



RESEARCH ARTICLE

RESEARCH ON THE SPATIAL SPILLOVER EFFECTS OF HIGH-QUALITY DEVELOPMENT OF HUNAN MANUFACTURING INDUSTRY AFFECTING DIGITAL ECONOMY IN HUNAN

Huimin Chen¹, Xuxia Deng¹ and Lishan Zeng²

¹School of Business, Hunan Institute of Engineering, Xiangtan 411104, China

²School of Mechanical Engineering, Hunan Institute of Engineering, Xiangtan 411104, China

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*Corresponding author: **Huimin Chen**

ABSTRACT

Based on data from 14 prefecture-level cities in Hunan Province from 2011 to 2023, this study employs the Spatial Durbin Model (SDM) to analyze the spatial spillover effects of high-quality manufacturing development on the digital economy. Moran's I index test indicates significant spatial correlation in high-quality manufacturing development across the Hunan region. Results from the Spatial Durbin Model show that the coefficients for both high-quality manufacturing and its spatial lag term are positive and statistically significant at the 10% level, demonstrating that high-quality manufacturing positively influences the digital economy and exhibits spatial spillover effects. Heterogeneity analysis reveals that the direct effect of high-quality manufacturing on the digital economy in the Chang-Zhu-Tan region is significantly higher than that in non-Chang-Zhu-Tan areas, with spillover effects showing regional gradient differences. The study proposes establishing a "core leadership - specialized undertaking - green empowerment" collaborative mechanism. By building innovation consortia, developing industrial internet platforms, and deploying digital infrastructure, this approach aims to strengthen the spatial interaction effects between manufacturing and the digital economy.

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INTRODUCTION

The core driving force to promote the high-quality development of regional economy lies in the high-quality development of digital economy and manufacturing industry, and it is also an important support for Hunan region to achieve the strategic goal of "three high and four new". In 2023, the scale of digital economy in Hunan will exceed 1 trillion (1) yuan, and the output value of manufacturing industry in the same period will reach 2.2 trillion yuan (2), accounting for about 40% of GDP. Digital economy is an important part of regional economy, and the manufacturing industry has entered the era of intelligent manufacturing from the era (3) of simple processing, which still plays a very important role in economic growth. Intelligent manufacturing is a feature of the high-quality development of manufacturing industry. Therefore, how to further promote the high quality of economy and drive the development of digital economy by improving the high-quality development of manufacturing industry is still an important direction of current research. To summarize the relevant core literature, there are few studies on the impact of the high quality of manufacturing industry on the digital economy, and most of the research mainly focuses on the impact of digital economy on the manufacturing industry, which is mainly reflected in three aspects.

The core mechanism of digital economy driving the high-quality development of manufacturing industry: Summarizing the research results of core literature, it is found that digital economy enables the high-quality development of manufacturing industry through multi-dimensional path, and its core mechanism is reflected in three levels: technological innovation, factor allocation and industrial structure upgrading. In terms of technological innovation, digital economy promotes technological breakthroughs in manufacturing industry by alleviating financial constraints and improving innovation efficiency (Peilei Sun et al., 2025(4)). In terms of factor allocation optimization, digital economy improves resource misallocation by breaking market segmentation and reducing financial frictions (Zhuangyu Wei, 2022(5); Zhiqiang Pang et al., 2025(6)). In terms of industrial structure upgrading, digital economy promotes the optimization and rationalization of manufacturing structure by promoting the integration of industrial digitalization and digital industrialization (Wenyu Fu et al., 2022(7); Hu Yue et al., 2024(8)). The heterogeneous characteristics of digital economy affecting manufacturing industry: By summarizing the research results of core literature, it is found that the impact of digital economy on manufacturing industry has significant regional, industry and enterprise heterogeneity.

From the regional heterogeneity, the eastern region because of perfect digital infrastructure, digital economy can be assigned to manufacturing effect more significant (Ziran Jiang, *et al.*, 2024(9)). Look from industry heterogeneity, digital economy to technology-intensive and capital-intensive manufacturing role stronger (Rongrong Zhou *et al.*, 2025(10); Haijie Wang, 2025(11)). From the enterprise heterogeneity, state-owned companies and large enterprises benefit from digital economy more (Jinzhu Du *et al.*, 2023(12)).

Digital economy reconstructs the industrial chain and spatial layout of manufacturing industry: By summarizing the research results of core literature, it is found that digital economy not only affects the micro efficiency of manufacturing industry, but also promotes the resilience of industrial chain and the optimization of spatial layout, forming a new pattern of industrial development. In terms of resilience of the industrial chain, digital economy enhances the anti-risk ability of the industrial chain through technological innovation and industrial collaborative agglomeration (Xiangdong Liang *et al.*, 2023(13); Li Zhang *et al.*, 2025(14)). In terms of spatial layout, digital economy promotes the manufacturing industry to present a two-way transfer mode of “internal migration” and “reflow”(Yuxiu Lu, 2024(15); Yunqian Cheng *et al.*, 2025(16)). In terms of global value chain reconstruction, digital economy helps the manufacturing industry to break through the “low-end lock” (Jiexi Zhu *et al.*, 2023(17)).

Literature of the digital economy affect the core of the manufacturing for this study provides a rich material, as well as the research method and perspective, but he seems to ignore the influence of manufacturing of digital economy. Huaichao Chen (2022)(18) based on provincial panel data to construct panel vector autoregressive model (PVAR) analysis of the “digital economy, talent quality and interactive relationship of manufacturing structure upgrade”, the “digital economy and the manufacturing structure rationalization and mutual promoting effect” in the high-grade exist significant conclusions. High-level manufacturing structure rationalization and belongs to the manufacturing quality of a performance, also means that the manufacturing of high quality digital economy has a positive influence on the role of, this argument naturally become a theory foundation of this research. Then, based on Hunan region, will the high-quality development of manufacturing industry play a role in promoting the development of digital economy, and there is a spatial spillover effect? What are the differences in its performance at different geographical scales? Analyzing the law that the high quality of manufacturing industry affects the digital economy can provide theoretical basis and policy reference for optimizing the layout of digital economy in Hunan region and promoting the high-quality development of manufacturing industry. It is of great academic significance to improve the high-quality development of regional economy.

Theoretical analysis and research hypotheses

High quality of manufacturing industry has spatial spillover effect: A manufacturing to achieve high quality development in the region, mainly through industrial agglomeration, technology spillovers, knowledge transmission to the surrounding areas have a positive impact. In terms of industrial agglomeration, manufacturing high quality development area will attract a large number of upstream and downstream enterprises gathered, industry cluster formation, improve the competitiveness of manufacturing industry in this region, also by industry correlation effect lead to the development of surrounding areas related industry. In the aspect of technology spillover, advanced manufacturing technology and management experience through the flow of people, such as cooperation between enterprise and the channel transmission to the surrounding areas. The surrounding areas of enterprises to absorb the advanced technology and experience, and then improve their production level and management ability, promoting the region’s manufacturing industry to develop in the direction of high quality. In terms of knowledge dissemination, in regions with high-quality manufacturing development, the close cooperation between enterprises and scientific research institutions will produce new knowledge and new technology. New knowledge and technology will be spread to the surrounding areas through academic exchanges and technical training, providing knowledge support for the innovative development of the manufacturing industry in the surrounding areas. Based on the above analysis, H1 is proposed: the high-quality development of manufacturing industry has spatial spillover effect.

Spatial spillover effect of high quality of manufacturing industry on digital economy: The high-quality development of manufacturing industry has a spatial spillover effect on the digital economy, which is mainly reflected in the following three aspects. One is that in the process of manufacturing high quality development demand for digital technology will lead to the development of digital economy. In the core region, the development of high quality manufacturing enterprises will actively introduce advanced digital technology, in order to realize intelligent manufacturing and product innovation research and development, agglomeration attracting digital technology companies in the core region, promote the development of local digital economy. Experience at the same time, the core area of the application of digital technology and demand information through the way such as industry associations and technical exchanges to surrounding areas, promote the spread of the digital economy in the adjacent area. Second, manufacturing high quality development brought about by the innovations and knowledge overflow has a promoting effect to digital economy, and produce space overflow. Manufacturing enterprises with high-quality development enhance their competitiveness through innovation, and also provide new technologies and application scenarios for the development of digital economy. The innovation achievements of high-quality development of manufacturing industry are spread to the surrounding areas through technology transfer and talent flow, and promote the innovation and development of digital economy in the adjacent areas. Three is, manufacturing high quality development of industrial ecology with supporting role of digital economy, and produce space overflow. High quality development of manufacturing industry will form a complete industry ecosystem, provides a good support for the development of the digital economy environment, attracting digital economy cooperation between enterprises and realize resources sharing and complementary advantages. At the same time, the advantages of this kind of industry ecology will through mechanisms such as the coordinated development of industry associations and regional spread to the surrounding areas, and promote the development of digital economy in the neighborhood. Based on the above

analysis, puts forward the research hypothesis H2: manufacturing high quality development of digital economy has significant spatial spillover effects, that is, a regional manufacturing high quality development of surrounding areas can promote the development of the digital economy.

Research design: In order to test the spatial interaction effect between digital economy and the high-quality development of manufacturing industry, an econometric model was constructed, variables were selected, and data sources were determined to lay an empirical research framework for subsequent research.

Construct the econometric model

Spatial weight matrix: The adjacent weight matrix and economic distance weight matrix were selected as the follow-up research.

Referring to Lesage and Pace(2009)(19), the binary adjacency matrix can be written as follows:

$$w_{ij} = \begin{cases} 1, & i \text{ is adjacent to } j \\ 0, & \text{thers} \end{cases}.$$

Referring to Tiiu Paas and Friso Schlitte(2006)(20), the weight of spatial distance can be expressed as:

$$w_{ij} = \begin{cases} 1/d_{ij}^2, & i \neq j \\ 0, & i = j \end{cases}.$$

Where d_{ij}^2 is the distance from the center of the two regions i and j . Referring to the literature of Azhong Ye *et al.* (2020)(21) and Huimin Chen(2018,2021,2024)(22-24), the economic geographic matrix can be expressed as:

$$w_{eg} = w_d * \text{diag} \left(\overline{\text{pgdp}}_1 / \overline{\text{pgdp}}, \overline{\text{pgdp}}_2 / \overline{\text{pgdp}}, \dots, \overline{\text{pgdp}}_n / \overline{\text{pgdp}} \right).$$

Where, w_d is the spatial weight matrix of geographical distance, $\overline{\text{pgdp}}_i = \frac{1}{t_1 - t_0 + 1} \sum_{t_0}^{t_1} \text{pgdp}_{it}$ is the per capita GDP of the first region during the sample period, and $\overline{\text{pgdp}} = \frac{1}{n(t_1 - t_0 + 1)} \sum_{i=1}^n \sum_{t_0}^{t_1} \text{pgdp}_{it}$ is the overall per capita GDP during the sample period.

Spatial correlation test: Standardized (Moran, 1950) Moran's $I(25)$ was used to identify the spatial correlation between digital economy and high quality of manufacturing industry. If Y is the observed value of the research object, Moran's I can be obtained by

$$\text{Moran's } I = \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij} (Y_i - \bar{Y})(Y_j - \bar{Y})}{S^2 \sum_{i=1}^n \sum_{j=1}^n w_{ij}}.$$

Where, $S^2 = \frac{1}{n} \sum_{i=1}^n (Y_i - \bar{Y})^2$, $\bar{Y} = \frac{1}{n} \sum_{i=1}^n Y_i$; Y_i is the observed value of the region i ; n is the total number of regions; w_{ij} is the i row and j column element of the spatial weight matrix.

The standardized statistic of Moran's I is

$$Z = \frac{\text{Moran's } I - E(I)}{\sqrt{\text{Var}(I)}}.$$

Where $E(I) = -\frac{1}{n-1}$, $\text{Var}(I) = \frac{n^2 w_1 + n w_2 + 3 w_0}{w_0^2 (n^2 - 1)} E^2(I)$, $w_0 = \sum_{i=1}^n \sum_{j=1}^n w_{ij}$, $w_1 = \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n (w_{ij} + w_{ji})^2$,

$w_2 = \sum_{i=1}^n \sum_{j=1}^n (w_i + w_j)$, and w_i, w_j are the sum of the rows and columns in the spatial weight matrix, respectively. The standardized statistics of Moran's I were used for the test, and the assumptions and judgment criteria are shown in Table 1.

Table 1. Moran' s I statistical test conditions and criteria

Condition of assumption		Criteria for judging Significance level (0.1, 0.05, 0.01)	
H_0	H_1	p Value greater than significance level	p Value is less than significance level
No spatial correlation was found	There is spatial correlation	There is no spatial correlation	There is spatial correlation

Spatial simultaneous equation model: In order to investigate the interactive influence and spatial spillover effect between digital economy and high quality of manufacturing industry, the spatial econometric model is constructed as follows:

$$D_{it} = \beta_0 + \beta_1 \sum_{j \neq i} W_{ij} D_{jt} + \beta_2 Q_{it} + \beta_3 \sum_{j \neq i} W_{ij} Q_{jt} + \beta X_{it} + \gamma_i + \eta_t + \mu_{it},$$

$$\mu_{it} = \lambda \sum_{j \neq i} W_{ij} \mu_{jt} + \varepsilon_{it}.$$

Where, Q_{it} the high quality index of manufacturing industry in the i year; X_{it} denotes the control variables affecting the digital economy; D_{it} denotes the indicators of digital economy in the i year of the region i ; β_0 is the constant term; β_1 is spatial autoregressive coefficient; β_2 is the influence coefficient of high quality of manufacturing industry; β_3 is the coefficient of spatial lag term of core explanatory variable; ε_{it} and μ_{it} is the random error term; γ_i is individual fixed effect; η_t is time fixed effect; λ is the coefficient of spatial error term; W is the exogenously determined standardized spatial weight matrix, including spatial adjacency matrix, second-order inverse distance spatial weight matrix and economic geography spatial matrix.

Variable selection

Core variables

Core variables include high quality of manufacturing industry(Q) and digital economy(D). High quality of manufacturing industry refers to the development state(26,27) of manufacturing industry that improves quality and efficiency, innovation-driven, green development and integration of data and reality. Here from innovation drive (industrial enterprises above designated size R&D expenses within budget revenue proportion, the proportion of output value accounted for revenue, new products R&D personnel) mention quality, increase efficiency, business tax and all additional RMB one hundred million, industrial workers, the annual average number of on-the-job worker number scale, operating cost accounts for the proportion of revenue and profits of the business income ratio) and green manufacturing (gauge Mode of comprehensive energy consumption and industry ten thousand tons of standard coal) three dimensions choose representative indicators, using entropy method to calculate.

Digital economy is a series of economic activities(28) that take digital knowledge and information as the key factors of production, modern information network as the important carrier, and the effective use of information and communication technology as the important driving force for efficiency improvement and economic structure optimization. Here, representative indicators are selected from three dimensions: digital industrialization (tens of thousands of Internet users, tens of thousands of local telephone users at the end of the year, telecom service income of 100 million yuan, mobile phone users of tens of thousands of yuan), industrial digitalization (postal service income of 100 million yuan), digital economic environment (total fixed asset investment of 100 million yuan, the number of patent applications), and the entropy method is used for calculation.

These two indicators have broad connotations, so composite indicators are selected. For specific calculation, see Huimin Chen *et al.* (2025)(29).

Control variables: Factors affecting the development of digital economy can be simply divided into internal and external factors. Market scale and economic scale are used as proxy variables for internal factors, while foreign capital dependence and foreign trade dependence are used as proxy variables for external factors.

Economic scale(x_1): Economic scale determines the cost and development environment of manufacturing industry. Referring to the literature of Bin Zhu(2024), the total retail sales of social consumer goods accounted for the proportion of GDP is selected as the proxy variable of the internal demand.

Market scale(x_2): The expansion of market scale can bring more users and demands, further promote the innovation and popularization of digital products and services, and promote the development of digital economy. Referring to the literature of Bingjie Su *et al.* (2022)(30), the number of permanent residents is used as a proxy variable.

Foreign capital dependence(x_3): the inflow of foreign capital increases, and the inflow of foreign technology and services also increases, which is conducive to the development of digital economy. Referring to the literature of Shaohong Cai *et al.* (2022) (31), the proportion of foreign direct investment in GDP is used to express it. Foreign trade dependence(x_4): export trade represents external demand, and the larger the export scale is, the more conducive the manufacturing industry is to digest inventory and overcapacity, stimulate its innovation ability, and thus improve its high-quality development level. Referring to the literature of Chunmei Li (2019) (32), the proportion of export trade in regional GDP is selected as the proxy variable of external demand. Data sources and descriptive statistics: Data source: Hunan Statistical Yearbook 2011-2023 (main economic and social statistical indicators of each city and prefecture), national economic and social development of 14 prefecty-level cities in Hunan Province (Lou Di, Yueyang, Changde, Zhangjiajie, Huaihua, Zhuzhou, Yongzhou, Xiangtan, Xiangxi, Yiyang, Hengyang, Shaoyang, Chanzhou, Changsha) from 2011 to 2023 Exhibition Statistical Bulletin and Statistical Yearbooks, 2024-2023 Hunan

Science and Technology Statistical Yearbooks. The fixed assets from 2018 to 2023 are calculated by multiplying the growth rate from 2017, and the fixed assets of the manufacturing industry from 2018 to 2023 are calculated by multiplying the fixed assets by the proportion of fixed investment in the manufacturing industry. The data of research variables before 2005 are missing, and the latest statistical yearbook of Hunan Province is in 2024, so the sample period is from 2005 to 2023. The descriptive statistics of the research variables are shown in Table 2. Analysis of Table 2 shows that: the annotation difference of digital economy is 0.0926, and the range difference is 0.4085; The standard deviation of manufacturing high quality is 0.1171, and the range is 0.5123. In general, there are great regional differences in the digital economy and the high quality of manufacturing industry in the 14 prefecture-level cities of Hunan.

Table 2. Descriptive statistics of variables

Variables	Sample size	Minimum	Maximum value	Mean	Standard deviation
Digital economy (D)	266	0.5079	0.9164	0.6000	(0.0926)
High quality in manufacturing (Q)	266	0.3885	0.9008	0.6000	(0.1171)
Economic size (x1)	266	26.8828	57.6143	37.3719	(5.7664)
Market size (x2)	266	26.2700	83.5900	48.1844	(11.7982)
Foreign capital dependence (x3)	266	0.0086	6.6720	1.7328	(1.4791)
Foreign trade dependence (x4)	266	0.0926	17.8198	4.3266	(3.5279)
Per capita regional product yuan	266	5026	139876.5	38683.6129	(28419.3883)

Empirical analysis results

Results of spatial correlation test: The spatial adjacency matrix, economic distance and economic geography weight matrix were used to test the global Moran index, and the results in Table 3 were obtained. The results show that the manufacturing high quality is not significant in 2019-2020 and 2021-2023, but positive in other years, which passes the significance level test of 5%, indicating that the manufacturing high quality in Hunan has obvious spatial correlation, which verifies Hypothesis H1.

Table 3. Moran's I of high quality of manufacturing industry in Hunan

Year	Adjacency matrix w1			Economic distance spatial weight w2			Economic geography weight matrix W3		
	I	Z	P-value	I	Z	P-value	I	Z	P-value
2005	0.267	2.20	0.028	0.134	2.38	0.017	0.310	2.53	0.011
2006	0.258	2.13	0.033	0.132	2.36	0.018	0.313	2.55	0.011
2007	0.519	3.62	0.000	0.257	3.59	0.000	0.420	3.10	0.002
2008	0.395	2.90	0.004	0.197	2.98	0.003	0.390	2.95	0.003
2009	0.400	2.78	0.005	0.195	2.81	0.005	0.407	2.90	0.004
2010	0.320	2.32	0.021	0.128	2.12	0.034	0.405	2.89	0.004
2011	0.311	2.24	0.025	0.163	2.45	0.014	0.417	2.93	0.003
2012	0.298	2.18	0.029	0.166	2.50	0.012	0.406	2.89	0.004
2013	0.268	2.05	0.040	0.152	2.41	0.016	0.388	2.83	0.005
2014	0.264	2.04	0.041	0.137	2.27	0.023	0.374	2.77	0.006
2015	0.393	2.82	0.005	0.197	2.91	0.004	0.327	2.49	0.013
2016	0.382	2.78	0.006	0.211	3.08	0.002	0.338	2.57	0.010
2017	0.333	2.52	0.012	0.167	2.66	0.008	0.272	2.20	0.028
2018	0.404	2.88	0.004	0.165	2.57	0.010	0.260	2.07	0.038
2019	0.113	1.33	0.185	0.054	1.62	0.105	0.134	1.51	0.130
2020	-0.074	0.02	0.981	-0.041	0.47	0.641	0.114	1.43	0.152
2021	0.230	2.09	0.036	0.138	2.59	0.010	0.217	2.06	0.039
2022	-0.047	0.19	0.849	-0.055	0.25	0.804	0.116	1.25	0.213
2023	-0.080	-0.02	0.986	-0.093	-0.17	0.862	0.069	0.91	0.361

The local Moran scatter plot of high quality in manufacturing in 2010 and 2015 shows that: It is found that there are high and high agglomeration in Xiangtan, Yueyang, Zhuzhou, Changsha and Changde, and low and high agglomeration in Zhangjiajie, Shaoyang, Xiangxi, Huaihua and Yongzhou except for the cities of Lodi, Yiyang and Hengyang, which indicates that there is a positive spatial correlation between the manufacturing high quality in Hunan.

Model selection test: In this paper, the test of OLS, sar and sem model selection, the test of sdm, sar and sem model selection of common spatial econometric models, and the Hausman test of the determined spatial econometric model are carried out first.

LM test of OLS, sar and sem model selection: Using w_1 、 w_2 、 w_3 , spatial weight matrix, LM test was conducted on the residuals after OLS analysis of the model to determine the necessity of spatial econometric model application. The test results are shown in Table 4.

Table 4. LM test results selected by ols-sar-sem

LM test	Spatial adjacency matrix (w1)		Economic Distance weight matrix (w2)		Economic Geography Weight Matrix (w3)	
	chi-square	P-value	chi-square	P-value	chi-square	P-value
LM sem	3.454	0.063	14.809	0.000	10.675	0.001
Robust LM sem	14.803	0.000	107.982	0.000	91.592	0.000
LM sar	33.801	0.000	3.068	0.080	2.720	0.099
Robust LM sar	45.151	0.000	96.242	0.000	83.637	0.000

The LM-sem test, which is related to the spatial error model (sem), has statistics of 3.454, 14.809 and 10.675 under the conditions of spatial adjacency matrix (w1), economic distance weight matrix (w2) and economic geography weight matrix (w3), respectively, indicating that the test is statistically significant at the 10% significance level. The LM-sar test related to the spatial error model (sar) reaches 33.801, 3.068 and 2.720 respectively under the conditions of spatial adjacency matrix (w1), economic distance weight matrix (w2) and economic geography weight matrix (w3), indicating that the test is statistically significant at the significance level of 10%. This indicates that the model is suitable for sar and sem spatial econometric models, and it also means that further robustness tests are needed. Robust_lm-sem test was conducted under the spatial adjacency matrix (w1), economic distance weight matrix (w2) and economic geography weight matrix (w3), and the statistics reached 14.803, 107.982 and 91.592, respectively, indicating that the test was statistically significant at the 1% significance level. Robust_lm-sar test was conducted under the spatial adjacency matrix (w1), economic distance weight matrix (w2) and economic geography weight matrix (w3), and the statistics reached 45.151, 96.242 and 83.637, respectively, indicating that the test was statistically significant at the 1% significance level. Based on the results of LM test, the spatial correlation is significant, but it is impossible to determine the specific choice of sar or sem model. Further LR and Wald tests are needed.

LR and Wald test for sdm, sar and sem model selection: The spatial weight matrix is used to perform LR and Wald tests on SDM-SAR and SDM-SEM to determine whether the spatial Durbin model (sdm) can be degenerated into spatial autoregressive model (sar) or spatial error model (sem). The test results are shown in Table 5.

Table 5. LR-Wald test results of sdm-sar-sem model selection

LR and Wald tests	Spatial adjacency matrix (w1)		Economic Distance weight matrix (w2)		Economic Geography Weight Matrix (w3)	
	chi-square	P-value	chi-square	P-value	chi-square	P-value
LR-sdm_sar	3.260	0.071	2.842	0.092	0.170	0.680
LR-sdm_sem	2.766	0.096	2.172	0.141	0.542	0.462
Wald-sdm_sar	5.079	0.079	4.828	0.089	5.863	0.053
Wald-sdm_sem	4.916	0.086	4.814	0.090	5.655	0.059

Under the conditions of LR-sdm_sar statistics, spatial adjacency matrix and economic distance weight matrix, the test passed the statistical test at the significance level of 10%, indicating that sdm was appropriate. However, under the condition of economic geography weight matrix, it did not pass the statistical test at the significance level of 10%, so the null hypothesis of “sdm degenerates into sar” cannot be rejected. Observing the LR-sdm_sem statistic, under the condition of spatial adjacency matrix, it passed the statistical test at the significance level of 10%, indicating that the sdm model is appropriate. However, under the conditions of economic distance weight matrix, and economic geography weight matrix, it fails to pass the statistical test at the significance level of 10%, which cannot reject the null hypothesis of “sdm degenerates into sem”. In order to further determine whether to use sdm model, further analysis of Wald test results is needed. Under the conditions of spatial adjacency matrix, economic distance weight matrix, and economic geography weight matrix, Wald-sdm_sar statistics all passed the statistical test at the significance level of 10%, indicating that sdm is appropriate. Under the conditions of spatial adjacency matrix, economic distance weight matrix, and economic geography weight matrix, the Wald-sdm_sem test passed the statistical test at the significance level of 10%, indicating that sdm is appropriate. Based on the results of LR and Wald test, sdm model is appropriate.

Hausman test of spatial econometric model: After determining the spatial Durbin model (sdm) as the appropriate basic model, it is necessary to further determine whether the model should be set by fixed effect (fe) or random effect (re) through Hausman test to ensure the consistency and reliability of parameter estimation. The test results are shown in Table 6. Spatial econometric model

Table 6. Hausman test results for sdm-fe-re model selection

Weights and statistics	Spatial adjacency matrix (w1)		Economic Distance weight matrix (w2)		Economic Geography Weight Matrix (w3)	
	chi-square	P-value	chi-square	P-value	chi-square	P-value
Hausman test	17.890	0.000	10.435	0.015	11.398	0.010

Table 6 shows that under the conditions of spatial adjacency matrix, economic distance weight matrix, and economic geography weight matrix, the statistics all pass the statistical test at the significance level of 5%, indicating that the sdm fixed effect model is appropriate.

Results of the benchmark model and spatial spillover effect

Analysis of benchmark model results: According to the test results of model selection, the spatial Durbin fixed effect models without and with control variables (Models 2,4,6) are carried out under the conditions of spatial adjacency matrix (w1), economic distance weight matrix (w2) and economic geography weight matrix (w3), respectively, and the results are obtained in Table 7. Under the condition of w1, w2 and w3 spatial weight matrix, the spatial Durbin fixed effect model (1,3,5) without introducing control variables shows that the coefficients of manufacturing high quality are 0.0192, 0.0186 and 0.0179 respectively, which all pass the statistical test at the significance level of 10%. It shows that the high quality of manufacturing industry has a positive role in promoting the digital economy; The coefficients before the spatial lag term ($w \square Q$) of manufacturing quality are 0.0362, 0.0371 and 0.0301 respectively, which also pass the statistical test at the significance level of 10%, indicating that the high quality of

manufacturing in adjacent areas has a positive spillover effect on the digital economy of the region. Under the condition of spatial weight matrix w1, w2 and w3, the spatial Durbin fixed effect model (2,4,6) with the introduction of control variables shows that the coefficients before the high quality of manufacturing industry are 0.0194, 0.0187 and 0.0181 respectively, which are slightly higher than the coefficients without the introduction of control variables and pass the statistical test at the significance level of 10%. It shows that the high quality of manufacturing industry has a positive role in promoting the digital economy; The coefficients before the spatial lag term ($w \otimes Q$) of manufacturing high quality are 0.0358, 0.0366 and 0.0290 respectively, which are slightly lower than the coefficients without introducing control variables, and also pass the statistical test at the significance level of 10%, indicating that the high quality of manufacturing in adjacent areas has a positive spillover effect on the digital economy of the region. In general, the high quality of the local manufacturing industry has a positive promotion effect on the local digital economy, and the high quality of the manufacturing industry in the adjacent region has a positive spillover effect on the digital economy in the region, which verifies H2.

Table 7. Results of spatial Durbin fixed effect model

Variables	Spatial adjacency matrix (w1)		Economic Distance weight matrix (w2)		Economic Geography Weight Matrix (w3)	
	1	2	3	4	5	6
Q	0.0192 ** (0.0097)	0.0194 ** (0.0097)	0.0186 * (0.0098)	0.0187 * (0.0098)	0.0179 * (0.0099)	0.0181 * (0.0099)
x2		-0.0008 (0.0067)		-0.0024 (0.0066)		-0.0016 (0.0067)
x3		0.0290 (0.0529)		0.0151 (0.0525)		0.0161 (0.0528)
$w \otimes Q$	0.0362 * (0.0205)	0.0358 * (0.0205)	0.0371 * (0.0215)	0.0366 * (0.0216)	0.0301 * (0.0184)	0.0290 (0.0186)
$w \otimes D$	-0.1244 (0.0869)	-0.1281 (0.0881)	0.1821 * (0.1136)	0.1835 * (0.1136)	-0.1153 (0.1011)	-0.1179 (0.1013)
Constant term	0.0080 (0.0004)	0.0079 (0.0004)	0.0079 (0.0004)	0.0079 (0.0004)	0.0080 (0.0004)	0.0080 (0.0004)
N	266	266	266	266	266	266

Results of spatial spillover effect: Because the high quality of the manufacturing industry has a spatial spillover effect and affects the digital economy in neighboring areas, it is necessary to further decomposition the direct effect, indirect effect and total effect of the impact of the high quality of the manufacturing industry on the digital economy to analyze the spillover effect, and the results are obtained in Table 8. Under the condition of w1 and w2 spatial weight matrix, the direct effect, indirect effect and total effect all pass the statistical test at the significance level of 10%, indicating that the high quality of manufacturing industry helps to promote the digital economy of the local region, and can also drive the digital economy of other neighboring regions. Which manufacturing high quality direct effect to the digital economy and spatial spillover effects are significantly positive influence. Under the condition of w3 spatial weight matrix, the direct effect and the total effect pass the statistical test at the significance level of 10%, but the indirect effect does not pass the statistical test at the significance level of 10%, indicating that the spatial spillover effect is not significant.

Table 8. Results of spatial spillover effect

Types of spillover effects	Spatial adjacency matrix (w1)			Economic Distance weight matrix (w2)			Economic Geography Weight Matrix (w3)		
	Effect size	Z-score	P-value	Effect size	Z-score	P-value	Effect size	Z-score	P-value
Direct effect	0.0192	1.96	0.050	0.0173	1.74	0.083	0.0173	1.72	0.086
Indirect effect	0.0271	1.68	0.100	0.0294	1.71	0.098	0.0228	1.35	0.178
Total effect	0.0463	2.46	0.014	0.0467	2.46	0.014	0.0400	2.42	0.015

Robustness analysis: The robustness test was carried out by changing the calculation method of the composite value of the core explanatory variables, changing the time period, and using geographical distance, and the results were obtained in Table 9.

Table 9. Results of robustness analysis

Variables	Calculation method of composite value of core explanatory variables (principal component calculation method) : w1	Change time period (2010-2020) :w1	Second-order inverse geographic distance :w4
Q	0.7162 *** (12.49)	0.0222 * (1.81)	0.0211 ** (2.20)
x2	0.2725 *** (3.46)	0.0191 (1.04)	-0.0022 (-0.32)
x3	-0.43 (-1.53)	0.2785 ** (-1.97)	0.0295 (-0.57)
$w \otimes Q$	0.3924 *** (-4.11)	0.0559 ** (-2.28)	0.0341 * (-1.91)
$w \otimes D$	0.1092 (1.39)	0.2427 * (-1.94)	0.3678 ** (-2.53)
Constant term	0.04	0.0059	0.0079
Observed values	266	140	266

Note: (1) *** p<.01, ** p<.05, * p<.1; Values within (2) () are z-values.

The principal component method is adopted to re-calculate the high quality and digital economy of manufacturing industry, and the spatial adjacency matrix w_1 is used for robustness analysis. It is found that the coefficient of high quality (Q) of manufacturing industry is 0.7162, which passes the statistical test at the significance level of 1%. The spatial lag term of manufacturing quality ($w \otimes Q$) is 0.3924, which also passes the statistical test at the significance level of 1%, indicating that changing the method of calculating core variables does not change the basic conclusion of the benchmark analysis. The research period is shortened to (2010-2020), and the spatial adjacency matrix w_1 is used for robustness analysis. It is found that the coefficient of manufacturing high quality (Q) is 0.0222, which passes the statistical test at the significance level of 10%. The spatial lag term of manufacturing quality ($w \otimes Q$) is 0.0559, which also passes the statistical test at the significance level of 5%, indicating that changing the time period does not affect the basic conclusion of the benchmark analysis. Changing the spatial weight to the second-order inverse geographical distance (w_4) for analysis, it is found that the coefficient of manufacturing high quality (Q) is 0.0211, which passes the statistical test at the significance level of 5%. The spatial lag term ($w \square Q$) of the high quality of manufacturing industry is 0.0341, which also passes the statistical test at the significance level of 10%, indicating that the use of the new spatial weight matrix does not weaken the benchmark analysis conclusion. Based on the above three robustness results, the coefficients of the core explanatory variables have changed partially, but the influence direction of the core explanatory variables on the explained variables has not been affected. Therefore, the conclusion of the benchmark analysis is relatively robust.

Heterogeneity analysis: Changsha-zhuzhou-xiangtan and non-Changsha-Zhuzhou-Xiangtan(33) were used for heterogeneity analysis, and Table 10 was obtained. For changsha-zhuzhou-xiangtan region, using spatial adjacency matrix (w_1), economic (w_2) and economic geographical distance weighting matrix weighting matrix to analyze SDM (w_3), found in manufacturing high quality (Q) coefficient is 0.6033, 0.6513, 0.5387, respectively, have passed the 5% significance level of statistical test, At the same time, the coefficients of the spatial lag term of manufacturing quality ($w \square Q$) are 0.3413, 0.0594 and 0.0075, which also pass the statistical test at the significance level of 1%, indicating that the high quality of manufacturing industry in Changsha-Zhuzhou-Xiangtan region has a positive impact on the digital economy, and the high quality of manufacturing industry in the adjacent areas has a spatial spillover effect on the digital economy of the region. For the non-Changsha-Zhuzhou-Xiangtan area, the sdm analysis of spatial adjacency matrix (w_1), economic distance weight matrix (w_2) and economic geography weight matrix (w_3) shows that the coefficients of manufacturing quality (Q) are 0.2074, 0.1955 and 0.1909 respectively, which all pass the statistical test at the significance level of 1%. At the same time, the coefficients of the spatial lag term ($w \square D$) of the digital economy are 0.3477, 0.4855 and 0.4619, which also pass the statistical test at the significance level of 1%, indicating that the high quality of the manufacturing industry in non-Changsha-Zhuzhou-Xiangtan region has a positive impact on the digital economy, and the digital economy in this region has a spatial spillover effect on the digital economy in the neighboring areas. However, the spatial lag term ($w \square Q$) of the high quality of manufacturing industry only passes the statistical test at the significance level of 10% under the condition of the economic geography weight matrix (w_3).

Table 10. Results of heterogeneity analysis

Variables	Chang-zhu-tan area			Non-chang-zhu-tan area		
	Spatial adjacency matrix (w_1)	Economic Distance weight matrix (w_2)	Economic Geography Weight Matrix (w_3)	Spatial adjacency matrix (w_1)	Economic Distance Weight matrix (w_2)	Economic Geography Weight Matrix (w_3)
Q	0.6033 ** (2.45)	0.6513 ** (2.49)	0.5387 ** (1.96)	0.2074 *** (7.12)	0.1955 *** (6.82)	0.1909 *** (6.59)
x2	1.0257 *** (4.68)	1.0462 *** (4.77)	1.1176 *** (5.16)	0.1351 *** (3.23)	0.0804 * (1.86)	0.0907 ** (2.00)
x3	1.5736 ** (-2.05)	1.4308 * (-1.79)	1.3784 * (-1.73)	0.0314 (0.23)	0.0525 (0.40)	0.0456 (0.34)
$w \square Q$	0.3413 *** (-3.64)	0.0594 *** (-3.07)	0.0075 *** (-2.95)	-0.0711 (-1.48)	-0.0445 (-0.55)	0.1059 * (-1.73)
$w \square D$	0.2301 * (-1.67)	-0.1341 (-1.08)	-0.1448 (-1.28)	0.3477 *** (5.61)	0.4855 *** (6.86)	0.4619 *** (6.56)
Constant term	0.0649	0.0676	0.0673	0.0161	0.0157	0.0158
Observed values	57	57	57	209	209	209

Notes: (1) *** $p < .01$, ** $p < .05$, * $p < .1$; Values within (2) () are z-values.

The direct effect, indirect effect and total effect of the impact of manufacturing high quality on digital economy are analyzed in Changsha-Zhuzhou-Xiangtan and non-Changsha-Zhuzhou-Xiangtan, and the spillover effect is analyzed, and the results are shown in Table 11.

Table 11. Results of spatial spillover effect under heterogeneity analysis

Changsha-Zhuzhou-Xiangtan									
Types of spillover effects	Spatial adjacency matrix (w_1)			Economic Distance weight matrix (w_2)			Economic Geography Weight Matrix (w_3)		
	Effect size	Z-score	P-value	Effect size	Z-score	P-value	Effect size	Z-score	P-value
Direct effect	0.76	3.67	0.001	0.73	3.19	0.001	0.623	2.57	0.006
Indirect effect	-1.36	-4.25	0.001	-1.09	-3.48	0.001	-1.032	-3.39	0.006
Total effect	-0.6	-2.46	0.010	-0.36	-2.72	0.01	-0.41	-2.89	0.002
Non-changsha-zhuzhou-xiangtan area									
Direct effect	-0.009	-1.36	0.174	-0.005	-0.53	0.593	0.012	-2.55	0.007
Indirect effect	-0.1	-1.45	0.147	-0.081	-0.54	0.588	0.185	-2.41	0.007
Total effect	-0.109	-1.44	0.149	-0.087	-0.54	0.589	0.197	-2.43	0.009

For Changsha-Zhuzhou-Xiangtan region, under the condition of w_1 , w_2 and w_3 spatial weight matrix, the direct effect, indirect effect and total effect all pass the statistical test at the significance level of 1%, indicating that the high quality of manufacturing industry helps to promote the digital economy of this region, and can also drive the digital economy of other adjacent areas. That is, the high quality of manufacturing industry has a significant positive impact on the direct effect and spatial spillover effect of digital economy. Under the condition of w_3 spatial weight matrix, the direct effect and the total effect pass the statistical test at the significance level of 10%, but the indirect effect does not pass the statistical test at the significance level of 10%, indicating that the spatial spillover effect is not significant. For the non-Changsha-Zhuzhou-Xiangtan region, under the w_3 spatial weight matrix, the direct effect, indirect effect and total effect all pass the statistical test at the significance level of 1%, indicating that the high quality of manufacturing industry helps to promote the digital economy of this region, and can also drive the digital economy of other neighboring regions. That is, the high quality of manufacturing industry has a significant positive impact on the direct effect and spatial spillover effect of digital economy. Under the condition of w_1 and w_2 spatial weight matrix, the direct effect, indirect effect and total effect did not pass the statistical test of significance level.

CONCLUSIONS AND IMPLICATIONS CONCLUSION

The results show that the high-quality development of manufacturing industry has a significant spatial spillover effect on the digital economy, and this effect varies at different geographical scales. The high quality of manufacturing industry in Changsha-Zhuzhou-Xiangtan region has a more significant impact on the digital economy, while the high quality of manufacturing industry in neighboring regions has a spatial spillover effect on the digital economy of the region.

INSPIRATIONS

The high-quality development of manufacturing industry can not only promote the development of local digital economy, but also drive the growth of digital economy in neighboring areas through spatial spillover effect. This shows that Huxiang region should further optimize the layout of digital economy and promote the high-quality development of manufacturing industry, so as to enhance the high-quality development of regional economy. Based on the research results, this paper puts forward some policy suggestions to optimize the layout of digital economy in Huxiang region and promote the high-quality development of manufacturing industry, so as to give full play to the spatial spillover effect of high-quality development of manufacturing industry on digital economy. First, strengthen the regional coordination and cooperation mechanism. We should build a digital economic spatial pattern of "Changsha-Zhuzhou-Xiangtan core leading - Southern and western Hunan characteristic carrying - green enabling area around the lake", establish a cross-city industrial cooperation alliance, and promote Changsha construction machinery, Zhuzhou rail transit and other advantageous manufacturing industries to form a complementary industrial chain with surrounding cities. We should improve the policy of "enclave economy", lay out digital manufacturing supporting parks in southern and western Hunan, promote the cross-regional flow of technology and capital through tax sharing, capacity sharing and other mechanisms, and amplify the radiation effect of the manufacturing industry in the core area on the whole province. Secondly, we should implement the project of improving the innovation capacity. We will build a national manufacturing innovation center, focusing on key areas such as intelligent equipment and industrial software, form an innovation consortium with leading enterprises such as Sany Heavy Industry and Zoomlion, and provide subsidies for R&D investment and special policies for intellectual property protection. We will implement the mechanism of "opening the list and taking charge", set up a special fund for digital technology transformation, support traditional manufacturing enterprises in upgrading their smart production lines, cultivate smart manufacturing demonstration plants, and form a source of technology spillovers. Third, build a digital industrial ecosystem. Build digital economy agglomeration areas such as Malanshan Video Culture and Innovation Park in Changsha, build industrial Internet public service platform, improve the whole chain ecology of "digital infrastructure-data elements - scene application", cultivate digital service providers, and form a collaborative development network of "core enterprises + supporting enterprises + service institutions".

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