

# Research on the Multidimensional Network Spatial Structure and Correlation Effect of Urban Agglomerations : Analysis of China's Five Major Urban Agglomerations

Tingying Peng<sup>1\*</sup>, Xiaoyue Huang<sup>2</sup>

1. Nanchang Normal University, Nanchang, Jiangxi, 330032, China

2. Macau University of Science and Technology, Macau 999078, China

\*Corresponding author: [Tingying Peng, pty198801@163.com](mailto:Tingying Peng, pty198801@163.com)

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**Abstract:** Because the flow of regional factors tends to be more diverse and complicated, strengthening research on the counterpoint network of urban agglomerations is highly important for promoting the high-quality development of urban agglomerations. Using the theory of regional growth, a theoretical framework of multidimensional network spatial connections among urban agglomerations is constructed. This paper analyzes the multidimensional network spatial structure and correlation effect of urban agglomerations in China. The results demonstrate that (1) the multidimensional network of urban agglomerations presents significant spatial differences in terms of a "point–line network". (2) The networks present a multithreaded, multicity, and cross-regional distribution pattern and exhibit "local area network" and "small world" characteristics. (3) The connections among commuting, capital, technology, and information have a significant positive effect on economic connections in urban agglomerations. Moreover, the Beijing–Tianjin–Hebei region and the middle reaches of the Yangtze River rely more on technology, the Yangtze River Delta relies more on commuting, and the Pearl River Delta and Chengdu–Chongqing rely more on information.

**Keywords:** Urban Agglomeration; Multidimensional Connection Network; Spatial Structure; Economic Connection; QAP Regression

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## 1. Introduction

With the rapid development of information technology and transportation, the connections between cities are becoming more complicated and diversified. The flow of various elements is intertwined, and networks are becoming increasingly diverse; in particular, the dynamic network of transportation, population, enterprise, information and technology has become the focus of attention (Pflieger & Rozenblat, 2010; Tirthankar et al., 2023). Research on urban flow spatial networks has gradually overcome the limitations of distance and physical flow, and more attention has been given to the network structure and virtual flow between regions. In this context, the big data of spatial locations and social media services provide rich, detailed and real-time information for urban network research, reducing the cost of data acquisition for and facilitating the systematic and comprehensive development of research on urban flow spatial networks (Zhen et al., 2019). Because diversified data have stimulated innovations in methods, the research content and scale of urban flow spatial networks have deepened (Liu et al.,

2012). Therefore, regional network connection research is complex and diverse. In the future, urban agglomerations will be an important force for promoting the coordinated development of regions. The urban pattern of coordinated development between large, medium, and small cities and small towns, with urban agglomerations as the main body, is developing in China. The study of the multidimensional network structure and correlation effect of urban agglomerations could enrich the existing research on urban agglomeration networks and expand the research on the effect of the spatial network of urban flows, contributing to the study of the interaction and impact of urban agglomerations as complex economic, cultural, administrative, and temporal distance systems. The study of multidimensional network structures and associated effects could effectively compensate for the problem of insufficient identification of the spatial structure of urban agglomerations through a single network study, providing city planners with insights into how to optimize the internal connectivity of urban agglomerations and improve their overall efficiency and competitiveness. By analyzing the transportation network, information flow, and economic linkages of urban agglomerations, planners could better design urban infrastructure and efficiently allocate and utilize resources.

Western scholars first deconstructed the logic of urban networks from the perspective of flow space, arguing that flow space is the material organization of social practices of shared time that operates through mobility (Castells, 1996). They proposed that complex networks of flows linked by cities as nodes in the context of globalization and informatization should be the point of departure for understanding modern urbanization (Pflieger et al., 2010). Since the 1990s, along with the reunderstanding of space in philosophy and the study of spatial economic activities in geography, there has been a gradual realization that space is constructed by a series of economic and social relations, leading to the development of the "Relationship Turn" in the field of economic geography (He et al., 2008). Bathelt & Glückler (2003) believe that the research elements of relational economic geography include organization, evolution, innovation, and the interaction of behavioral themes, emphasizing the heterogeneity of regional network relations. In terms of network types, scholars have focused mainly on production networks (Derudder et al., 2010; Xu et al., 2024; Yang, 2024), innovation networks (Huggins & Prokop, 2017; Gui et al., 2019), the internet (Jacobs et al., 2011; Malecki, 2002a), and transportation networks (Malecki, 2002b; Yang et al., 2019; Tenkanen et al., 2023). In terms of spatial scale, geographic network research is divided into global and regional networks. Global network research includes production (Brown et al., 2010), innovation (Bathelt et al., 2004; Ma et al., 2023), and trade networks (Li, 2014), while regional network research comprises innovation, transportation, and capital connection networks. The theoretical methods mainly include gravity (Jung et al., 2008) and membership network models (Peter et al., 2010). These studies provide the theoretical and methodological basis for subsequent urban multidimensional network analysis.

The networks between regions are complex and diverse. In recent years, with the advancement of big data technology and network analysis methods, some scholars have begun to pay attention to the relationships among multidimensional networks across regions. Urban networks are diverse and include "multidirectional flows" of economic, social, cultural, and environmental activities (Davoudi, 2008). Different places are functionally connected not only through labor market relationships but also through trade, capital flows, consumer travel, school commuting, social visits, and leisure travel. This leads to a complex network of interregional relationships, where cities and regions rely on other cities and regions for education, labor, capital, intermediate products, and product markets (Burger, 2013). Zhang et al. (2019) analyzed the spatial and topological structure of the Yangtze River Delta's urban agglomeration network using transportation, enterprise, population, and technology data, positioning this research framework as an empirical exposition of the formation of a diverse urban network. Urban networks are typically diverse with different forms of spatial interaction between cities, including spatial interactions among people, objects, and information (Hu et al., 2020). Moreover, Zhang et al. (2019) analyzed the multicity network in the Yangtze River Delta region using transportation, enterprise, population, and technology data. Therefore, a single-element network can no longer accurately describe the network relationships between regions, and research on multidimensional regional networks has gradually become a focus.

Huggins & Thompson (2014) proposed the concept of "network capital" and noted that the network relationship established by conscious investment is an important part of regional assets. The notion of network capital has been increasingly discussed and developed in the literature in recent years (Huggins & Johnston, 2010; Kramera et al., 2011), providing a useful and

necessarily specific means of conceptualizing and incorporating the asset value of investments in interorganizational networks into growth models. The network metaphor has become highly prevalent in research on economic geography and regional economic development, mostly related to innovation performance and economic development (Huber, 2012), which highlights the relevance of networks to economic growth and performance. Although the network concept is often applied broadly, few studies have sought to apply it in a more formal and constrained way, which would allow for a more precise rendering of the potential role of networks in regional growth processes. Therefore, drawing on the concept of network capital and incorporating flow space theory, this paper constructs a formal model to capture the network value of these processes.

Given the above theoretical and practical background, this paper makes the following three main contributions: First, on the basis of the theory of "flow space", a theoretical analytical framework is constructed for the multidimensional flow space network of urban agglomerations, which integrates the relevant theories of regional economic growth and spatial structure and reveals the mechanism of multidimensional elemental flow networks on economic linkage networks. Second, the multidimensional flow spatial networks of the five major urban agglomerations in China are established using data on traffic, information, science and technology, and capital flows, and their differential characteristics are comparatively analyzed via social network and GIS spatial analysis methods. In addition, the QAP analysis method is used to empirically test the promotion effect of the multidimensional flow spatial network of the five major urban agglomerations on the static network and to compare the differences in the network role relationships of different urban agglomerations.

The first part is described above. The second section introduces the theoretical mechanism. The third section describes the research methods and data sources. The fourth and fifth parts present the multidimensional network spatial structure and correlation effect of urban agglomerations, respectively. The sixth section presents the conclusions and policy implications.

## 2. Scoring Efficiency

### 2.1. Theoretical Mechanism of Network Growth

Economic growth rates are increasingly considered to depend on endogenous factors, with most treatments commonly assuming that economic growth is partly a function of either human capital (Lucas, 1988) or R&D (Romer, 1986). To better analyze the relationships and mechanisms of the multidimensional network structure of urban agglomerations, this paper conducts an in-depth analysis of the theoretical mechanism of urban agglomeration network growth using the basic theory of regional growth and the Cobb–Douglas production function model.

According to the Cobb–Douglas production function theory, there is a certain relationship between the number of production factors used in production and the maximum output that can be produced within a certain period of time, and the technology level remains unchanged. The specific model is as follows:

$$Y_i = F(K_i, L_i) = K_i^\alpha L_i^{1-\alpha}, 0 < \alpha < 1 \quad (1)$$

Here, suppose a country or city agglomeration has  $i$  cities, where  $K_i$  and  $L_i$  represent the capital and labor invested by city  $i$ , respectively, and where  $Y_i$  represents the production output of city  $i$ . Therefore, urban economic growth mainly depends on improvements in labor productivity, which involves improvements in factor allocation efficiency and increases in knowledge stock (Romer, 1986; Aghion & Howitt, 1998). With the development of science and technology, innovation has become an important force for promoting economic growth (Xu & Zhao, 2020). Some scholars have confirmed that the information development level represented by the digital economy also significantly promotes regional economic growth (Beckman et al., 2012).

Although these theories are still developing, there is little scholarly understanding of the mechanisms by which factors are transferred between organizations (Storper & Venables, 2004), which highlights the need for a research agenda that identifies the role of factor mobility in the spillover channel that promotes economic growth (Audretsch & Feldman, 1996). The production function theory has been introduced into the field of urban agglomeration network connections, and the network connections between cities are believed to have multiple attributes. The economic connection network is affected by financial, commuting, information, and technological connections. According to the neoclassical regional economic growth theory characterized by diminishing marginal returns, the self-accumulation and external inflow of capital, labor and technology are emphasized in the promotion of economic growth, with the interregional flow of production factors regarded as a critical factor driving economic growth. When there is no exogenous technological progress, the economic growth of various

countries or regions will converge (Taylor & Williamson, 2006; Justin et al., 2004). Population mobility has a significant effect on regional development (Barro & Sala-i-Martin, 1992). Capital flows could promote the reduction or expansion of regional economic differences (Jiao et al., 2021). Information flows reflect the economic and social connections between cities and a city's comprehensive strength to a certain extent (Zhen et al., 2013). Yao et al. (2001) noted that the association of high-tech enterprises could promote the formation of urban networks, enhance regional innovation competitiveness, and promote the coordinated development of cities. The model can be characterized as follows:

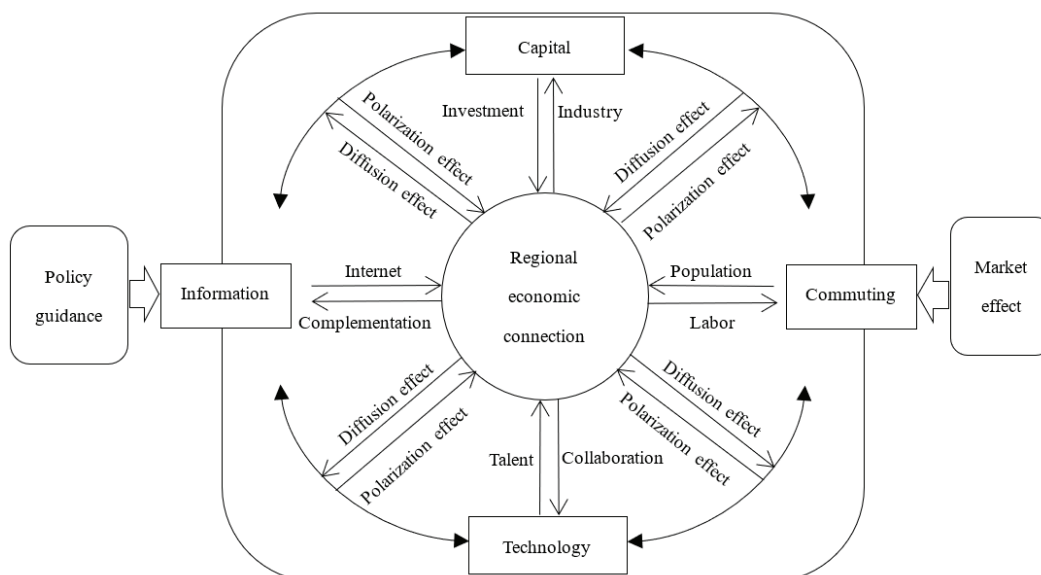
$$Y_{ij} = (FK_{ij}, L_{ij}, T_{ij}, I_{ij}) \tag{2}$$

Assuming that a city cluster has several cities,  $Y_{ij}$  is the economic connection between cities  $i$  and  $j$ , and  $K_{ij}$ ,  $L_{ij}$ ,  $T_{ij}$ , and  $I_{ij}$  represent the capital, commuting, technology, and information connections between cities  $i$  and  $j$ , respectively. Capital connections refer to the collection of capital flows between cities, which could promote regional development and reduce regional differences by establishing regional industrial linkages and strengthening the intensity of regional linkages (Qian & Sun, 2021). Commuting flow refers to the intensity of population movements between cities, which could have an impact on the economic connections between cities by accelerating or slowing the population flow between cities. Technological connection refers to the strength of the relationship between the production and transformation of knowledge between cities, which could strengthen the economic connections between regions by deeply embedding knowledge in global or regional production networks. Information connection refers to the strength of network information connections between cities, which helps reduce the impact of urban agglomeration spatial distance and promote more coordinated and high-quality development of the economic connection network of urban agglomerations. Moreover, spatial agglomeration in different industries is a result of different driving mechanisms (Bing, 2020), and urban agglomeration network growth also has its own driving mechanism.

### 2.2 Structural Mechanism of Network Connections

According to the theoretical mechanism of network growth constructed in this research, the economic connection network is at the top of the model. The four networks of capital, commuting, technology, and information connections are located at the next level of the model. Among them, the diffusion and polarization effects of large cities to small and medium cities run through the connections between the various networks. Because the market plays a dominant role in the flow of factors, the market is in the core dominant position. For example, the density of urban networks in the developed eastern regions of China is greater than that in the western regions. In addition, policy guidance has a moderating effect on network connections. Regional development strategies promote cooperation within urban agglomerations, the flow of elements, and the development of urban agglomeration networks. For example, urban agglomerations include the Beijing–Tianjin–Hebei region, the Yangtze River Delta, the Guangdong–Hong Kong–Macao Greater Bay Area, the middle reaches of the Yangtze River, and Chengdu–Chongqing. The specific structural relationships are shown in Figs. 1.

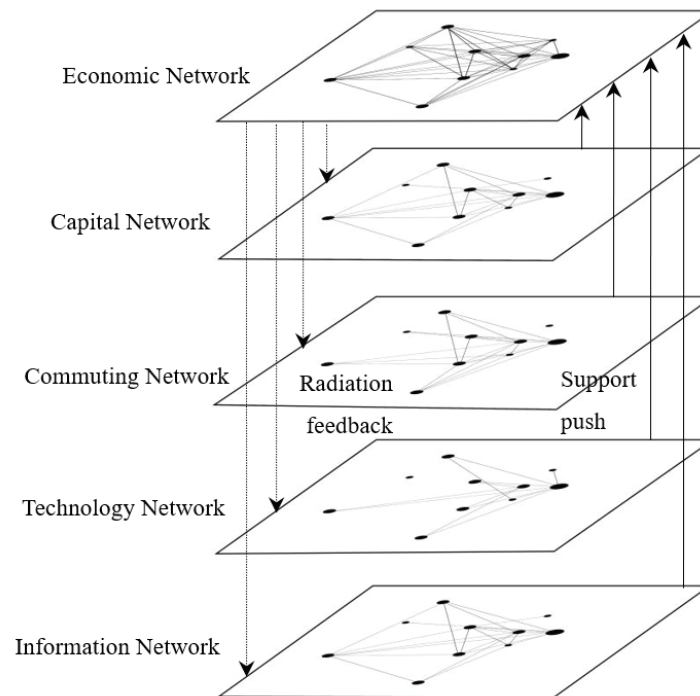
Figure 1. The multidimensional network structure of regional economic connections



### 2.3 The Mechanism of Network Interaction

The multilayer network of the economic connections of urban agglomerations is interdependent and interactive, which is manifested in the spatial relationship of agglomeration and diffusion. The connection networks of capital, commuting, technology, and information support and promote the economic connection network. In turn, the economic connection network radiates feedback on the other connection networks (Fig. 2).

Figure 2. The superposition mechanism of multidimensional connection networks of urban agglomerations



On the one hand, given the role of support and promotion, the most direct role of capital connections between cities is to increase the degree of industrial relevance between regions. Shared capital connections between cities are important in promoting regional development and reducing regional differences (such as parent companies setting up branches in different cities or mergers and reorganizations) (Qian & Sun, 2021). Therefore, the agglomeration and diffusion of capital in urban agglomerations brought about by enterprise investment have important impacts on promoting economic connections between cities. Commuting connections between cities represent the inter-city flow of human capital, which is not only related to the development gradient between regions but also to urban industrial connections and business exchanges. Therefore, commuting connections between cities accelerate the flow efficiency of people, logistics, and capital flows, thereby promoting the improvement of urban economic connections. Specifically, the number of trains is characterized by urban commuting connections, which can further deepen our understanding of the evolution of the spatial connection pattern and regional integration of urban agglomerations supported by high-speed rail networks (Zhang et al., 2020). Technological connections are the endogenous force driving the growth of the economic connection network between cities. With rapid technological innovation, increasingly frequent knowledge flows, and increasingly close innovation cooperation, the network theory of global production emphasizes external shocks such as cross-border production organizations and technological innovation networks. Therefore, knowledge spillovers between regions should be fully exerted to form a strong spillover relationship and innovation field to drive the high-quality integrated development of regional collaborative innovation and economic linkage networks. The information connection represents the transience and effectiveness of the internet, which could make the geographic space become more homogeneous. Therefore, information connections weaken the laws of spatial distance attenuation, promote connections between center and periphery cities, and accelerate the coordinated development of the economic connection network of urban agglomerations.

On the other hand, the radiation feedback effect of the urban economic connection network on other networks occurs mainly

through market regulation and government policy formulation. For example, strengthening regional economic connections in the Yangtze River Delta would encourage the government to strengthen the construction of infrastructure, such as internal high-speed rail and information networks, which would improve commuting and information connection networks within urban agglomerations. In addition, improvements in economic connections promote the flow of capital, technology and other factors, which manifest mainly in the transfer of industries and technology from central cities to small and medium-sized cities. As a result, the multidimensional connection network between cities is superimposed on the radiation feedback. For example, because the economic connections within the Pearl River Delta urban agglomeration are relatively high, the policies formulated by Guangdong to help promote the construction of the Guangzhou–Shenzhen Science and Technology Corridor would effectively improve the regional science and technology network and other network connections.

### 3. Research Methods and Data Sources

#### 3.1 Overview of the Study Area

This paper studies the five major urban agglomerations in China: Beijing–Tianjin–Hebei, the Yangtze River Delta, the Pearl River Delta, Chengdu–Chongqing, and the middle reaches of the Yangtze River. This quadrilateral also includes two isosceles triangles: one is Beijing–Shanghai–Chengdu, where the distance from Chengdu to Beijing and from Chengdu to Shanghai is approximately 1500 kilometers; and the other is Shanghai–Guangzhou–Chengdu, where the distance from Guangzhou to Chengdu and from Guangzhou to Shanghai is approximately 1200 kilometers. The five urban agglomerations are exactly "diamond shapes". The five major urban agglomerations are the four pivot points and the intersection of the diagonal lines of the "diamond shape" structure. According to the Communiqué of the Seventh Population Census of All Regions of China in 2020, these five urban agglomerations constitute approximately 37.14% of the country's resident population. The five urban agglomerations constituted nearly 52.52% of the country's GDP in 2019 and are the core carriers of China's urbanization and economic growth, as well as the urban agglomerations with the most active factor flows and the highest degree of networking in China. The five urban agglomerations have polycentric, monocentric, and bicentric spatial structures, representing the spatial organizational structure characteristics of most of the cities in China. Research on the multidimensional network structure within the five urban agglomerations could provide references and lessons for identifying the network structure of other urban agglomerations as well as for planning and managing urban agglomerations.

#### 3.2 Research Methods

##### 3.2.1 Gravity model methods

The traditional gravity model measures the strength of economic connections between two cities on the basis of their GDP, population, and distance, with relatively few indicators measuring urban quality. This paper improves the traditional gravity model by comprehensively using GDP, population, fixed asset investment, and total retail consumer goods to characterize city size and choosing the shortest road distance between cities to represent the distance between cities. The specific model is as follows:

$$T_{ij} = \frac{\sqrt[4]{G_i \times P_i \times I_i \times S_i} \times \sqrt[4]{G_j \times P_j \times I_j \times S_j}}{D_{ij}^2} \quad (3)$$

where  $T_{ij}$  is the degree of connection between city  $i$  and city  $j$ ;  $G$ ,  $P$ ,  $I$  and  $S$  represent the GDP, population, fixed asset investment and total retail consumer goods of the city, respectively;  $D_{ij}$  represents the shortest road travel distance between city  $i$  and city  $j$ ; and the coefficient of friction is generally taken as 2 (Lu et al., 2021).

##### 3.2.2 Social network analysis

This paper introduces social network analysis to reveal the network structure and network correlation characteristics of the urban economic flow space. Social network analysis is an interdisciplinary analysis method for "relational data" (Ducruet & Beauguitte, 2014) that takes "relationships" as the basic unit and describes them using graph theory tools and algebraic model technology. The social network analysis tool used systematically describes the network structure characteristics of economic, capital, commuting, technological, and information connections in China's five major urban agglomerations. The quadratic assignment procedure (QAP) of social network analysis is used to analyze the supporting and promoting effects of capital, commuting, technology, and information connections on economic connections.

(1) Network density. Network density characterizes the closeness of overall urban connections. The formula for calculating the overall tightness of urban agglomeration networks via social network analysis is as follows (Ducruet & Beauguitte, 2014):

$$D^K = 2L/n(n-1), K \quad (4)$$

The value of K is between 0 and 1. The closer the value of the network density DK is to 1, the more cities there are in the network, and the closer the relationships are. The maximum density in reality is 0.5 (Liu et al., 2017).

(2) Average path length. The average path length (L) refers to the number of edges in the shortest path connecting two points in all connected paths (i,j), which characterizes the degree of node separation in the network.

$$L = \frac{2}{n(n-1)} \sum_{i \neq j} d_{ij} \quad (5)$$

L refers to the average value between two nodes in the network, and  $d_{ij}$  represents the shortest distance from node  $i$  to node  $j$  (Camagni, & Salone, 1993).

(3) Average clustering coefficient. The ratio of the number of edges connected between all adjacent nodes to the maximum possible number of edges is used to measure the local clustering of network nodes (Cao et al., 2023).

$$C = \frac{1}{n} \sum C_i = \frac{1}{n} \sum \frac{2E_i}{k_i(k_i-1)} \quad (6)$$

where  $C$  is the average of the cluster coefficients of all nodes and  $E_i$  and  $k_i$  are the actual and possible maximum numbers of edges of node  $i$ , respectively (Cao et al., 2023).

(4) Network efficiency

$$E = \frac{1}{n(n-1)} \sum \frac{1}{d_{ij}} \quad (7)$$

where  $E$  is the reciprocal average of the shortest distance between two nodes in the network and where  $d_{ij}$  is the shortest distance between cities  $i$  and  $j$  in the network.

(5) QAP regression analysis. To examine the support or impact of commuting, capital, technological, and information networks on economic connections, it is necessary to conduct a correlation or regression analysis between networks. The quadratic assignment procedure (QAP) method converts the matrix of dependent and independent variables into a long vector matrix and compares the lattice values of the corresponding network nodes. In addition, using the similarity coefficient between matrices as the regression result can avoid the multicollinearity problem in traditional econometric regression analysis. The significance test of similarity coefficients adopts the random permutation method of row and column data. Using the multiple row and column permutations of matrix data, nonparametric tests are conducted on the coefficients and  $R^2$ , including matrix correlation, local array joint table, and multiple regression analyses. The specific expression is as follows:

$$m \cdot y = \beta + \sum_r \beta_r (m \cdot x_r) + \sum_s \beta_s (m \cdot x_s) + v \quad (8)$$

where  $m \cdot y$  is the matrix of the connection network between different attributes in the sending and receiving relationships and is the comprehensive economic connection theory matrix.  $m \cdot x_r$  represents the attribute relationship matrix formed by the attribute characteristics of the city in the  $r$ -dimension, which are commuting, capital, technological, and information connection network matrices.  $m \cdot x_s$  represents the covariate matrix of network relationships between cities in the  $s$  dimension.  $\beta$ ,  $\beta_r$ , and  $\beta_s$  are the parameters to be estimated, and  $v$  is the residual.

### 3.3. Matrix Construction and Data Sources

(1) Economic network. A gravity model is used to calculate the strength of economic connections between cities. The specific indicators include GDP, the permanent population, investment in fixed assets, and social retail consumer goods. The data were obtained from the "China City Statistical Yearbook (2019)".

(2) Capital network. With the nonlocal investment of enterprises representing interregional capital connections, the database of listed companies and holding subsidiaries of the CSMAR is used to match the cities where the parent company and the subsidiaries are located according to the direct holding ratio and registered capital of the listed companies and clearing data on holding relationships outside of urban agglomerations. Finally, the paper constructs the capital connection matrixes of the five major urban agglomerations.

(3) Commuting network. High-speed rails are important for assessing cross-city commuting within urban agglomerations. To more accurately represent the intensity and scale of commuting, the frequency of intercity HSR trains is used to measure the intensity of intercity commuting. The 12306 platform can be used to query high-speed rail (trains with G, D and C

prefixes) data between two cities, eliminate duplicate trains, and obtain data matrix data for high-speed rail trains in five major urban agglomerations.

(4) Technology network. The current common academic approach to science and technology linkage networks is to jointly file patents or publish papers. The number of patent collaborations is used to measure the scientific and technological connections between cities. Using the smart bud patent query website, data on national patent cooperation between cities in 2019 were obtained, and the scientific and technological cooperation matrix data of the five major urban agglomerations were obtained via data cleaning and screening.

(5) Information network. The attention given by residents of one city to another on cell phones and PCs is calculated using a large amount of data from the Baidu web and news search. Network attention is used to characterize the information connections. The geographical comparison function of the Baidu Index website is used to construct the information connection matrix of the five major urban agglomerations between cities.

## 4. Multidimensional Spatial Network Structure of Urban Agglomerations

### 4.1 Spatial Network Differences

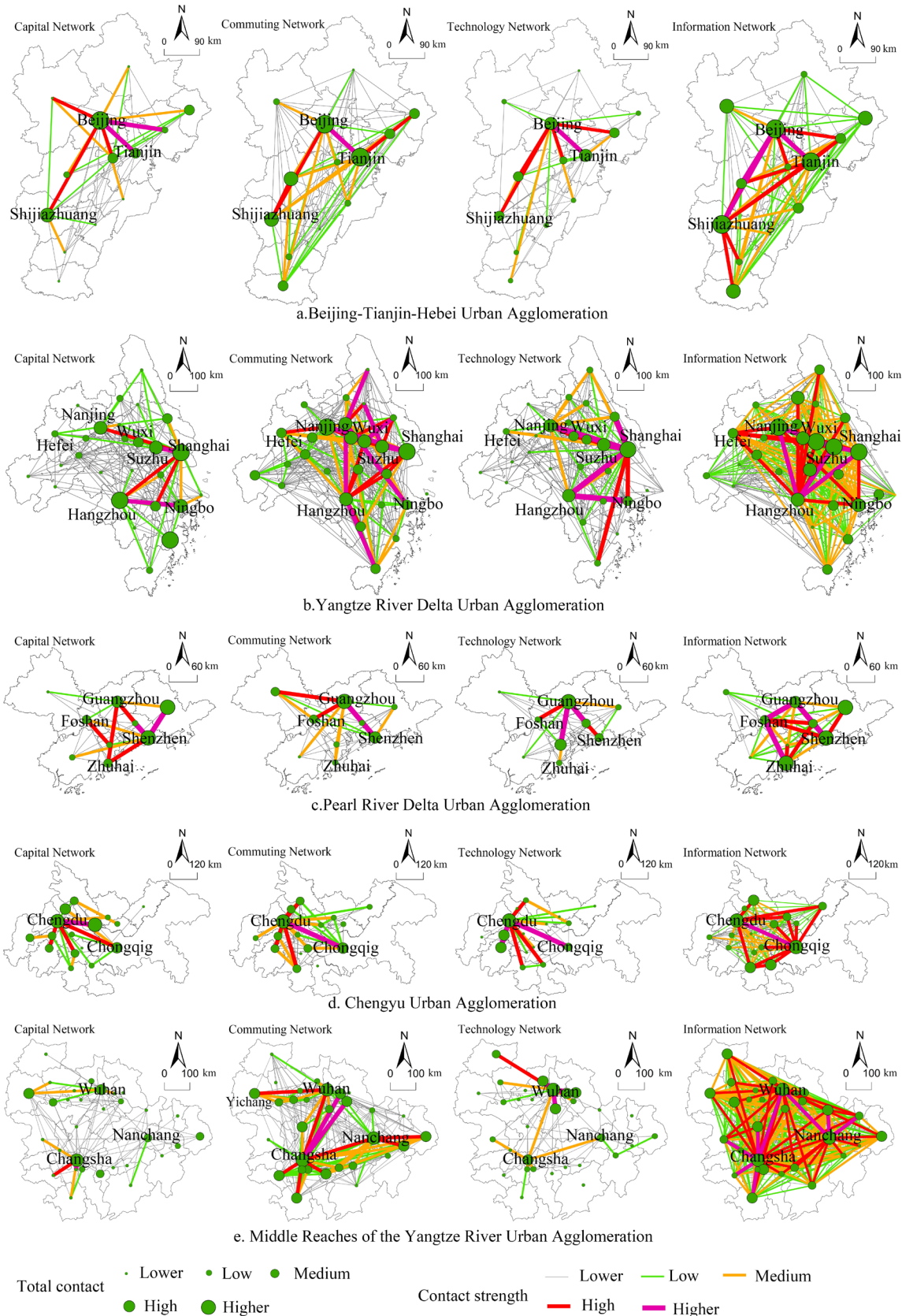
#### 4.1.1 City node level

Beijing, Shanghai and Chengdu have always been the most connected cities in their respective urban agglomerations. The Pearl River Delta shows a dual-core competition model between Guangzhou and Shenzhen, and the urban agglomeration in the middle reaches of the Yangtze River presents three core patterns. In the Beijing–Tianjin–Hebei urban agglomeration, Tianjin is at the first level of commuting and information connections, Shijiazhuang is at the first level of information connection, and the total number of connections in other cities is relatively low. This is related to the long-standing prominent dualistic structure of regional development in the Beijing–Tianjin–Hebei urban agglomeration, with Beijing and Tianjin having a better foundation for development and other cities having a larger development gap with these two cities. In the Yangtze River Delta city cluster, Shanghai and Hangzhou are at the first level of capital connection, ahead of Suzhou, Nanjing and Ningbo. Shanghai and Nanjing are at the first level of commuting connections, whereas cities such as Suzhou, Wuxi and Hangzhou are at the second level. Shanghai is dominant in technological connections, while Suzhou, Nanjing and Hangzhou are at the second level. The information connections show the multihead patterns of Shanghai, Suzhou, Wuxi, Nanjing and Hangzhou. The spatial pattern of these network nodes is consistent with the characteristics of the polycentric structure of the Yangtze River Delta. Shenzhen and Huizhou have the highest total capital connections among the Pearl River Delta urban agglomerations, while Guangzhou ranks second. This shows that in terms of industrial spillover and foreign investment in Shenzhen, Huizhou has become the city of choice, and the external radiation effect of Guangzhou's capital is still insufficient. Guangzhou is a railroad hub city with significantly more commuting links than Shenzhen, and Zhaoqing is at the third level. Guangzhou has the largest number of scientific and technological connections, which are closely related to the concentration of its high-level research institutes and universities. Guangzhou's scale of foreign scientific and technological cooperation is significantly greater than that in Shenzhen and other cities. Zhongshan, on the other hand, lacks the resources of scientific research institutes and universities and relies mainly on external cooperation for innovation; thus, its scale of external scientific and technological cooperation is large. Shenzhen, Zhuhai and Huizhou rank first in information connections, whereas Guangzhou ranks second. In the Chengdu–Chongqing urban agglomeration, the total number of connections in Chengdu is generally greater than in Chongqing, which is related to the administrative boundary barrier. The number of multidimensional connections in Chengdu is at the highest level. Chongqing's information connections are at the first level, commuting and capital connections are at the second level, and scientific and technological connections are at the third level. This is related to the fact that 14 of the Chengdu–Chongqing urban agglomerations are located in Sichuan Province and have close interconnections with each other yet relatively weak connections with Chongqing. In addition, the nodes are tripartite in the urban agglomeration of the middle reaches of the Yangtze River. Wuhan's total number of connections ranks first, except for capital connections. Changsha ranks first in technological connections and other connections. The total number of capital and technological connections in Nanchang is relatively weak.

#### 4.1.2 Urban core axis

On the one hand, from the point of view of network connection strength and node status, network connection strength shows a significant geographical attenuation law, and the characteristics of the core edge are more significant. On the other hand, from the point of view of the node form of the network connection, the network connection presents a "single center", "dual center" and "multicenter" network spatial relationship.

Figure 3. The multidimensional geographic network of urban agglomerations in China



The central cities of the five major urban agglomerations occupy the core position in the network connection, and the number of connections is relatively large, as shown in Fig. 3. In the Beijing–Tianjin–Hebei urban agglomeration, Beijing and Tianjin have the highest contact strengths. The economic connection framework of the Chengdu–Chongqing urban agglomeration revolves around the central cities of Chengdu and Chongqing. The urban agglomeration in the middle reaches of the Yangtze River is centered on three core cities: Wuhan, Changsha and Nanchang. The Yangtze River Delta urban agglomeration forms a core framework around a few central cities, including Shanghai, Hangzhou, Suzhou and Nanjing.

## 4.2 Overall Network Structure Comparison

### 4.2.1 Overall network density characteristics

The density of the economic connection network is between 0.1 and 0.3, indicating that the urban agglomeration has spatial correlation characteristics that form a multithread, multicity and cross-regional network distribution trend. The economic connection network density of the Chengdu–Chongqing urban agglomerations exceeds 0.267, indicating they have a small network development gap, relatively balanced internal development, and relatively close connections. The network density of the Pearl River Delta urban agglomeration is only 0.111. There is a large gap in the development of the internal network of the Pearl River Delta urban agglomeration, which is more concentrated in the connections between a few internal core cities, and the siphoning effect of the central cities is more significant. The network densities of Beijing–Tianjin–Hebei, the Yangtze River Delta and the middle reaches of the Yangtze River are greater than those of the Pearl River Delta, indicating a relatively high network coordination of the three regions and a relatively small development gap within the network.

### 4.2.2 Stability characteristics of the spatial network

In addition to some indicators, the multidimensional network efficiency of the five urban agglomerations exceeded 0.6, indicating that more than 60% of the connections are effective. However, there are a few repeated superposition phenomena of dynamic correlation between urban agglomeration networks, indicating that the stability of the multidimensional network of the five major urban agglomerations is still insufficient. The network efficiency of technology and capital connections is relatively high, indicating that the superposition effect of the science and technology and capital connection networks in the five major urban agglomerations is insufficient. This means there are more independent connection nodes in the networks in these urban agglomerations and they have significant network edge areas.

### 4.2.3 Correlation characteristics of the spatial network

Social network analysis usually uses "average distance" to quantitatively reveal the small-world characteristics of the network (Ducruet & Beauguitte, 2014). The average distance of the economic, capital, commuting, technology and information connections of the five major urban agglomerations in China is between 1 and 3. The largest average distance of the capital connection networks of the urban agglomerations in the middle reaches of the Yangtze River is only 2.488, as shown in Table 1. Any two urban nodes in different types of spatial networks of the five urban agglomerations could establish connections with 1–3 intermediate cities; that is, the urban connection network presents significant small-world characteristics. The characteristics of spatial association networks promote interactions between urban connection networks, and the superposition effect of multidimensional urban networks on urban economic connections is prominent.

Table 1 Network structure characteristics

Network indicators	Contact Network	Beijing-Tianjin-Hebei	Yangtze River Delta	Pearl River Delta	Chengdu-Chongqing	Yangtze river middle reaches
Density	Capital	0.128	0.111	0.208	0.113	0.072
	Commuting	0.269	0.272	0.306	0.254	0.209
	Technology	0.179	0.119	0.833	0.154	0.084
	Information	0.339	0.291	0.333	0.254	0.358
	Economic	0.179	0.188	0.111	0.267	0.148
Efficiency	Capital	0.909	0.858	0.857	0.897	0.953
	Commuting	0.756	0.697	0.893	0.756	0.803
	Technology	0.946	0.913	0.214	0.956	0.946
	Information	0.636	0.643	0.643	0.743	0.621

Network indicators	Contact Network	Beijing-Tianjin-Hebei	Yangtze River Delta	Pearl River Delta	Chengdu-Chongqing	Yangtze river middle reaches
	Economic	0.861	0.809	0.667	0.838	0.880
Average distance	Capital	2.012	1.111	1.778	2.140	2.448
	Commuting	1.727	1.917	1.833	1.665	1.967
	Technology	1.788	2.071	1.167	1.829	2.347
	Information	1.509	1.591	1.400	1.729	1.642
	Economic	2.067	2.079	1.333	1.767	2.151

## 5. Multidimensional Network Correlation Effect of Urban Agglomerations

### 5.1 Correlation Analysis

In the five urban agglomerations, all correlation coefficients between multidimensional networks are positive. There is a significant positive correlation between the economic, capital, commuting, technology, and information connections of the five urban agglomerations in China.

On the one hand, from a dimensional perspective, the correlations between the information and economic connections of urban agglomerations in the Pearl River Delta are significant at the 5% level, and those between the information and economic connections of urban agglomerations in Beijing–Tianjin–Hebei, the Yangtze River Delta, Chengdu–Chongqing and the middle reaches of the Yangtze River are significant at the 1% level. The overall correlation coefficient remains between 0.4 and 0.7, the value of which is relatively average. The correlation between commuter and economic connections passed the 5% significance level test, and those between the urban agglomerations of Beijing–Tianjin–Hebei, the Yangtze River Delta, Chengdu–Chongqing and the middle reaches of the Yangtze River passed the 1% significance level test. The overall correlation coefficient is 0.24–0.72. In addition to the Pearl River Delta urban agglomeration, the correlations between technological and economic connections in Beijing–Tianjin–Hebei, the Yangtze River Delta, Chengdu–Chongqing and the middle reaches of the Yangtze River urban agglomeration passed the significance test at the 1% level, and the correlation coefficients ranged from 0.3 to 0.94. The spatial correlation coefficient between capital and economic connections is significantly lower than that between information, commuting and technological connections. These results show that information, commuting and technology connections greatly impact regional economic connections.

On the other hand, from a regional perspective, the spatial correlation coefficients between economic connections and the capital, commuting, technology and information connection indicators are relatively high in the Beijing–Tianjin–Hebei urban agglomeration. The correlation coefficient of technological connections reached 0.94, indicating the Beijing–Tianjin–Hebei regional connections are more dependent on scientific and technological cooperation. The degree of economic connection of the Yangtze River Delta shows great volatility, with a correlation coefficient of only 0.143, indicating a low impact of capital connections on the Yangtze River Delta's economic connection network, which depends more on commuting and information connections. The Pearl River Delta urban agglomeration is consistent with the Yangtze River Delta urban agglomeration, and commuting contact and information contact play a significant role in economic relations. The role of the science and technology connection network of the Chengdu–Chongqing urban agglomeration lags behind and depends more on the capital and commuter connection networks. The urban agglomeration in the middle reaches of the Yangtze River is consistent with the Beijing–Tianjin–Hebei urban agglomeration and relies more on patent cooperation; however, the overall correlation is not high.

Table 2 QAP correlation analysis of the spatial correlation of the economy

Variable	Beijing–Tianjin–Hebei	Yangtze River Delta	Pearl River Delta	Chengdu–Chongqing	The Yangtze river middle reaches
Capital	0.642***	0.143***	0.05	0.677***	0.271***
Commuting	0.724***	0.558***	0.452**	0.689***	0.243***
Technology	0.940***	0.452***	0.306*	0.449***	0.517***
Information	0.696***	0.518***	0.408**	0.584***	0.420***

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

## 5.2 Network Regression Analysis

On the basis of the correlation analysis, QAP regression analysis of the spatial correlation of the economic urban network is conducted to further explore the spatial connection and role of the information, commuter, technology and capital connections in economic connections, as shown in Table 3. Although the adjusted R2 of the Pearl River Delta urban agglomeration passed the significance test at the 5% level, the R2 values of the four urban agglomerations of Beijing–Tianjin–Hebei, the Pearl River Delta, Chengdu–Chongqing and the middle reaches of the Yangtze River all passed the significance test at the 1% level. According to the numerical analysis, the R2 of the Beijing–Tianjin–Hebei urban agglomeration is 0.882, which is the highest. The explanatory capacities of the Yangtze River Delta, the middle reaches of the Yangtze River and the Chengdu–Chongqing urban agglomerations are 63.2%, 53.6% and 48.3%, respectively. However, the explanatory capacity of the Pearl River Delta is low, at only 23.7%, which shows that capital, commuting, technology and information connections have a good explanatory capacity for the economic connections in the four urban agglomerations of Beijing–Tianjin–Hebei, the Pearl River Delta, Chengdu–Chongqing and the middle reaches of the Yangtze River.

In terms of dimensions, information connections passed the 10% significance level test, and three urban agglomerations passed the 1% significance test. The regression coefficients are relatively average and positive. Except for the urban agglomerations in the middle reaches of the Yangtze River Basin, the commuting connections of other urban agglomerations passed the 10% significance test, but the regression coefficient had two negative values, which remained in the range of [-0.025,0.396]. This finding indicates that the network relationships represented by the HSR train frequency data are not characterized by a regular distance decay pattern but rather by a "leapfrog" linking relationship with strong connections, mainly between large cities. Three urban agglomerations of technological linkages passed the 10% significance test, but the coefficient fluctuation was the largest, in the range of [-0.047,0.970]. Only two urban agglomerations passed the 5% significance test, and one urban agglomeration passed the 1% significance test for capital connections. Therefore, the subindicators of capital, commuting, technology, and information connections play an average role in supporting overall economic connections.

In terms of the regions, the regression coefficient of patent cooperation in the Beijing–Tianjin–Hebei urban agglomeration is 0.97, which passes the 1% significance test, whereas the regression coefficients of the other indicators are small, indicating that technological connections play a very significant role in supporting economic connections. The high-speed train frequency and Baidu index of the Yangtze River Delta urban agglomeration passed the significance test at the 1% significance level, and the regression coefficients were 0.396 and 0.222, respectively, indicating that the economic connection of the Yangtze River Delta urban agglomeration depends more on information and commuter connections. The Baidu index of the Pearl River Delta urban agglomeration passed the significance test at the 1% level, and the coefficient is the highest, indicating the economic connection network depends more on information connections. The regression coefficient of the frequency of high-speed trains in the Chengdu–Chongqing urban agglomeration is the highest at the 1% significance level, indicating that the economic connection network depends more on the commuter connection network. The patent cooperation, Baidu Index and capital connection of the urban agglomeration in the middle reaches of the Yangtze River passed the 1% significance test, reaching 0.405, indicating that economic connections depend more on the patent network.

Table 3 QAP regression analysis of the spatial correlation of the economy

Variable	Beijing-Tian-jin-Hebei	Yangtze Riv-er Delta	Pearl River Delta	Cheng-du-Chongqing	The Yangtze river middle reaches
Intercept	47.470	-50.578	-305.812	6.171	0.335
Capital	0.005	-0.007	-0.191**	0.051	0.140***
Commuting	-0.025**	0.396***	0.263*	0.159***	-0.023
Technology	0.970***	0.085	0.126*	-0.047	0.405***
Information	0.020*	0.222***	0.296***	0.156**	0.228***
Adj-R2	0.882***	0.632***	0.237**	0.483***	0.536***
Obs	156	702	72	240	930

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

## 6. Conclusions and Implications

### 6.1 Research Conclusions

According to the general theory of economic growth and multidimensional flow data, a theoretical model of multidimensional network connections in urban agglomerations is constructed, and an empirical analysis is conducted on the five major urban agglomerations in China. The main conclusions are as follows: (1) The multidimensional connection network of urban agglomerations presents significant spatial differences in the "point–line–network", and the heterogeneity of the spatial structure of multidimensional connection networks in different dimensions and urban agglomerations is highly significant. (2) The multidimensional spatial correlation network of urban agglomerations presents multithreaded, multicity, and cross-regional network distribution trends, with significant "local area network" and "small world" characteristics. (3) The QAP regression analysis reveals that the capital, commuting, technological and information connections of the five major urban agglomerations have a significant effect on economic connections. The impact of different dimensions of connections between different cities on economic connections is heterogeneous, and the four-dimensional connection network of Beijing–Tianjin–Hebei has a greater supporting effect on economic connections. The effects of different indicators on the economic connection network are similar, but the influence varies greatly among different urban agglomerations. The urban agglomerations of Beijing–Tianjin–Hebei and the middle reaches of the Yangtze River depend more on technology connections, the Yangtze River Delta urban agglomeration rely more on commuting connections, and the Pearl River Delta and Chengdu–Chongqing urban agglomerations rely more on information connections.

### 6.2 Policy Implications

First, the coordinated development of multidimensional connections among urban agglomerations should be promoted. An urban connection is a multidimensional comprehensive complex network system in which connection networks of different dimensions impact one another through economic connections. Therefore, attention should be given to promoting the coordinated development of capital, commuting, technological, and information connections in urban agglomerations. On the one hand, it is necessary to improve the hard connections within urban agglomerations. The construction of transportation, energy, information, financial networks and other facilities in urban agglomerations should be accelerated, and the carriers of factor flow should be optimized and improved. In particular, rapid transportation's driving role should be considered to accelerate the flow efficiency of human, capital, information, and technology flows. On the other hand, the soft connections within urban agglomerations should be optimized. The policy system for constructing urban agglomerations could be improved to break down internal administrative barriers. Furthermore, the integration of internal registered residences, medical care, education and other systems is explored to optimize the business environment, strengthen the stickiness of capital, population, technology, and information flows between cities, and enhance the spillover effect of central cities on small and medium-sized cities.

Second, urban agglomerations should be encouraged to develop their own strengths in multidimensional connections. Owing to differences in the resource environment, geographical location, industrial development and policy, the development of urban agglomerations in China are very heterogeneous, with differences in the supporting role of economic connections in the urban spatial network structures. The development of urban agglomerations in China remains unbalanced and insufficient, with significant internal development gaps. However, the differences in urban agglomeration network connections should be taken seriously, allowing for asymmetric development within a certain range and expanding and strengthening the core growth network. For example, the Beijing–Tianjin–Hebei region and the middle reaches of the Yangtze River urban agglomeration should leverage the advantages of patent cooperation between cities, further enhancing the overall level of technological network cooperation in the urban agglomeration. An urban agglomeration supported by science and technology networks should be built to promote the improvement of urban connections with scientific and technological support. For example, the Yangtze River Delta urban agglomeration should leverage the advantages of a well-developed high-speed rail network to further enhance the transportation accessibility of the urban agglomeration and create a rapid transportation-supported urban network.

Third, the connections between central cities and small and medium-sized cities should be strengthened. Small and medium-

sized cities should leverage the high-speed rail economy, knowledge economy, and information revolution; accelerate the connections of capital, technology, commuting, and information with central cities; and improve the economic connections between small and medium-sized cities and large cities. For example, in the context of the exchange opportunities created by high-speed rail, more opportunities for technology and industrial transfer should be provided, enhancing technology and commuting connections with central cities. In addition, central cities should expand their radiation and driving role in small and medium-sized cities and jointly build intercity collaborative innovation circles, industrial transfer parks, rapid commuting circles, and information-sharing platforms through targeted assistance and industrial transfers. The flow of elements between cities and the internal connections within urban agglomerations are increasingly promoted through agglomeration and diffusion.

### 6.3 Discussions

With the advent of globalization and informatization, factor flows have increasingly become an important force in shaping the spatial structure of regional economies, and "flow space" has become a hot issue in urban networks. The portrayal of the spatial structure of urban networks by a single flow element is insufficient, while multidimensional flow elements capture the spatial structure of urban agglomerations in a relatively comprehensive and adequate way. Since the network spatial structure of cities in different dimensions and different urban agglomerations is characterized by heterogeneity, the multidimensional flow spatial structure of multiple urban agglomerations is compared and analyzed, which has important theoretical and practical significance. This shows that the status of a city is not completely consistent with its economic scale, administrative level, or geographical location. It is necessary to pay attention to the high-level agglomeration of urban agglomeration network connections and to the balanced development of gradient differences, which are highly important for revealing the spatial structure of urban agglomeration networks more comprehensively.

Cities in the mobility space environment could transcend the limitations of geographic proximity to access key resources from distant partners; thus, the status of networks in the mobility space is becoming increasingly important in comparison to geographic location in the place-space environment. Factor mobility is increasingly embedded in different types of network connections; thus, the synergistic effects of multidimensional networks of factors of mobility should be considered. This indicates that the development of the urban economy is promoted by various factors breaking through local and regional spatial scales, and various factors are actively integrated into the domestic cycle and the national urban network, which provides a broader space for improving urban economic growth.

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