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Spatial Structure and Dynamic Evolution of Urban Cooperative Innovation Network in Guangdong-Hong Kong-Macao Greater Bay Area, China: An Analysis Based on Cooperative Invention Patents*

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Abstract

With the increasing pressure of international competition, urban agglomeration cooperation and innovation had become an important means of regional economic development. This study analyzed the spatial characteristics of the Urban Cooperative Innovation Network in Guangdong-Hong Kong-Macao Greater Bay Area, found out the dynamic evolution law of innovation, provided suggestions for policy management departments, and effectively planned the industrial layout. According to the data of the State Intellectual Property Office of China, this study researched invention patents from 2005 to 2019. This paper constructed the urban cooperative innovation network, and took 11 cities in the bay area as the research objects, and used social network analysis to study the spatial structure and dynamic evolution of the urban innovation network. Every indicator reflected the urban cooperative innovation, but they all showed a certain decline in 2008–2010. And it is inferred that the innovation network space of each city will be "obvious fist advantages, significant spillover effect and weakening role of Hong Kong and Macao". This paper divided urban cooperative innovation of Guangdong-Hong Kong-Macao Greater Bay Area into three stages. Summing up the characteristics of each stage is helpful to recognize the changes of urban cooperative innovation and to do a good job in industrial layout planning.

Keywords: Urban Cooperative Innovation Network, Dynamic Evolution, Invention Patents, Guangdong-Hong Kong-Macao Greater Bay Area

JEL Classification Code: E03, R10, R12, R51

1. Introduction

Innovation is considered a framework for achieving national development and progress. One of the goals of innovation is to allocate resources efficiently. The research paradigm of the regional innovation system tends to be networked. More and more urban geographers believe that the network interaction between cities is the essential feature of the urban system. An urban agglomeration is a highly developed spatial form of integrated cities. It occurs when the relationships among cities shift from main competition to both competition and cooperation. Cities are highly integrated within an urban agglomeration, which renders the agglomeration one of the most important carriers for global economic development The development mode of urban agglomeration makes cities become important network nodes, which is more meaningful than the traditional urban hierarchy. Economic geographers have attempted many times to accurately measure and decompose the relationship of the urban networks, using traditional geographical analysis methods (gravity model, breakpoint), based on geography and time distance to calculate the innovation scale, delineate the radiation range, and divide the city level.

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(Elena et al., 2020). Innovation blurs the boundaries of administrative regions. Social network analysis is gradually incorporated into the research paradigm of the innovation network. Many studies use microdata to construct regional innovation networks and discovered that network structure and innovation division have positive feedback effects (Seppo et al., 2020). Then, from the perspective of the integration of geography and sociology, some scholars try to construct the index of urban innovation gravity, examine the relationship between network structure and innovation, and think that the division of labor between cities promotes the development of innovation (Hannington et al., 2020).

A cooperative invention patent is an important index of cooperative innovation. In 2020, Shenzhen and Guangzhou ranked third and sixth in the number of invention patent applications in China, showing the strong innovation ability of Guangdong-Hong Kong-Macao Greater Bay Area. Hence, the question raised is: What is the innovation quality in the Guangdong-Hong Kong-Macao Greater Bay Area, given the continual development of innovative power? How can Guangzhou, Shenzhen, Hong Kong, and Macau compete and cooperate in the bay region while also promoting the innovative capabilities of other cities in the Guangdong-Hong Kong-Macao Greater Bay Area?

Based on the geographical gravity model and social network analysis method, the dynamic evolution of innovation cooperation in Guangdong Hong Kong Great Bay region is predicted by using Ucinet software, network/cohesion-density software, and ArcMap software. Therefore, the entire empirical research process from the perspective of patent cooperation can find the law of patent cooperation and exchange, which is useful in improving the innovation level of the Guangdong-Hong Kong-Macao Greater Bay Area and the construction of the national innovation system.

2. Literature Review

2.1. Research on Integration of Absolute Space and Relative Space

Early physics circles believed that absolute space and relative space were contradictory and opposite (Zachary, 2011; Taylor, 2010). With the deepening of research in space, the economic field broke through the limitations of traditional physics and believed that absolute space and relative space are both contradictory and unified, that is, the existence of any relative space is based on absolute space. Space has the characteristics of diversity, hierarchy, and systematicness. Space, as the objective form of system existence, not only embodies the system's geographical space but also expresses the relative space of the elements' relationships. Therefore, the evolution of innovation cyberspace is represented in network space agglomeration, such as the aggregation of small groups and the emergence of a nuclear structure produced by various innovation subjects with distinct resources based on relationships in a specific geographical region. (Diez, 2002). Researchers have studied the differentiation law of relative space and absolute space in the context of innovation networks, but only a few have looked into the integration (spatial pattern) of relative space and absolute space.

2.2. Research on Influence of Innovation Network Information

Researchers investigate maker spaces and enterprises to build an innovative collaboration network, and they identify two types of utility: information influence and behavior influence. Information influence mainly refers to potential cooperative maker space and the tendency of enterprises to seek cooperation information from other network members (Kiesling et al., 2012). The influence of behavior mainly refers to the potential cooperative maker space and the tendency of enterprises to imitate the behavior strategies of other network members, and the influence utility of core member nodes and ordinary members' nodes in the network is also different (O'Malley & Christakis, 2011; Tariq et al., 2020). At the same time, when considering the impact of positive and negative reputation information on the formation of the cooperative relationship and the expansion of the innovation cooperation network, reputation is based not only on direct experience but also on information exchange, which has a significant impact on the formation of cooperative relationships (Wong & Bhatti, 2019). Especially at the beginning of the network establishment, it will affect the strategy selection of the new node and the existing member nodes of the network (Cojoc & Stoian, 2014). Some researchers pointed out that local segmentation is a unique phenomenon in economic development, especially in the economic transition. Problems such as administrative decentralization and industrial layout left over by the traditional system have strengthened the tendency of market segmentation (Nguyen et al., 2020).

2.3. Research on Relationship Between Industrial Agglomeration and Innovation Network

Considering the impact of the social network on industrial agglomeration and knowledge innovation, an inter-organizational network structure of innovation cooperation should be constructed in society (Petruzzelli, 2011; Elvekrok et al., 2018). Some researchers looked into community users' linearization roles in social networks from the standpoint of knowledge sharing, which can help community members not only increase their knowledge capabilities but also share them to create innovation spillovers (Shah et al., 2020). Even the exchange of knowledge innovation decreased with the increase of geographical location (West & Lakhani, 2008). Some researchers came to an entirely different conclusion as a result of their investigation. They examined the intellectual property data and discovered that while the Internet has grown in popularity, geospatial has not hampered knowledge exchange or invention, and knowledge innovation cooperation has not been adversely affected by geospatial expansion (Schwartz et al., 2016; Karim & Giovanni, 2013). With the continuous integration of the world economy, the technological innovation network is becoming increasingly complex, and the equity form of "you have me, I have you" also makes innovation cooperation indispensable (Melissa & Corey, 2007).

The research on the social innovation network has laid a solid foundation, but there is still a paucity of research on the prediction of spatiotemporal dynamic evolution. This research will extract 11 cities from the Greater Bay Area of Guangdong, Hong Kong, and Macao, and analyze data from cooperative invention patents to estimate the spatial structure of the dynamic evolution form and path.

3. Study Design

3.1. Data Source

"The development planning outline of Guangdong-Hong Kong-Macao Greater Bay Area" in 2019 clearly points out that 9 cities in Guangdong Province, including Guangzhou, Shenzhen, Dongguan, Foshan, Zhuhai, Huizhou, Zhongshan, Jiangmen and Zhaoqing, together with the Hong Kong and Macao, will be the main body of the bay area. The invention patents of intercity cooperation can reflect the deep cooperation among innovation subjects and can depict the picture of the innovation network of major cities in the bay area. The Incopat technology innovation information platform of Beijing Hexiang Intelligent Technology Co., Ltd. and the patent database of China Intellectual Property Office are the download sources of the patent data in this paper. The platforms collect patent information of all countries (regions) in the world, including more than 100 million pieces of patent information of 117 countries/organizations/regions in the world. The data is purchased from intellectual property officials and commercial institutions of all countries (regions), and the update speed is fast. The time condition of the patent application is from 2005 to 2019. The main condition of application is more than two cooperative cities among 11 cities in Guangdong, Hong Kong, and Macao. In addition, it is necessary to exclude the situation of invention patents cooperated by parent and subsidiary companies. After data deletion, 17171 invention patents were obtained, 122 invalid patents were eliminated, and 17049 invention patents were finally obtained, which met the analysis requirements. The map data comes from the standard map service website of the China Bureau of surveying, mapping, and geographic information.

3.2. In the Dex Selection

To analyze the urban innovation network, we can choose the characteristic index of spatial section and spatial evolution density change index. The first reflects the reality of the urban innovation network, and the other one reflects the dynamic evolution of space (Dong et al., 2020).

3.2.1. Characteristic Index of Spatial Section

This index is a basic index to analyze the urban innovation network. It is used to measure the topological structure properties of the innovation network in a specific time section. We choose three indicators: center degree, the average size of the structural hole, and Average path length.

The central potential reflects how the whole network is constructed around some points. The calculation idea and process are as follows: make the difference between the maximum centrality and other points respectively, sum up the difference arithmetic, and then compare with the sum of the maximum theoretical difference, then the central potential CZ can be expressed as:

$$C_z = \frac{\sum_i (C_{\max} - C_i)}{n^3 - 4n^2 + 5n - 2} \tag{1}$$

Where C_Z is the centrality, $C_{\max}$ is the maximum centrality, and n is the number of nodes.

Structural hole refers to the continuous or discontinuous relationship between two points in the innovation network. Individuals establish connections with other individuals in the network, and structural holes are in a favorable position in the network so that individuals in the network system can benefit from each other through information exchange. The average size of a structural hole S can be expressed as:

$$S = \sum_a (S_a^2 / \sum S_a) \tag{2}$$

Where $S_a = \sum_b (1 - \sum_k R_{ak} M_{bk})$ $R_{ak} M_{bk}$ represents the redundancy between a and b. R_{ak} represents the ratio of the relationship between a and k and the total relationship. M_{bk} represents the marginal strength of the relationship between b and k. $\sum_k R_{ak} M_{bk}$ represents the proportion of the relationship between a, b, and other network points.

There will also be more convenient routes in the network. Based on the small world effect, we only need to grasp the sum of all possible paths of two points and take the average value to get the average distance between two points. P is used to reflect the strength of the relationship between two points. D_{eab} is the minimum value of many paths between nodes *a* and *b*. Z is all path lengths between two nodes in the network. The average path length P is as follows:

$$P = \frac{\sum(d_{eab})}{\sum Z} \tag{3}$$

3.2.2. Spatial Evolution Density Change Index

Spatial network density is an important index and core variable of spatial evolution. Generally, the higher the density value, the richer the resources, the more frequent the connection, and the more concentrated the knowledge. This paper selects this index as the order parameter of the urban cooperative innovation network, reflects the change of spatial evolution with the density value in different periods, and makes a dynamic prediction. The overall density of urban innovation network space $\bar{\sigma} = 2V / \left[N \times (N-1)\right]$, the regional density of regional space $\overline{\sigma_i} = 2V_i / \left[N_i \times (N_i - 1)\right]$. In this paper, 11 cities are selected, so $i = 1, 2, \cdots, 11$. Morans'1 is the index is used to measure the spatial density, and the evolution trend of innovation network space is judged. ω_{ij} is a weight value of the spatial weight matrix. When the first-order spatial adjacency weight is used, the value can only be taken as 1 or 0. When two points are adjacent to each other, take 1 and other states are 0. The formula is:

$$I_i = \frac{(\sigma_i - \bar{\sigma}) \sum_{j=1}^{11} \omega_{ij} (\sigma_i - \bar{\sigma})}{\sum_{j=1}^{11} (\sigma_i - \bar{\sigma})} \tag{4}$$

4. Results and Discussion

4.1. Main Data Statistics

The number of cooperative invention patents among cities in the Bay Area had increased year after year for the past 15 years, from 2005 to 2019. There are only 467 cooperative invention patents in 2005 and 2429 in 2019. In terms of growth rate, it increased by 420.13% in the past 15 years, with an average annual growth rate of 12.50%. The overall growth rate fluctuated from 2014 to 2016, after that, the growth rate slowed down significantly, and then increased year by year. In 2019, the growth rate showed explosive growth, reaching the highest of 25.59%.

4.2. Spatial Structure Data Results

Further using the modules of network/betweenness and network/centrality in Ucinet software v6.186, we can calculate the central potential, the average effective size of structural holes, the average length of the path, entropy weight, and other indicators in each year from 2005 to 2019. See Table 1 for details.

The central potential of the entropy weight network is used to reflect the level of a subject's dependence on the resources of other subjects in the development of the network. The lower the central potential index is, the higher the degree of balanced development among the agents is. According to the statistics in Table 1, the central potential index is high first and then low, which reflects that the development of the 11 cities has a balanced trend year by year. The central node role of urban innovation network space in the bay area is becoming more and more prominent, and the technology spillover formed by cooperation will continue to radiate the surrounding cities.

The average size of the structural hole is the inverse index of redundant information in the network. The larger the average effective scale is, the less redundant information in the network is, and the higher the innovation cooperation efficiency of the whole network is. It can be found in Table 1 that the average size of structural holes began to increase year by year after reaching the lowest level in 2009. With the help of the regional economic growth effect, universities

Table 1: Changes of Main Indicators of Urban Innovation Network over the Years

Year	Central Potential	Average Size of Structural Hole	Average Path Length
2005	5.37	1.5244	4.25
2006	5.94	1.4287	4.12
2007	5.41	1.5378	3.95
2008	8.34	1.6247	3.62
2009	8.28	1.3258	3.15
2010	7.25	1.7892	2.97
2011	7.36	2.1345	2.85
2012	5.48	2.2474	2.86
2013	5.29	2.2587	2.75
2014	4.37	2.3687	2.27
2015	4.85	2.3745	2.16
2016	3.94	2.2457	3.45
2017	3.87	2.5875	3.14
2018	3.85	2.4595	2.86
2019	2.17	3.1145	2.63

and enterprises gradually find a shortcut to obtaining resources through innovation and cooperation, reducing and cleaning up the redundant information in the network.

The average path length index reflects the test requirements of small-world effects. When the average path length is less than 6, it means that there is a small world effect between nodes. In 2005, the innovation cooperation among 11 cities was affected by the limited technological resources, and the average path length was only 4.25 until 2019, which dropped to 2.63. The overall trend shows a downward trend with an obvious small-world effect, which indicates that the innovation cooperation of 11 cities tends to be frequent.

4.3. Dynamic Evolution of Urban Innovation Network Space

The dynamic evolution of innovation network space is generally reflected by the change index of spatial evolution density. By observing the center potential, the average effective size of the structural cavity, the average length of the path, and other indicators in Table 1, it can be found that most indicators have obvious trend changes or fluctuations around 2008 and 2018. In 2008, affected by the international financial crisis, Guangdong Province took the initiative to carry out the economic transformation, and the data trend changed for the first time. Then, the policy of Guangdong-Hong Kong-Macao Greater Bay Area has led to the second mutation of data. Therefore, when analyzing the spatial density change of the innovation network formed by 11 cities in this region, we can take 2008 and 2018 as two times segmentation points, thus forming three time periods to judge the evolution law of cyberspace. According to the annual number of cooperative patents, it can be divided into five levels. Through Table 2, we can find the change law of 11 cities in three different periods.

4.3.1. Spatial Evolution Density Change Results

In this paper, the network/cohesion density software is used to measure the index to reflect the change of spatial evolution density. Figure 1 reflects the spatial evolution density of three times nodes in 2005, 2009, and 2019. The average density of spatial evolution was 0.32 in 2005, 0.45 in 2009, and 0.68 in 2019, showing that the average density of spatial evolution was increasing. Especially, the cities whose spatial evolution density is more than 0.8 also show an increasing trend. The density values of Guangzhou Dongguan and Shenzhen Hong Kong in 2009 were 0.82 and 0.83, respectively. In 2019, the density values of Foshan Guangzhou, Guangzhou Dongguan, Shenzhen Hong Kong, and Zhuhai Macao were 0.92, 0.91, 0.88, and 0.85, respectively.

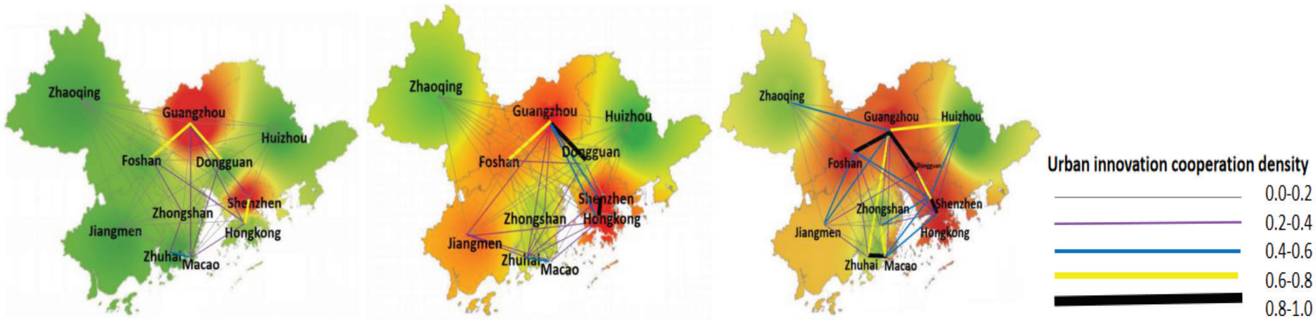
Combined with ArcMap software, the thermal maps of the intercity innovation network in 2005, 2009, and 2019 are constructed, as shown in Figure 2. In 2005, the urban innovation functions based on invention patents in Guangdong-Hong Kong-Macao Greater Bay Area were mainly concentrated in Guangzhou and Shenzhen, which showed obvious red color, while other cities were still at a low level of innovation cooperation. In 2009, Hong Kong, Foshan, and Jiangmen outside Guangzhou and Shenzhen had become active, showing a red or pink state, and the regional innovation cooperation of invention patents had strengthened. By 2019, Guangzhou, Shenzhen, Foshan, Dongguan, Hong Kong, and Macao in the bay area of Guangdong, Hong Kong, and Macao were in red, which shows that the innovation cooperation among these cities is very close. Jiangmen, Zhongshan, and Zhuhai are in the pink or pink green state, but the enthusiasm for innovation and cooperation in these cities is slightly lower. Huizhou and Zhaoqing have no obvious color change. They are green in 2005 and 2009, and yellow-green or green in 2019, indicating that the two cities are marginalized in innovation cooperation in the construction of Guangdong-Hong Kong-Macao Greater Bay Area.

4.3.2. Results of Dynamic Deduction Direction

Fist advantage is obvious. The trend of the network center is decreasing from 5.37 in 2005 to 2.17 in 2019,

Table 2: Average Number and Tier of Cooperative Patents

Levels	Annual Average Quantity	2005–2008	2009–2018	2019
1	>100	Guangzhou, Shenzhen	Guangzhou, Shenzhen, Hongkong	Guangzhou, Shenzhen, Hongkong, Macao
2	50–100	Hongkong	Foshan,Jiangmen	Macao, Dongguan
3	20–50	Foshan, Dongguan	Zhuhai, Macao, Dongguan	Jiangmen, Zhuhai, Zhongshan
4	10–20	Zhuhai, Macao	Zhongshan	Huizhou
5	<10	Huizhou, Zhongshan, Zhaoqing, Jiangmen	Huizhou, Zhaoqing	Zhaoqing



(2005) (2009) (2019)

Figure 1: Urban Spatial Evolution Density and Innovation Network Thermal Map in 2005, 2009, 2019

which indicates that the innovation cooperation of cities in Guangdong-Hong Kong-Macao Greater Bay Area is further concentrated. In the future, Guangzhou, Shenzhen, Hong Kong, Foshan, Dongguan, and Macao will play a greater role in innovation cooperation. In terms of the intensity of innovation cooperation among cities, Guangzhou and Shenzhen will be called the centers of the center. There are 83 colleges and universities in Guangzhou, including 36 undergraduate colleges such as one, two, and three universities, and 47 junior colleges. The innovation ability of colleges and universities is very strong, which lays the foundation for Guangzhou to become the fulcrum city of innovation and cooperation in the district. There are 7 world top 500 enterprises in Shenzhen in 2019, with strong innovation ability. In terms of colleges and universities, the number is increasing and the level is constantly improving, which has become another fulcrum city for innovation in Guangdong-Hong Kong-Macao Greater Bay Area.

The spillover effect is significant. With the continuous improvement of the innovation ability of core cities, the spillover effect of core cities on innovation cooperation among other cities will be more obvious, the gap of innovation cooperation among cities will be smaller, and the network will show a balanced state. In the early days, Guangzhou and Shenzhen, as core cities, played an important role in innovation cooperation. In recent years, Guangzhou, Shenzhen, Foshan, and Dongguan have formed a series of innovation corridors. At the same time, it has attracted the participation of Zhuhai and other cities, reflecting the coexistence of "proximity" and "Leaping" in innovation cooperation. The network connection of urban innovation cooperation in these cities will be closer, and the spillover effect of core cities will be more significant.

The role of Hong Kong and Macao is weakening. In the early stage of reform and opening up, Hong Kong and Macao had strong innovation capacity, especially the spillover effect on Shenzhen and Zhuhai. However, with the innovation and development of Guangzhou, Shenzhen, Foshan, Dongguan, and other cities, the cooperation and exchange between mainland cities were obviously more, which makes the role of Hong Kong and Macao in the innovation cooperation gradually weakened. The number of invention patent cooperation between Hong Kong and other cities in the bay area has not changed much in the past 15 years and has even declined in recent years. Although the number of cooperation between Macao and other cities in the bay area has been growing, the total number of cooperation between Macao and other cities in the region has been stagnant. It can be concluded that Guangzhou and Shenzhen are the leaders of the cooperation and innovation in the Guangdong-Hong Kong-Macao Greater Bay Area. Foshan and Dongguan have a strong late development advantage. The dynamic deduction shows that the role of Hong Kong and Macao in the bay area is weakening.

5. Conclusion

Through the analysis of urban cooperative innovation network, the spatial evolution is divided into three stages:

2005–2008 is the initial stage of the urban cooperative innovation network. At that time, the concept of Guangdong-Hong Kong-Macao Greater Bay Area had not been put forward. The urban cooperative innovation network of 11 cities in the region based on invention patents is still in a very loose state. Guangzhou and Shenzhen have become the centers of cooperative innovation. Hong Kong has a higher level of individual innovation but has less cooperation with other cities, and other cities have not participated in the cooperative innovation network.

2009–2018 is the development stage of the urban cooperative innovation network. At this stage, the number of innovation subjects is increasing, the scale of cooperation is also growing, and the level of technology resources obtained by each city's cooperative innovation subjects is constantly improving.

From 2019 to now is the new policy advantage stage of the urban cooperative innovation network. Driven by the policy of Guangdong, Hong Kong, Macao, and the Great Bay area, intercity cooperation and innovation have formed a fist advantage. Under the action of the government, universities, scientific research institutes, and enterprises, intercity cooperation and innovation have formed the first major advantage, forming a huge thrust in the high-quality economic development of the bay district.

To promote cooperation and innovation among cities in Guangdong-Hong Kong-Macao Greater Bay Area, we should build an international science and technology industry innovation center, optimize the regional cooperation platform, and strengthen the interconnection of infrastructure within and outside the region.

Using invention patent data, the impact of utility model patents and papers on the innovation network is ignored. With the continuous increase of data collection, this study will be supplemented to enhance the cooperative innovation ability of Guangdong, Hong Kong, and Macao.

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