income is only $f^2/2c$, and the region is more likely to lock into the barren area of product space. The expanded industrial multiple iteration model increases the optimal distance to ndf/c and the income to $dn^2f^2/2c$. Products no longer rely solely on the linear path for industrial transformation and upgrading, enabling regional leapfrog path breakthroughs and spatial iteration, as shown in Eqs. (8) and (9), and Figures 4 and 5.

$$\max_{n,\delta_{n,2}} R_n = f\delta_{n,1} - \frac{c\delta_{n,1}^2}{2} + f\delta_{n,2} - \frac{c(\delta_{n,2} - \delta_{n,1})^2}{2}, \tag{8}$$

where $\delta_{n,1} = \frac{2f}{c}, \quad \delta_{n,2} = \frac{3f}{c}$.

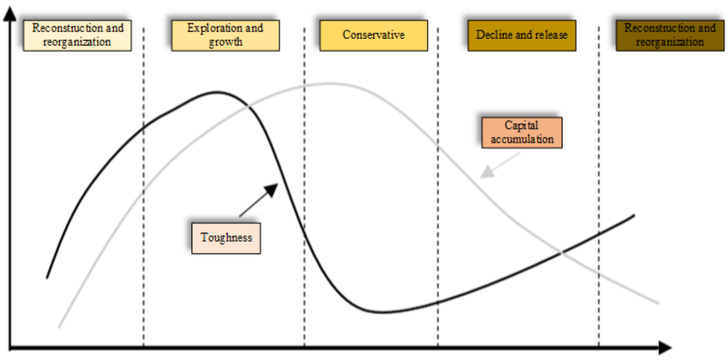

Fig. 4. Relationship between industrial transformation and spatial effect

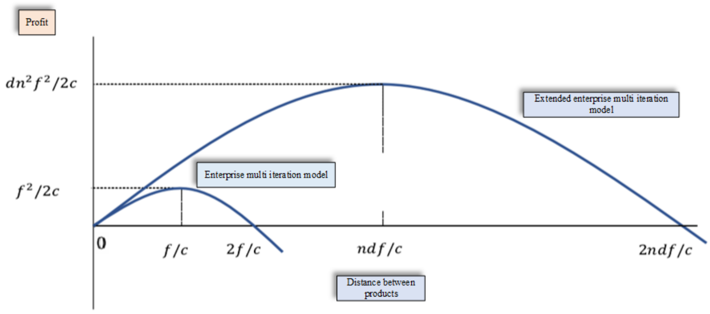

Fig. 5. Relationship between industrial transformation and spatial iteration

$$\varphi_{n^*n} = \begin{bmatrix} 0 & \delta_{1,2} & \delta_{1,3} & \cdots & \cdots & \delta_{1,n} \\ & 0 & \delta_{2,3} & \cdots & \cdots & \vdots \\ & & 0 & \cdots & \cdots & \vdots \\ & & & 0 & \cdots & \vdots \\ & & & & 0 & \delta_{n-1,n} \\ & & & & & 0 \end{bmatrix}. \quad (9)$$

From the above mathematical formulas and models, we derive two basic assumptions:

H1: The increase in spatial density of industrial areas is conducive to the transformation and upgrading of the industrial structure.

H2: The transformation and upgrading of regional industrial structures follow the spatial development path of existing capacity and endowment advantages.

3. Methods

This study takes the cities in the economic belt of the Yangtze River Delta as the analysis object of the empirical study.

The Yangtze River Delta is located at the "T"-shaped junction along the river and coast of China. With excellent natural endowments and prominent regional advantages, it is the region with the highest level of economic development, the most densely populated, and the most urbanized area in China. It has become an important engine to enhance national comprehensive strength and international competitiveness, driving national economic development [3].

In recent years, in line with the new trend of international industrial development, the Yangtze River Delta has continuously increased its industrial structure adjustment efforts. By developing high-end industries and modern service industries, it has promoted the industrial structure from heavy to light, and from hard to soft. In 2013, the proportion of the added value of the three industries in the Yangtze River Delta was 4.7:47.0:48.3, significantly higher than the national average of 10.0:43.9:46.1 in the same period. It was the first region to achieve a breakthrough from "two-three-one" to "three-two-one" in industrial composition, as shown in Table 2.

Year	Enterprises	Employees (Avg.)	Output Value	Business Income	Export Value	Profit	Profit + Tax
2005	5460	1819180	11815	11915	7345	426	606
2008	8770	3025925	20510	20333	13260	977	1345
2009	9175	2952155	21248	21133	12690	950	1360
2010	9633	6445790	26590	26515	16000	1495	1999
2011	6950	3506700	30230	30065	17165	1635	2226
2012	7770	3726958	-	33890	18530	1866	2710

Table 2. Economic indicators of high-tech industry transformation in the Yangtze River Delta

As shown in Figure 6, the spatial distribution of high-tech industries in the Yangtze River Delta demonstrates strong agglomeration. With high-tech parks and industrial bases as the carrier, the spatial pattern of "core, one belt, and one network" has been formed. Shanghai, Nanjing, and Hangzhou serve as the core, with Suzhou, Wuxi, Changzhou, and Ningbo as important nodes. Industrial belts such as the Shanghai-Nanjing-Hangzhou, Shanghai-Hangzhou-Ningbo, and the Torch High-tech Belt along the Yangtze River, along with the Ningbo-Taiwan-Wenzhou Coastal Industrial Belt, form the backbone of this evolution. Spatially, the region is evolving from a "Z"-shaped to an "S"-shaped pattern.

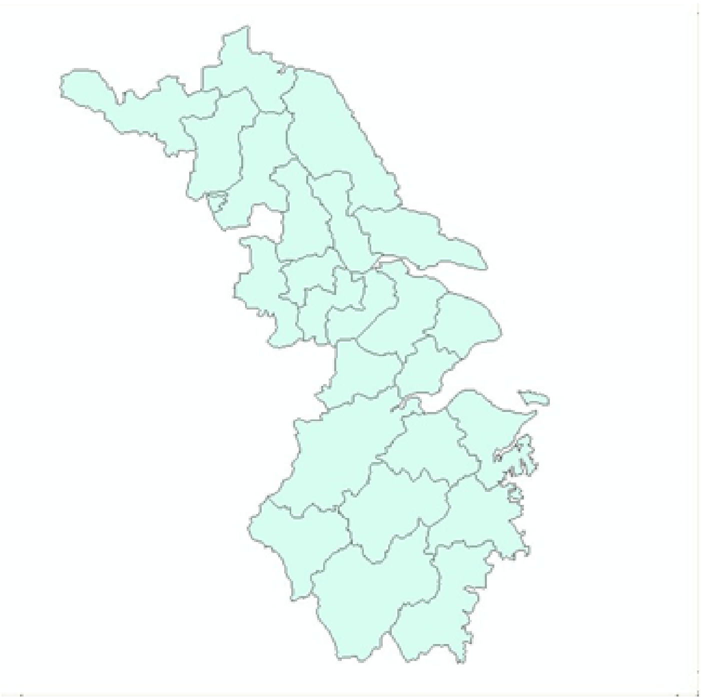

Fig. 6. Schematic diagram of cities in the Yangtze River Delta Economic Belt

3.1. *Evaluation Index System and Data Set Construction*

Based on the principle of measuring whether the internal capacity of the industry is improved, this study considers that the changes in industrial transformation, upgrading, and spatial measurement in the entire region are mainly reflected in the improvement of transformation rate and upgrading. These are detailed in Tables 3, 4, and 5.

Level I Indicators	Secondary Indicators	Third-Level Indicators	Direction	Calculation Formula
Efficiency Upgrading	Productivity	Total labor productivity	(+)	$TLP = \frac{V_z}{L_z}$
Efficiency Upgrading	Profitability	Profit margin of main business	(+)	$OPE = \frac{OP_z}{I_z}$
Advanced Transformation	High-quality production capacity	Proportion of high-tech industry	(+)	$PHT = \frac{I_h}{V_z}$
Advanced Transformation	Energy consumption and environmental protection	Energy consumption per unit income	(-)	$ECI = \frac{E_z}{I_z}$
Advanced Transformation	Energy consumption and environmental protection	Utilization ratio of solid waste	(+)	$ISW = \frac{W_u}{W_t}$

Table 3. Evaluation index system of industrial transformation and upgrading and spatial measurement level

Descriptive statistical results of variables are presented in Table 4.

Variable	Sample Size	Mean Value	Standard Deviation	Minimum Value	Maximum Value
MTU	270	0.303	0.105	-0.292	0.574
DE	270	0.205	0.086	0.073	0.545
FDI	270	2.088	1.897	0	12.096
HR	270	9.176	0.894	7.477	12.683
GI	270	0.289	0.235	0.108	1.486
IC	270	0.335	0.188	0.033	0.841
PGDP	270	5.233	2.625	1.603	16.175
KRA	270	0.356	0.353	0.002	1.919
LRA	270	0.242	0.177	0.002	0.884
EI	270	0.788	0.353	0	1.864
MSD	270	0.520	0.717	0.002	4.299

Table 4. Descriptive statistical results of variables

Weights of digital transformation development level indicators are listed in Table 5.

Third-Level Indicators	Weight After Time Decay	Normalized Weight
Length of optical cable line per square kilometer (X1)	0.1008	0.0299
Number of Internet broadband access terminals per square kilometer (X2)	0.2716	0.0796
Number of domain names per 100 people (X3)	0.2916	0.0858
Number of websites per 100 people (X4)	0.2944	0.0868
Manufacturing industry in GDP (X5)	0.1691	0.0496
Services in GDP (X6)	0.2563	0.0755
Number of employees in electronic and communication equipment manufacturing industry (X7)	0.3494	0.1024
Technology services (X8)	0.1931	0.0566
Mobile phone penetration rate (X9)	0.0915	0.0266
Internet broadband access user penetration rate (X10)	0.0658	0.0191
Digital TV user penetration rate (X11)	0.0676	0.0196
Number of terminals in electronic reading rooms of public libraries (X12)	0.0663	0.0196
Per 100 people (X13)	0.1046	0.0306
Proportion of enterprises with e-commerce transactions (X14)	0.0862	0.0255
Proportion of e-commerce transactions in GDP (X15)	0.1744	0.0511
Integrated government service capacity index (X16)	0.0527	0.0153
Technical market turnover (X17)	0.2834	0.0834

Table 5. Weights of digital transformation development level indicators

4. Case Study

4.1. Spatial Autocorrelation Test

In this study, the adjacent spatial weight matrix of the Yangtze River Delta is selected for spatial autocorrelation tests. To test the robustness of the results, the 0-1 adjacency matrix W_1 and longitude-latitude adjacency matrix W_2 are used for measurement. The specific digital transformation development level (DE), industrial production scale (MI), and industrial upgrading (UMI) are measured as explained above, and the test results are shown in Table 6.

Year	MI/W_1	MI/W_2	DE/W_1	DE/W_2	UMI/W_1	UMI/W_2
2008	0.385***(3.663)	0.274***(4.105)	0.282***(2.808)	0.114**	-	-
2009	0.192**(1.875)	0.075*(1.453)	0.263***(2.657)	0.111**(2.004)	-	-
2010	0.378***(3.499)	0.297***(4.341)	0.233***(2.424)	0.103**(1.912)	0.386***(3.486)	0.356***(5.003)
2011	0.346***(3.433)	0.306***(4.301)	0.207**(2.212)	0.095**(1.818)	0.395***(3.614)	0.345***(4.931)
2012	0.343***(3.192)	0.313***(4.486)	0.222***(2.346)	0.106**(2.005)	0.513***(4.606)	0.377***(5.314)
2013	0.313***(2.893)	0.303***(4.424)	0.177**(1.944)	0.092**(1.775)	0.525***(4.674)	0.403***(5.614)
2014	0.314***(2.907)	0.295***(4.331)	0.178**(1.985)	0.083**(1.722)	0.391***(3.525)	0.355***(5.044)
2015	0.299***(2.793)	0.280***(4.122)	0.211***(2.313)	0.097**(1.868)	0.497***(4.413)	0.395***(5.575)
2016	0.282***(2.655)	0.265***(3.869)	0.197**(2.135)	0.102**(1.931)	0.563***(4.955)	0.426***(5.969)
2017	0.270***(2.591)	0.257***(3.784)	0.195**(2.111)	0.089**(1.900)	0.586***(5.153)	0.454***(6.353)
2018	0.275***(2.596)	0.260***(3.888)	0.197**(2.122)	0.085**(1.725)	0.555***(4.902)	0.423***(5.924)
2019	0.273***(2.576)	0.266***(3.888)	0.211**(2.267)	0.091**(1.744)	0.577***(5.144)	0.434***(6.046)

Table 6. Test results of spatial effects of global autocorrelation coefficients

From the measurement results in Table 6, whether based on the 0-1 adjacency matrix or the longitude-latitude adjacency matrix with a threshold, digital transformation and industry show positive spatial correlation, significant at a level greater than 5%. This confirms Hypothesis 1. The trend of exponential growth is shown in Figure 7.

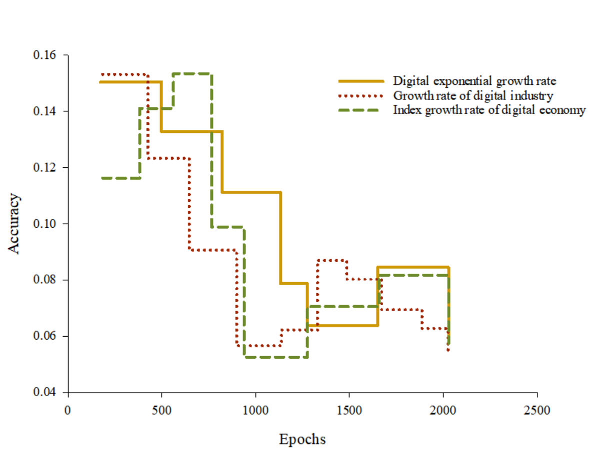

Fig. 7. Change trend of spatial effect index of digital transformation

After standardizing the adjacency matrix, we derive the Moran's I scatter diagram for digital transformation and industry, as shown in Figure 8. Digital transformation and industrial production scale are measured for 2008 and 2019, while industrial upgrading is measured for 2010 and 2019.

The spatial econometric model results under the two spatial matrices are consistent, indicating robust results. The national-level spatial models show that digital transformation significantly

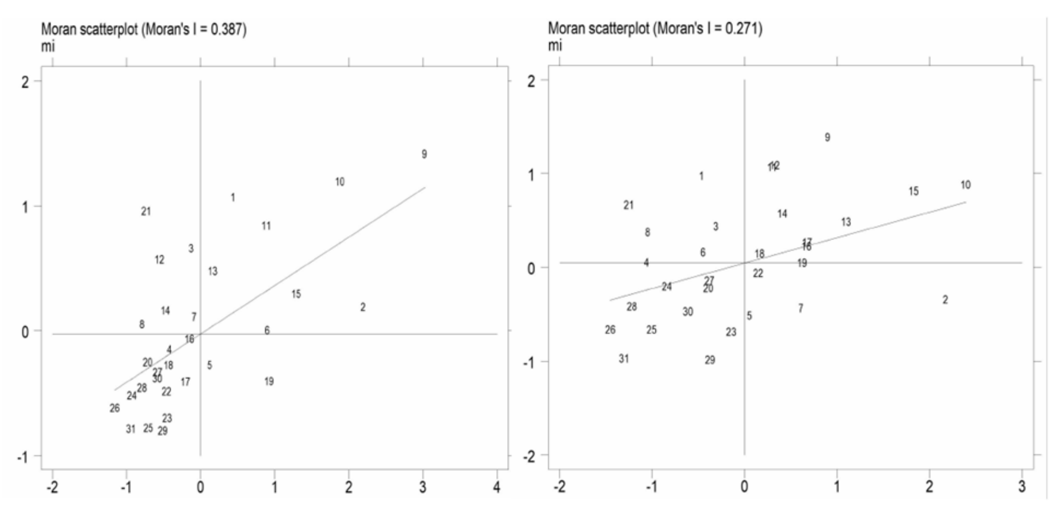

Fig. 8. Moran's I scatter chart of industry and spatial effect scale

promotes industrial upgrading. However, while digital transformation positively affects industrial production scale, its significance level is low. This supports Hypothesis 2, as shown in Figures 9 and 10.

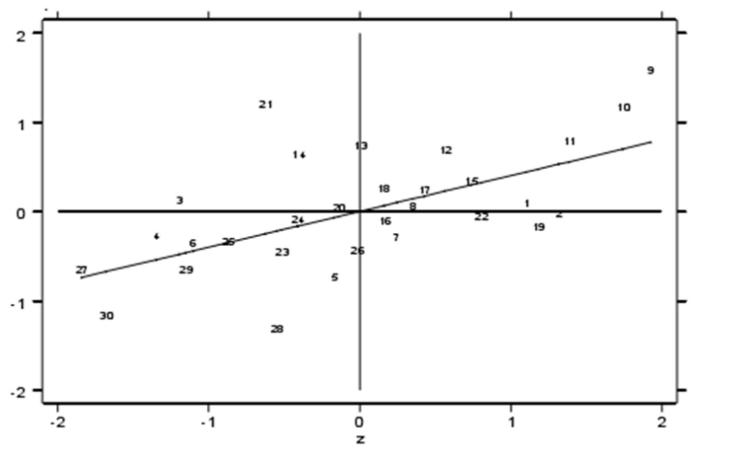

Fig. 9. Local Moran test results of industrial transformation and upgrading level space

The digital transformation of the industrial chain as a threshold value verifies whether digital levels in industrial chains influence industrial space upgrading driven by digital transformation. The results are shown in Table 7.

Threshold Type	**F Value**	**P Value**	**Bootstrap Times**	**Critical Value (1%)**	**Critical Value (5%)**	**Critical Value (10%)**
Double Threshold	34.13	0.0631	500	64.4181	37.8633	28.2543
Triple Threshold	6.31	0.7165	500	55.6174	37.3943	23.2791
Single Threshold	4.78	0.8365	500	28.5644	21.9484	17.6788

Table 7. Verification results of spatial effect threshold of industrial transformation and upgrading

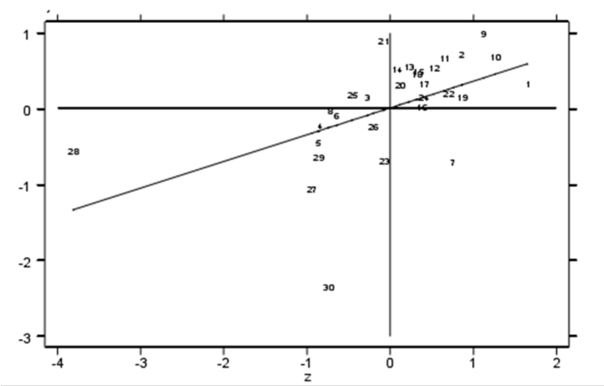

Fig. 10. Local Moran test results in the deep space of industrial transformation and upgrading

5. Conclusion

This paper conducts a comprehensive study on the digital transformation-driven spatial layout reconstruction and industrial upgrading of the industrial chain through literature review, conceptual interpretation, and development analysis. The theoretical logic behind the spatial layout reconstruction and industrial upgrading of digital transformation-driven industrial chains, the development level of digital transformation and industrial chain digitization, and the spatial effect and threshold characteristics of digital transformation-driven manufacturing upgrading are thoroughly explored. From the perspective of industrial chain spatial layout, this paper constructs a model for the digital transformation-driven industrial upgrading path and conducts empirical research using cities in the Yangtze River Delta Economic Belt as case studies. The experimental results demonstrate that the model is significant at a confidence level greater than 95%, making it suitable for the spatial measurement model selection. The mean square error of the network simulation output is 0.1333, verifying the proposed hypotheses and confirming that digital transformation has a significant spatial driving effect on industrial upgrading. This study provides valuable insights into how digital transformation can effectively drive industrial upgrading and offers a theoretical and practical framework for optimizing the spatial layout of industrial chains in the digital economy era.

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