Evolution of the Spatial Pattern of Manufacturing Innovation Capacity and Influencing Factors in the Yangtze River Delta Region

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Abstract： This paper aims to reveal the temporal and spatial evolution characteristics and influencing factors of manufacturing innovation capacity in the Yangtze River Delta region, providing empirical references for formulating regional manufacturing innovation center layout policies. Using the number of patents granted in the manufacturing industry to represent manufacturing innovation capacity, exploratory spatial data analysis, the Modified Herfindahl-Hirschman Index, and panel data regression analysis are employed to analyze the temporal and spatial evolution characteristics of manufacturing innovation capacity at regional, provincial, prefectural, and county levels. The study explores the factors affecting the spatial differences in manufacturing innovation capacity and their strength. The spatial equity of manufacturing innovation capacity in the Yangtze River Delta region has improved, the gap in innovation capacity among various areas has narrowed, and the degree of spatial agglomeration in innovation capacity has decreased. High-value and high-growth areas of manufacturing innovation capacity exhibit hierarchical and central city adjacency distribution, with hotspots evolving from "single core" to "multi-core." Income levels play a prominent role in enhancing manufacturing innovation capacity. The scale of scientific and technological talents, the level of financial development, economic foundation, and informatization level significantly influence various industries. Therefore, each region should scientifically and rationally plan the configuration of manufacturing innovation centers based on location advantages and resource endowments. Establish a regional manufacturing innovation center system, create manufacturing innovation centers of different levels, build cross-regional innovation cooperation networks, and promote the construction of regional innovation communities.

Keywords: Manufacturing Innovation Capacity; Yangtze River Delta Region; Spatial Pattern; Influencing Factors

1. Introduction

High-quality development of the manufacturing industry is a top priority for high-quality economic development in China, with innovation being the driving force and main engine. Faced with a new round of technological revolution and industrial transformation, industrial science and technology innovation centers are strong engines for the high-quality development of regional advanced manufacturing industry clusters, emerging industries, and future industries. These centers promote industrial upgrading and the development of new quality productivity and attract widespread attention from government leaders and scholars.

According to the "Guidance on Improving the Manufacturing Innovation System and Promoting the Construction of Manufacturing Innovation Centers" from the Ministry of Industry and Information Technology of China, various regions are accelerating the construction of national and provincial manufacturing innovation centers in line with national manufacturing development strategy needs and industrial transformation and upgrading. By 2022, China had established 24 national manufacturing innovation centers, 2 national-local joint manufacturing innovation centers, over 200 provincial manufacturing innovation centers, and 125 industrial technology foundation public service platforms. Since 2022, provinces and cities have issued policies such as the "Guidelines for the Construction of Manufacturing Innovation Centers" to accelerate the construction of these centers. Given the construction boom of manufacturing innovation centers across the country, it is essential to address issues of blind construction and disorderly expansion. An in-depth understanding of the spatial pattern evolution laws of manufacturing R&D centers and identifying key influencing factors for their development is urgently needed. Objectively evaluating the manufacturing innovation capacity and its element conditions in various regions will facilitate the formulation of more scientific and reasonable functional positioning and layout planning schemes for manufacturing innovation centers. Therefore, focusing on the construction of manufacturing innovation centers and exploring the temporal and spatial evolution of manufacturing innovation capacity is highly necessary.

Research on the temporal and spatial evolution of regional innovation capacity is a crucial topic in management, economics, and geography, primarily exploring the spatial pattern and influencing mechanisms of innovation capacity. Scholars have analyzed the spatial heterogeneity of innovation capacity and its influencing factors from enterprise, city, and regional scales. At the enterprise level, factors like entrepreneurship, innovation output, innovation input, and innovation atmosphere significantly impact enterprise innovation, with a continuous spatial agglomeration trend (Xu et al., 2015). At the city scale, the innovation capacity gap between cities is narrowing, with high-level and relatively high-level innovation cities displaying strong economic dependency, influenced by economic foundation, human capital, and education level (Wang et al., 2017; He et al., 2017). For instance, Shanghai exhibits a suburbanization trend of innovation resources, evolving from a single-core to a multi-core resonance, while Beijing's innovation space remains dominated by the city center's single-core model (Duan et al., 2015). At the regional level, China's regional innovation capacity shows a gradient distribution from high to low from the eastern coastal areas to the western inland areas, with coastal areas demonstrating strong innovation capacity (Liu and Hu, 2004). Innovation output is highly concentrated in a few eastern provinces, with per capita GDP, R&D investment, R&D personnel, and the number of college students having significant direct impacts on provincial innovation output. There are significant spatial agglomeration and spatial spillover effects in innovation activities between Chinese provinces (Cheng et al., 2014; Zhang and Li, 2007).

Previous research typically focuses on the spatial evolution of urban, enterprise, and regional innovation capacity and its influencing factors, with less analysis on the temporal and spatial evolution of industrial innovation capacity. In recent years, the study of temporal and spatial evolution of industrial innovation capacity has begun to attract scholars' attention, exploring spatial differences, spatial connections, spatial transfers, and their influencing factors in industries such as manufacturing and new energy (Liu and Du, 2019; Xie and Wang, 2022; Huang et al., 2023). However, current research results are relatively few due to data availability, and further research is still needed.

Given this, this study focuses on manufacturing innovation capacity in the Yangtze River Delta region, using the number of manufacturing invention patents from 2004 to 2018 to represent manufacturing innovation capacity. By employing exploratory spatial data analysis, the Modified Herfindahl-Hirschman Index, and panel data regression analysis, this study analyzes the temporal and spatial evolution characteristics of manufacturing innovation capacity at regional, provincial, prefectural, and county levels, revealing the influencing factors of spatial differences in manufacturing innovation capacity. This aims to enrich the theoretical results of manufacturing innovation capacity research and provide empirical references for regional manufacturing innovation center layout policies.

2. Data Sources and Research Methods

2.1 Study Area and Data Sources

This study focuses on the Yangtze River Delta region, which includes Shanghai, Jiangsu Province, Anhui Province, and Zhejiang Province, encompassing 41 cities above the prefecture level and 304 counties, according to the "Yangtze River Delta Regional Integration Development Planning Outline."

Patent indicators are important measures of technological activity output, reflecting regional technological innovation activity capacity (Cui et al., 2018). Using the number of authorized manufacturing invention patents to represent the manufacturing innovation capacity level in the region, this study analyzes the spatial differences and influencing factors of manufacturing innovation capacity in the Yangtze River Delta region. Manufacturing invention patent authorization data comes from the "China Microeconomic Data Query System - Innovation Enterprise Database," which provides patent application and authorization information for industrial enterprises above designated size in China from 1998 to 2018, sourced from the National Intellectual Property Administration. The database provides the number of authorized patents for each enterprise, the location of the enterprise, and national economic industry classification information. From this database, we selected the number of manufacturing patents authorized in the counties and prefectural cities of the Yangtze River Delta region from 2004 to 2018. Socio-economic data for 41 cities in the Yangtze River Delta region were obtained from the "Chinese City Statistical Yearbook" from 2005 to 2019.

2.2 Research Methods

2.2.1 Exploratory Spatial Data Analysis (ESDA)

Exploratory Spatial Data Analysis (ESDA) is used to detect the spatial autocorrelation of data, including global spatial autocorrelation and local spatial autocorrelation. Global autocorrelation is measured using Moran's *I* index and local autocorrelation is measured using the *Getis-Ord Gi** to identify hotspot and cold spot areas (Jiang et al., 2010).

To reveal the spatial autocorrelation of manufacturing innovation capacity in the Yangtze River Delta region, this article uses the Global Moran's *I* index and local autocorrelation analysis by *Getis-Ord Gi**. The Globa Moran's *I* index indicates the degree of clustering or dispersion of manufacturing innovation capacity in space, while the *Getis-Ord Gi** identifies hotspot and cold spot regions.

2.2.2 Modified Herfindahl-Hirschman Index (*MHHI*)

The Modified Herfindahl-Hirschman Index (*MHHI*) measures the concentration of geographic elements' spatial distribution. *MHHI* and the number of authorized manufacturing patents are used to indicate the balance level of regional manufacturing innovation capacity.

$$MHHI^k = \sqrt{\frac{\sum_{i=1}^{n} (c_i^k)^2}{n}} \text{，其中} c_i^k = w_{i,k} / \sum_{i=1}^{n} w_{i,k}$$

Where c_i^k is the share of attribute k in sub-region i, $w_{i,k}$ is the value of attribute k (number of authorized patents) in region i, n is the number of sub-regions, and $MHHI^k$ is the Modified Herfindahl-Hirschman Index of attribute k. A larger index indicates a higher concentration of elements.

2.2.3 Panel Data Regression Model Analysis

Panel Data Regression Model Analysis is used to explore the factors influencing the spatial differences in regional manufacturing innovation capacity and their strength. The basic setting of the econometric model is:

$$\ln Y_{it} = \beta_0 + \sum_{j=1}^{k} \beta_j X_{it} + \varepsilon_{it}$$

Where Y represents the dependent variable (number of authorized manufacturing invention patents), indicating regional manufacturing innovation capacity, and X represents the independent variables (socio-economic influencing factors). i represents cities above the prefecture level, and ε_{it} is the random disturbance term. To avoid heteroscedasticity and cointegration relationships between sequences, the indicators in the equation are logarithmically transformed.

3. Analysis of the Temporal and Spatial Evolution of Manufacturing Innovation Capacity in the Yangtze River Delta Region

3.1 Development Trend Analysis of Manufacturing Innovation Capacity in the Yangtze River Delta Region

3.1.1 Changes in the Number of Authorized Manufacturing Invention Patents in the Yangtze River Delta Region

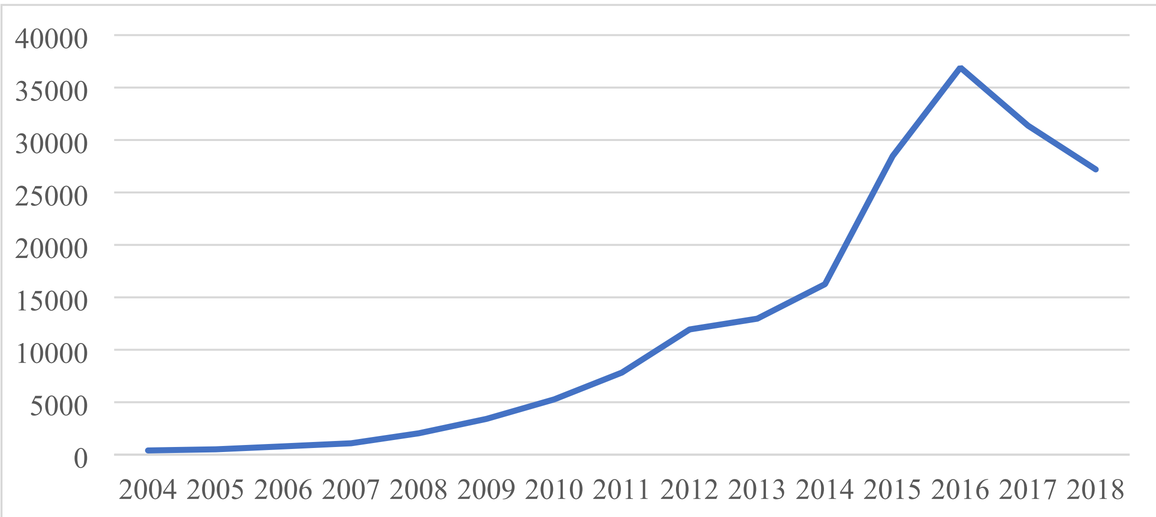


Figure 1 Trend analysis of the number of authorized invention patents in the manufacturing industry in the Yangtze River Delta region from 2004 to 2018

Figure 1 shows the trend in the number of manufacturing invention patents granted in the

Yangtze River Delta region from 2004 to 2018. Through exponential analysis and linear prediction analysis of the data, it was found that although the number of manufacturing invention patents granted fluctuated between 2004 and 2018, it exhibited a rapid overall upward trend. Specifically, from 2004 to 2008, the number of patents granted showed a linear growth trend, while from 2008 to 2016, it displayed an exponential growth trend with accelerated patent grants. However there was a slight decline in the number of patents from 2016 to 2018. Overall, the innovation capability of the manufacturing industry in the Yangtze River Delta region is continuously strengthening.

3.1.2 Analysis of the Development Trend of Manufacturing Innovation Capability by Province in the Yangtze River Delta Region

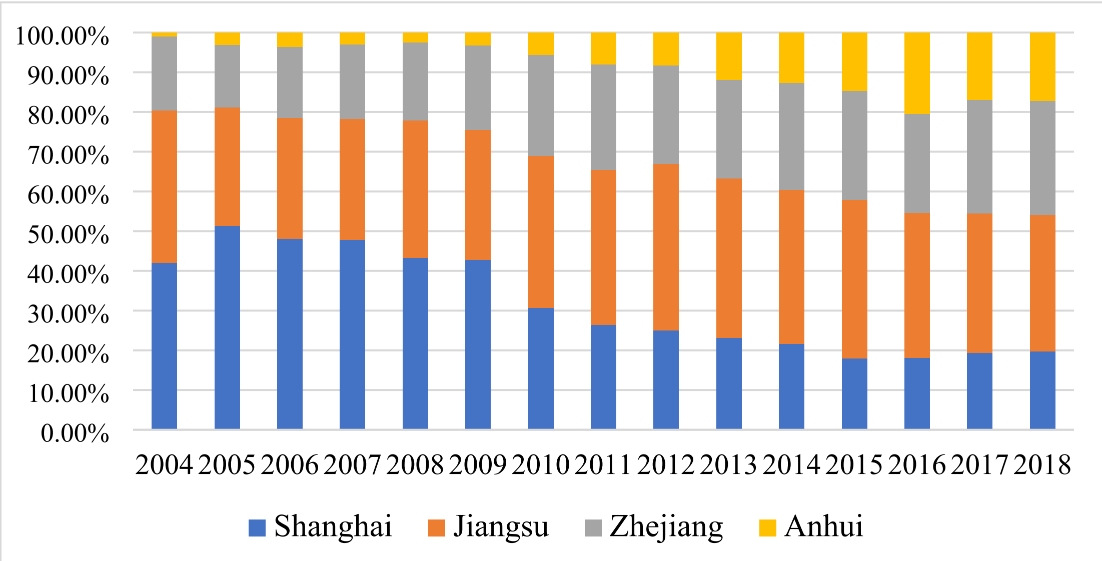


Figure 2: Trends in the number of manufacturing invention patent authorizations in various provinces of the Yangtze River Delta region from 2004 to 2018

Figure 2 shows the trend in the number of manufacturing invention patents granted by province in the Yangtze River Delta region from 2004 to 2018. The share of patents granted in Shanghai decreased steadily from 51.27% in 2005 to 19.67% in 2018. In Jiangsu, the number of manufacturing invention patents granted remained generally around 35%. Zhejiang's share increased significantly from 18.72% in 2004 to 28.74%. Anhui's share rose from 0.88% in 2004 to 17.14%, indicating a particularly notable growth in the number of manufacturing patents granted. This data shows that the gap in manufacturing innovation capabilities among the three provinces and one municipality has been decreasing year by year.

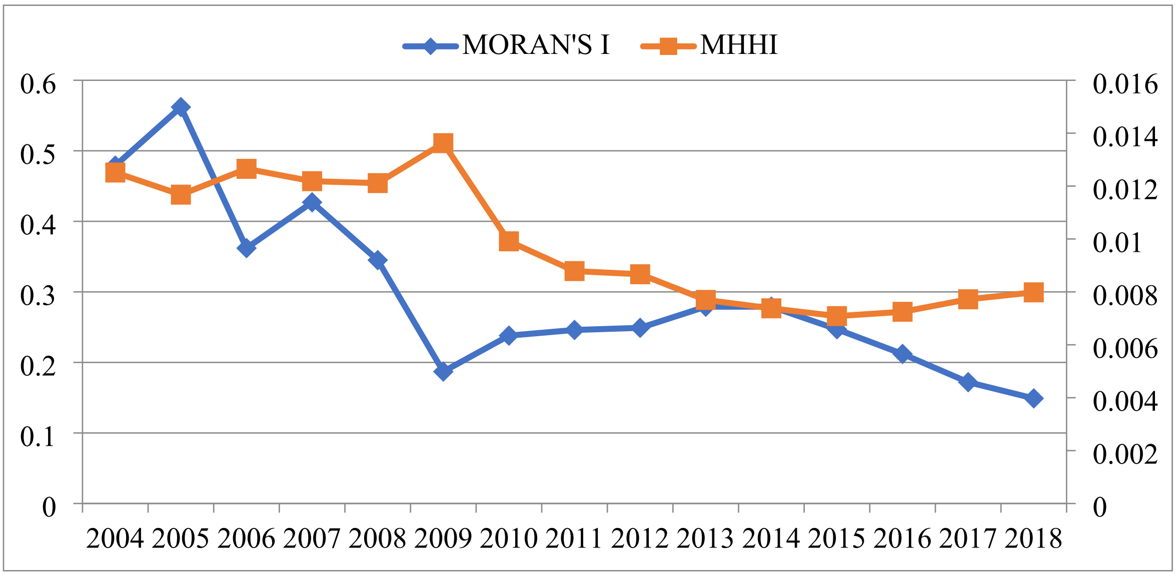
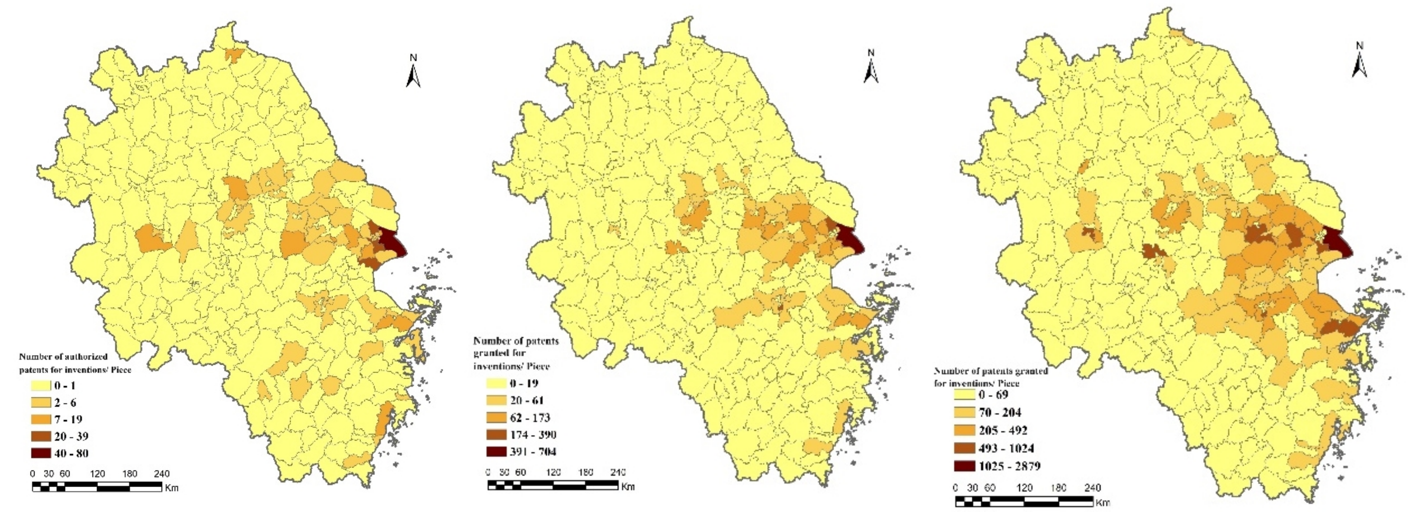


Figure 3 Global Moran's I index and *MHHI* of manufacturing invention patent authorizations in counties and districts in the Yangtze River Delta region

3.2 Analysis on the spatial pattern evolution of manufacturing innovation capability in the Yangtze River Delta region



a. Invention patent authorizations in 2005 b. Invention patent authorizations in 2010 c. Invention patent authorizations in 2018

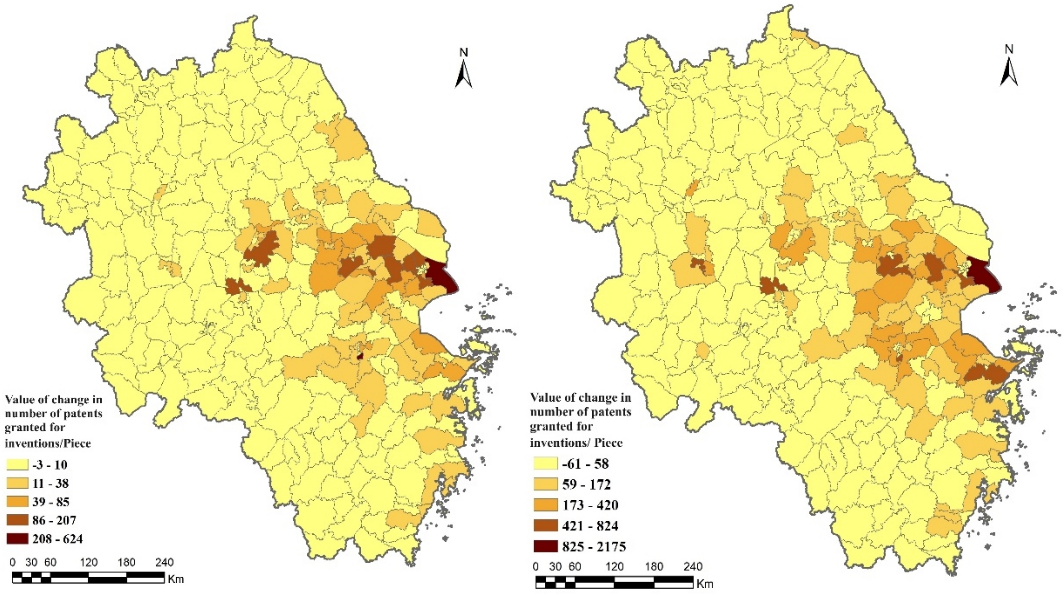
Figure 4 Spatial Analysis of Manufacturing Innovation Capacity in Counties and Districts of the Yangtze River Delta Region from 2005 to 2018

3.2.1 Analysis on Spatial Autocorrelation and equity of Manufacturing Innovation Capability

The spatial autocorrelation and equity of manufacturing innovation capability in the Yangtze River Delta region from 2004 to 2018 are analyzed using the global Moran's I index and the *MHHI* index respectively. These indices represent the spatial clustering and spatial balance characteristics of manufacturing innovation capability as shown in Figure 3.

On one hand, Figure 3 shows a continuous decline in the level of global spatial autocorrelation of manufacturing innovation capability at the county level. The global Moran's *I* index for the number of manufacturing patents granted decreased from 0.479 in 2004 to 0.149 in 2018. Specifically, from 2004 to 2009, the global Moran's *I* index rapidly declined to 0.187, and from 2009 to 2018, it remained relatively stable. This trend indicates a significant change in the clustering distribution pattern of high-value innovation regions, with high-value innovation areas becoming more dispersed.

On the other hand, this study calculates the *MHHI* of authorized manufacturing invention patents in the Yangtze River Delta region from 2004 to 2018 to measure the balance level of regional manufacturing innovation capacity. As shown in Table 2, the *MHHI* of manufacturing innovation capacity in the Yangtze River Delta region has declined over the study period, indicating an improvement in equity of regional innovation capacity. The overall spatial balance of manufacturing innovation capability at the county level has significantly improved. In other words, the *MHHI* for the number of manufacturing patents granted decreased from 0.0125 in 2004 to 0.00798 in 2018 (Figure 3). Between 2004 and 2009, the *MHHI* slightly increased from 0.0125 to 0.0136, but from 2009 to 2015, it continuously declined to 0.00708. The *MHHI* saw a slight increase again from 2015 to 2018. These data indicate that the gap in manufacturing innovation capability at the county level has generally narrowed from 2004 to 2018, with the degree of balance improving. Since 2015, the level of balance in manufacturing innovation capability in the Yangtze River Delta region has remained relatively stable.



a. Analysis on the growth of invention patent authorizations from 2005 to 2010

b. Analysis on the growth of invention patent authorizations from 2010 to 2018

Figure 5 Spatial analysis of changes in manufacturing innovation capacity in counties and districts of the Yangtze River Delta region from 2005 to 2018

3.2.2 Analysis on the Spatial Pattern and Changes in Manufacturing Innovation Capability

This section analyzes the spatial pattern and changes in manufacturing innovation capability at the county level, using natural break classification to categorize the number of manufacturing patents granted in 2005, 2010, and 2018, as well as the changes in patent numbers from 2005 to

2010 and 2010 to 2018 into five levels: high, relatively high, medium, relatively low, and low. Figures 4 and 5 illustrate these findings.

(1) Spatial Distribution of High-Value Innovation Areas

The high-value areas of manufacturing innovation capability exhibit a "Z"-shaped axial belt distribution, with a "center-periphery" structure in some local areas. The analysis shows a hierarchical nature in manufacturing innovation capability:

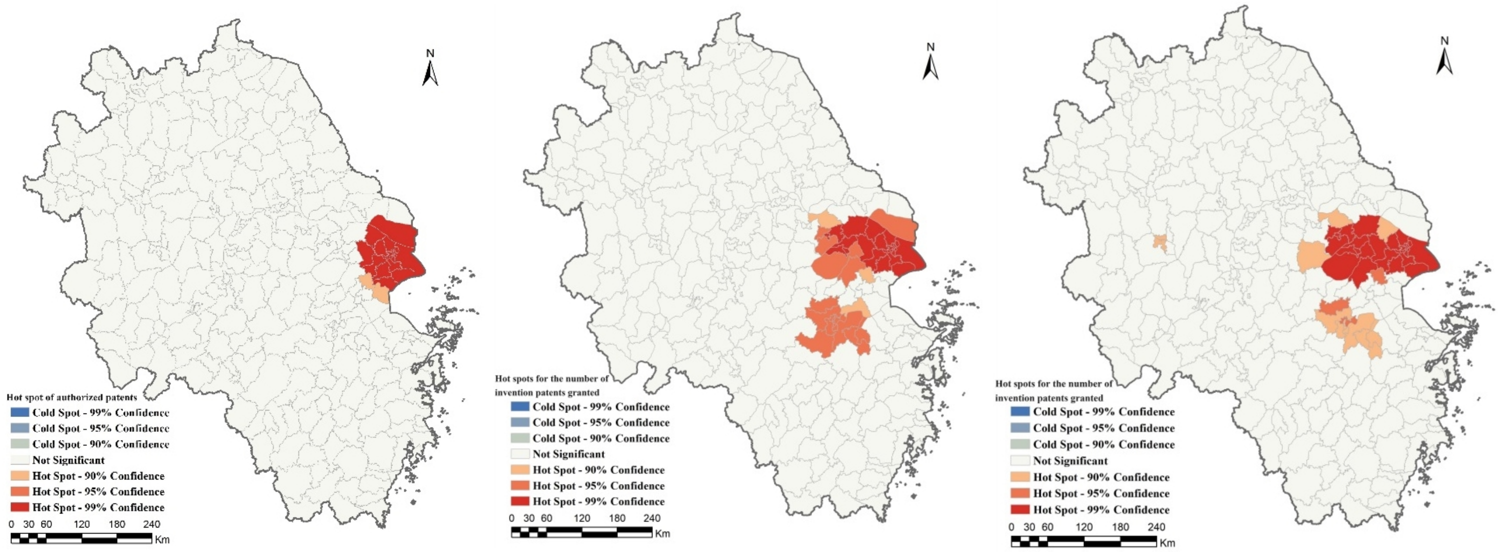
- In 2005: High-value innovation areas were concentrated in Shanghai, with medium-level areas including Nanjing, Hefei, Hangzhou, and Ningbo. Cities along the Shanghai-Nanjing axis demonstrated relatively strong innovation capabilities.
- In 2010: High-value areas included Shanghai's Pudong New Area and Hangzhou's Binjiang District. Regions with relatively low and higher levels were mainly distributed in counties and districts of Shanghai, Suzhou, Wuxi, Changzhou, Hangzhou, Ningbo, Nanjing, and Hefei.
- In 2018: The scope of areas with relatively low and higher levels expanded but remained primarily in Shanghai, Suzhou, Wuxi, Changzhou, Hangzhou, Ningbo, and Nanjing. The "Z"-shaped axial belt formed by the Shanghai-Nanjing, Shanghai-Hangzhou, and Hangzhou-Ningbo lines showed generally strong manufacturing innovation capabilities, while peripheral areas tended to be low-value zones. High-value areas became more dispersed, with places like Pudong New Area, Suzhou, Ningbo, Wuhu, and Hangzhou emerging as high-value zones. In some regions, a "center-periphery" structure was evident, with the number of manufacturing invention patents decreasing from the core areas of central cities to the surrounding counties.

(2) High-Growth Areas of Manufacturing Innovation Capability

High-growth areas in manufacturing innovation capability from 2005 to 2010 and 2010 to 2018 were mainly concentrated in Shanghai, provincial capitals, and their neighboring counties:

- From 2005 to 2010: High-growth counties and districts were mainly found in Shanghai, Suzhou, Wuxi, Nanjing, Hangzhou, and Wuhu (Figure 5). Medium-growth areas included Changzhou and Ningbo.
- From 2010 to 2018: High-growth areas included Shanghai's Pudong region, Suzhou, Wuxi, Hefei, Hangzhou, Ningbo, and Wuhu. Medium-growth areas encompassed Nanjing and Changzhou, as well as counties surrounding high-growth regions, with most other areas experiencing low growth.

Overall, the high-value and high-growth areas of manufacturing innovation capability in the Yangtze River Delta region primarily display a hierarchical distribution and proximity to central cities. Spatially, the regions along the "Z"-shaped axial belt represent the core regions for manufacturing innovation development in the Yangtze River Delta, making them the focal points of innovation growth.

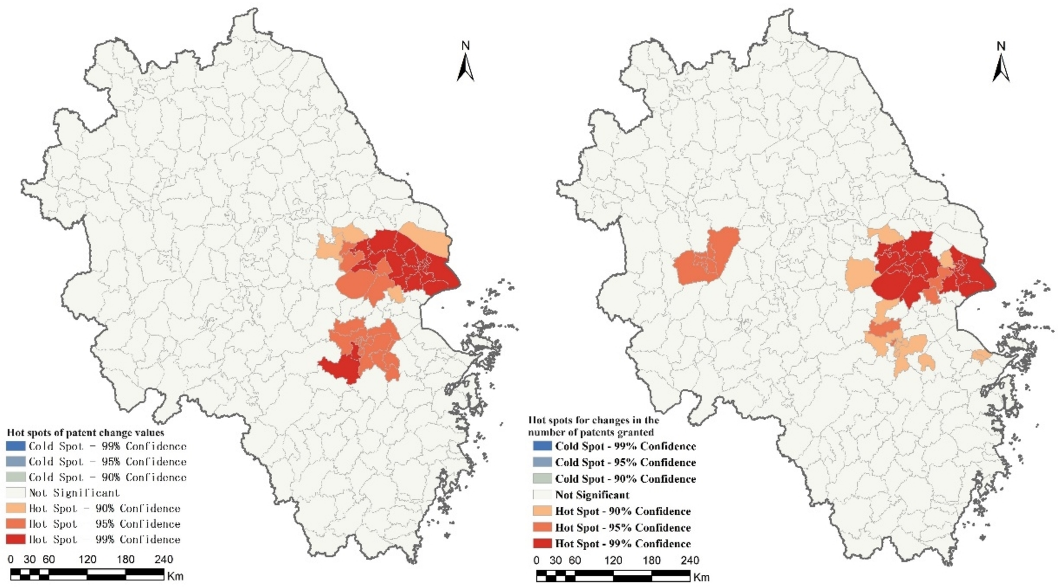


a. Hotspots in Invention patent authorizations in 2005

b. Hotspots in Invention patent authorizations in 2010

b. Hotspots in Invention patent authorizations in 2018

Figure 6 Analysis of the Evolution of Manufacturing Innovation and Development Hotspots in the Yangtze River Delta Region



a. Hotspots in the growth of invention patent authorizations from 2005 to 2010

b. Hotspots in the growth of invention patent authorizations from 2010 to 2018

Figure 7 Evolution analysis of hotspots in the growth of manufacturing innovation capacity in the Yangtze River Delta Region.

3.2.3 Hotspot Analysis on the Spatiotemporal Evolution of Manufacturing Innovation Capability

To analyze the hotspots of spatiotemporal evolution in manufacturing innovation capability, the local spatial association index *Getis-Ord Gi* was calculated for the number of manufacturing invention patents granted in 2005, 2010, and 2018, as well as the changes in patent numbers from 2005-2010 and 2010-2018. GIS software was then used to generate hotspot maps of manufacturing innovation capability and its changes (Figures 6 and 7).

(1) Innovation Capability Hotspots

Figure 6 shows the significant hotspot areas for innovation capability in 2005, 2010, and 2018, with 20, 42, and 42 hotspots identified, respectively.

In 2005: Hotspots were concentrated in Shanghai and its neighboring counties.

In 2010: Hotspots expanded to include Shanghai, Suzhou, Wuxi, and the Hangzhou area.

In 2018: Hotspots further extended to include Shanghai, Suzhou, Wuxi, Changzhou, Hangzhou, and Hefei.

The evolution of hotspots from 2005 to 2018 indicates an overall expansion in the range of manufacturing innovation capability hotspots, transitioning from a "single-core" area to a "multi-core" area. Shanghai, Suzhou, Wuxi, and Changzhou have emerged as the largest manufacturing innovation hotspot regions in the Yangtze River Delta, while Hangzhou and Hefei, along with their surrounding areas, have become rapidly growing hotspots.

(2) Growth Hotspots of Innovation Capability

Figure 7 shows the significant growth hotspots for manufacturing innovation capability in the periods 2005-2010 and 2010-2018:

From 2005 to 2010: There were 44 growth hotspots, primarily concentrated in Shanghai, Suzhou, Wuxi, Changzhou, and Hangzhou.

From 2010 to 2018: The number of growth hotspots increased to 47, expanding into new regions such as Hefei and Ningbo while maintaining the original regions.

The distribution of growth hotspots during these periods highlights that the main areas of increasing manufacturing innovation capability are concentrated in Shanghai, Suzhou, Wuxi, Changzhou, Hangzhou, Hefei, and Ningbo. This expansion suggests a broadening of high-growth areas, reinforcing the trend towards multiple core regions of innovation.

Overall, the analysis of hotspots indicates a significant spatial expansion and evolution of manufacturing innovation capability in the Yangtze River Delta region. From a single-core focus on Shanghai, the region has evolved into multiple core areas with strong innovation capabilities, notably including Suzhou, Wuxi, Changzhou, Hangzhou, Hefei, and Ningbo. This trend underscores the dynamic and distributed nature of innovation growth across the Yangtze River Delta.

4 Analysis on Influencing Factors on the Spatiotemporal Evolution of Manufacturing Innovation Capability in the Yangtze River Delta Region

4.1 Variable Selection and Explanation

For this analysis, the number of granted manufacturing invention patents is selected as the dependent variable. Using the classification method for manufacturing industry types from this reference (Zhou and Li, 2017), the number of granted manufacturing invention patents is divided into labor-intensive, technology-intensive, and capital-intensive manufacturing patents. Based on relative references (He et al., 2017; Xie and Wang, 2022), the influencing factors of manufacturing innovation capability include economic foundation, scale of scientific and technological talent, level of industrialization, development level of the financial industry, level of openness to the outside world, level of informatization, wage level, higher education level and science and technology innovation policies.

Data was collected for 41 cities in the Yangtze River Delta region from 2004 to 2018, encompassing nine independent variables such as GDP, number of employees in the financial industry, and average wage of urban employees (Table 1).

Table 1 Selection of Regression Model Variables for Panel Data of Urban Manufacturing Innovation Capacity in the Yangtze River Delta Region

Variable types	**Variable/Unit**	**Variable abbreviations**	**Variable implication**
Independent variable	Regional GDP/10,000 yuan	*GDP*	Economic foundation
	Number of scientific research, technical services and geological survey personnel/10,000 people	*Research*	Science and technology talent scale
	Proportion of secondary industry/%	*Industry*	Industrialization level
	Actual use of foreign direct investment/10,000 US dollars	*F_Invest*	Degree of opening up to the world
	Number of financial industry employees/10,000 people	*Finance*	Financial industry development level
	Science expenditure in local fiscal budget expenditure/10,000 yuan	*Policy*	Science and technology innovation policy
	Average wage of urban employees/yuan	*Salary*	Income level
	Number of students in ordinary colleges and universities/100 million yuan	*Education*	Higher education level
	Number of international Internet users/10,000 households	*Infor*	Informatization level
Dependent variable	Number of patents granted in the manufacturing industry / piece	*Inno*	Manufacturing innovation capability
	Number of patents granted in the labor-intensive manufacturing industry / piece	*Labor*	Labor-intensive industry innovation capability
	Number of patents granted in the capital-intensive manufacturing industry / piece	*Capi*	Capital-intensive industry innovation capability
	Number of patents granted in the technology-intensive manufacturing industry / piece	*Tech*	Technology-intensive industry innovation capability

Table 2 Panel Regression Model Results of Determinants of Urban Manufacturing Innovation Capacity in the Yangtze River Delta Region

Variable	***Ln(Inno$_{it}$)* (1)**		**ln(*Labor$_{it}$*)(2)**		**ln(*Capi$_{it}$*) (3)**		**ln(*Tech$_{it}$*)(4)**	
	Coef.	*t value*	*Coef.*	*t value*	*Coef.*	*t value*	*Coef.*	*t value*

ln(*Policy*$_{it}$)	0.143***	2.89	0.051	0.87	0.006	0.10	0.255***	3.72
ln(*GDP*$_{it}$)	0.523***	4.00	0.259*	1.68	0.455***	3.14	0.411**	2.28
ln(*Industry*$_{it}$)	-1.390***	-4.00	-1.783***	-4.35	-2.147***	-5.58	-2.789***	-5.82
ln(*F_Invest*$_{it}$)	0.097	1.46	-0.065	-0.83	-0.058	-0.79	-0.263***	-2.86
ln(*Finance*$_{it}$)	0.519***	2.77	0.617***	2.80	0.639***	3.08	1.145***	4.43
ln(*Research*$_{it}$)	0.407***	3.70	0.232*	1.79	0.496***	4.07	0.601***	3.96
ln(*Salary*$_{it}$)	0.922***	4.12	0.952***	3.61	0.935***	3.77.	1.238***	4.00
ln(*Education*$_{it}$)	-0.029	-0.18	-0.022	-0.11	0.226	1.23	-0.011	-0.05
ln(*Infor*$_{it}$)	0.601***	6.53	0.365***	3.37	0.400***	3.93	0.071	0.56
_cons	-13.892***	-5.08	-6.689**	-2.07	-9.998***	-3.30	-6.031	-1.60
Model Settings	*Fixed effect*		*Fixed effect*		*Fixed effect*		*Fixed effect*	
R^2	0.8709		0.6931		0.7773		0.7670	
Observation numbers	615		615		615		615	

Note: *, **, ***, represent the significance levels of 10%, 5% and 1% respectively.

4.2 Model Results Analysis

Using Stata software and a panel data regression model, the *Hausman* test was employed to determine whether to use a fixed effects model or a random effects model. The random effects model used Generalized Least Squares (*GLS regression*), while the fixed effects model used Within regression. The results are shown in Table 2, with R^2 values of 0.87, 0.69, 0.77, and 0.77, indicating a good fit for the models and effectively explaining the influencing factors of spatial differences in regional manufacturing innovation capability.

The results from the models suggest that several key factors significantly influence the spatial differences in manufacturing innovation capability across the Yangtze River Delta region. These factors include economic foundation, scale of scientific and technological talent, level of industrialization, financial development, openness to the outside world, informatization, wage levels, higher education levels, and science and technology innovation policies.

The regression model results reveal that the scale of scientific and technological talent, economic foundation, science and technology innovation policies, income levels, financial development level, and informatization level have a significant positive impact on manufacturing innovation capability. Most of these factors are statistically significant at the 1% significance level. Among these, science and technology innovation policies have the weakest impact on manufacturing innovation capability, while income levels have the strongest effect. The effects of informatization level, economic foundation, and financial development level are also significant. Conversely, the level of openness to the outside world and higher education level do not have significant effects.

(1) Income Levels

Income levels play a prominent role in enhancing manufacturing innovation capability. In all models as shown in Table 3, the coefficient for ln(*Salary*$_{it}$) is 0.922, 0.952, 0.935, and 1.238, respectively. This indicates that, ceteris paribus, a 1% increase in wage levels contributes to an improvement in manufacturing innovation capability ranging from 0.922% to 1.238%, with the highest contribution observed in technology-intensive manufacturing sectors. This highlights the importance of R&D personnel's income levels for manufacturing innovation, especially for technology-intensive industries. In other words, in a market economy system, the income levels of high-tech manufacturing R&D personnel play a decisive role in attracting and retaining talent.

(2) Scale of Scientific and Technological Talent

A large pool of high-quality talent is crucial for manufacturing innovation, and high-level R&D centers tend to be concentrated in areas with rich scientific and technological talent. In all models, the coefficient for ln($Research_{it}$) is 0.407, 0.232, 0.496, and 0.601. This shows that the scale of scientific and technological talent is a critical factor in building manufacturing innovation capability. It has the strongest effect on technology-intensive industries and the weakest on labor-intensive industries, where the coefficient is only 0.232 and significant only at the 10% level. High-quality R&D teams including engineers, scientists and designers are essential for manufacturing innovation, as their expertise and creativity significantly influence the innovation level of manufacturing enterprises.

(3) Financial Development Level

The development level of the financial sector plays a key supporting role in nurturing manufacturing innovation capability. The coefficient for ln($Finance_{it}$) is 0.519, 0.617, 0.639, and 1.145 across the models, with its impact ranking just behind income levels in three models and having the strongest effect on technology-intensive industries. The high cost and risk associated with R&D in manufacturing are mitigated by financial services such as venture capital and diversified financing, which create a favorable environment for technological innovation and reduce the investment risk pressure on manufacturing enterprises or researchers.

(4) Informatization Level

Higher informatization levels typically provide faster access to market demand information, industry technology developments, and industrial policy information. In Model 1, the coefficient for ln($Infor_{it}$) is 0.601, indicating that informatization level has an impact on manufacturing innovation capability second only to wage levels. However, in labor-intensive and capital-intensive industries, its effect is 0.365 and 0.4 respectively with less pronounced impact on technology-intensive industries.

(5) Economic Foundation

The impact of the economic foundation on the enhancement of innovation capability varies by industry type. It has a weaker effect on labor-intensive industries, with a coefficient of 0.259, while its impact on other industry types exceeds 0.4, which suggest that these industries are more dependent on a strong economic foundation for innovation development.

(6) Science and Technology Innovation Policies

The effect of science and technology innovation policies on manufacturing innovation capability is relatively weak. In all models, the coefficient for ln($Policy_{it}$) is 0.143, 0.051, 0.006, and 0.255 in Table 2. The effect is notably weak across all models, although it is relatively stronger for technology-intensive industries. In labor-intensive and capital-intensive industries, the impact is not significant, indicating that science and technology innovation policies have a limited but present role in promoting innovation in technology-intensive sectors. Government policies such as tax incentives, subsidies, and intellectual property protection directly affect R&D investment and innovation motivation in enterprises.

(7) Industrialization Level

The level of industrialization significantly impacts the enhancement of manufacturing innovation capability. The coefficients for ln($Industry_{it}$) are -1.390, 1.783, -2.147, and -2.789, indicating that a higher proportion of the tertiary sector relative to the secondary sector, which reflects higher industrialization, results in a more significant improvement in manufacturing innovation capability.

(8) Openness to the Outside World and Higher Education Level

The levels of openness to the outside world and higher education generally have insignificant effects on manufacturing innovation capability. The coefficient for ln(F_Invest_{it}) in technology-intensive industries is -0.263 and is significant at the 1% level, suggesting a significant negative effect. This reflects that foreign direct investment is not beneficial for enhancing R&D and innovation capabilities in manufacturing.

In summary, income levels, the scale of scientific and technological talent, financial development and informatization are crucial for boosting manufacturing innovation capability, with income levels and financial development having the strongest effects. Conversely, science and technology innovation policies, openness to the outside world and higher education levels show weaker and more varied impacts.

5. Conclusion and Discussion

5.1 Conclusion

Firstly, data analysis at both provincial and county levels indicates that the spatial equity of manufacturing innovation capability in the Yangtze River Delta region has improved with a gradual reduction in disparities in manufacturing innovation capability across different regions and a decrease in the degree of spatial agglomeration.

Secondly, the high-value and high-growth regions for manufacturing innovation in the Yangtze River Delta exhibit a hierarchical distribution and proximity to central cities. The manufacturing innovation hotspots have evolved from a "single-core" model to a "multi-core" model. Shanghai and Suzhou-Wuxi-Changzhou (Su-Xi-Chang) are the core regions and largest hotspots for manufacturing innovation in these regions, while Hangzhou and Hefei along with their surrounding areas, which represent the rapidly growing hotspots for manufacturing innovation capability.

Lastly, income levels play a crucial role in enhancing manufacturing innovation capability. Other significant factors include the scale of scientific and technological talent, the level of financial development, economic foundation, informatization and industrialization. The impact of these factors varies among labor-intensive, capital-intensive, and technology-intensive industries, with technology-intensive industries being more significantly affected by income levels, the scale of scientific and technological talent, financial development, and science and technology innovation policies.

5.2 Discussion

On one hand, manufacturing innovation centers should be strategically located based on regional advantages and resource endowments. Enhancing manufacturing innovation capability requires improving the level of enterprise R&D activities. These activities are typically oriented towards accessing scientific support and market demand information, as well as a sufficient supply of high-quality scientific and technological talent (Li et al., 2018). High-level innovation centers are characterized by substantial investment in technological resources, innovation value chains and industrialization capabilities (Zhang, 2022). Therefore, the planning and layout of manufacturing innovation centers in China should follow the spatial evolution patterns of enterprise R&D activities, considering key influencing factors for different types of R&D activities and regional comparative advantages. It is essential to establish functional positions and development goals for various types of manufacturing innovation centers based on local industry characteristics and avoid blindly developing innovation centers without considering local factors, resource endowments and location conditions.

On the other hand, establishing a system of regional manufacturing innovation centers with different levels including national, provincial and municipal innovation centers, which is crucial to fostering regional innovation communities and enhancing spatial balance in manufacturing innovation capability. To better integrate into the global industrial innovation network, accelerate the transformation and diffusion of technological achievements, and promote the flow of technological resources and innovation elements within the region, it is necessary to create innovation centers at various administrative levels. Utilizing collaboration platforms and mechanisms involving government bodies, industry associations, enterprises, universities, and research institutions can build cross-regional innovation networks. This approach will help integrate more small and medium-sized cities into the manufacturing innovation network, increase regional scientific exchanges and cooperation, and enhance the innovation capabilities and industrial competitiveness of these smaller cities.

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