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The Characteristics and Modes of Urban Network Evolution in the Yangtze River Delta in China from 1990 to 2017

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ABSTRACT In the context of regional integration development, research on the urban network in the Yangtze River Delta (YRD) has received extensive attention from academia. Existing research mainly uses listed companies to construct urban networks. However, most of China's listed companies are concentrated in large cities. Giving too much attention to the urban network composed of listed companies may cause small cities to be "off the map." This article uses 8,061 financial companies of different sizes in the YRD from 1990 to 2017 as research data combined with complex network models to explore the evolutionary characteristics, modes, and influencing factors of urban networks. The findings show that the connection strength and resilience of the urban network are gradually increasing, and its evolutionary mode has changed from a single center to a multicenter network. The radiation and agglomeration capabilities of urban networks have strong asymmetry. Shanghai's network agglomeration capacity is only 1/22 of its radiation capacity, which implies that Shanghai has played a bridge function in urban network links. Notably, the networks of most peripheral cities continued to expand from 1990 to 2017, while Shanghai was in a state of contraction. This finding indicates that the overall urban network is developing in a balanced and coordinated direction. In addition, economic growth provides critical support for the urban network, and technological progress may improve the level of production management of companies, thereby promoting cooperation and exchanges between cities. Further, cities with similar industrial structures may have industrial synergy or complementary relationships and are likely to have spatial connections. Finally, we suggest promoting the expansion of urban networks in the YRD by forming a multicenter development model, transforming local government functions, exploring differentiated development, and strengthening infrastructure construction.

INDEX TERMS Urban network, finance, interlocking network model, Yangtze river delta.

I. INTRODUCTION

Since the 21st century, with the development of modern transportation, informatization, and economic globalization, the traditional hierarchical spatial structure has been difficult to explain and adapt to the current economic and social development model [1]–[4]. Therefore, urban networks, as a new form of spatial organization, have attracted wide attention from policymakers and scholars. On the one hand, the urban network facilitates professional knowledge exchange and a division of labor based on members' common interests, which can effectively reduce transaction costs and enhance cities' competitiveness [5]–[8]. On the other hand, the concepts of "multicenter balanced development" and "multilevel governance" advocated for by the urban network can reduce the risk of opportunistic behavior to a certain extent and strengthen the cooperation and links between cities. We can find examples of urban network applications from the European Spatial Development Strategy (ESDP) to the Tokyo Metropolitan Area in Japan [9], [10]. Likewise, with the implementation of the integration strategy in the Yangtze River Delta (YRD), the trend of spatial interaction among various elements has continued to increase, and a multicenter, networked spatial pattern has emerged [11], [12].

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With the development of informatization and modern transportation, the spatial interaction trend of diverse resource elements has accelerated, which has promoted the growth of urban networks. Current research on urban networks focuses on three aspects. First, the concept of the urban network has no uniform definition, and urban networks based on different research perspectives/scales vary. In the early stages of regional development, tangible networks, such as roads, railways, and aviation, constitute a vital part of the urban network. For example, Smith *et al.* studied the global city network through air passenger flow data and found that the global city network has strong hierarchical characteristics; major cities in the United States and Europe always occupy the core position of the network [13]. Li *et al.* believed that the more developed the road transportation network, the higher the level of economic development and the denser the population [14]. Using indicators such as centrality, network density, and degree centrality, Cao *et al.* explored China's high-speed railway network and affirmed that it has typical small-world, scale-free features [15].

With the expansion of the fragmentation of production and global production networks, enterprises as crucial carriers of numerous elements such as talent, capital, and information are reshaping the new urban network development pattern [16], [17]. Taylor is one of the earliest scholars who applied enterprise networks and interlocking network models to examine urban networks. With the deepening of research, more scholars have realized the importance of urban networks for regional coordinated and efficient development [18]. For example, using data from international freight companies, Liang *et al.* revealed that the growth of the urban network in the YRD is relatively balanced, and the connections between the four nonprovincial capital cities (Suzhou, Ningbo, Nantong, and Lianyungang) form its core [19]. However, Pan *et al.* discovered that most high-quality resources (such as funds and talent) are concentrated in major urban hubs, such as Beijing, Shanghai, Guangzhou, and Shenzhen, resulting in unbalanced urban network development [20]. Ma *et al.* scrutinized the urban network through the equity investment data of listed companies in China and claimed that network core cities have greater economic and resource advantages and have a strong impact on the development of peripheral cities [21].

Second, the evolution of urban network structure and functions. From the traditional central place system to the urban network, not only is the spatial structure transformed but urban functions are also upgraded. Under the central place system, the level of transportation development is low, the connections between cities are weak, and the coverage of goods and services is small. However, the expansion of urban networks has changed the urban spatial form and connection methods and optimized the distribution pattern and exchange capacity of resources [22]. For example, Zhen *et al.* asserted that the spatial structure tends to be scattered and disordered in the early phases of urban development. With the progress of science and technology and advancements in modern transportation, the urban spatial structure has begun to shift toward networking and integration, and its network functions have become increasingly complex (Figure 1) [23]. Gao *et al.* used patent cooperation data and complex network models to prove that the patent cooperation network has enhanced the innovation capabilities of underdeveloped regions and accelerated technology transfer and knowledge flow [24]. Bruinsma examined the transportation networks of 41 major cities in Europe based on diversified traffic flow data (highways, high-speed railways, aviation) and argued that the expansion of the transportation network has boosted the efficiency of population flow and cargo transfer, which has greatly promoted the development of the European economy [25]. Thus, the urban network is a significant manifestation of the transition from ''place space'' to ''flow space'' and is the main way of realizing the modernization and efficiency of the regional governance system and governance capabilities.

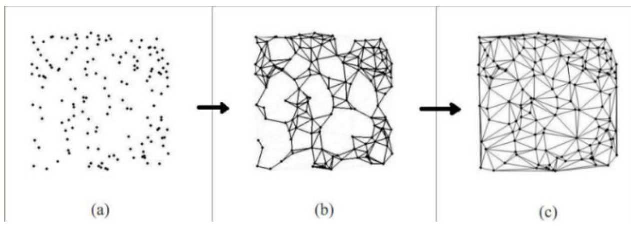

FIGURE 1. Evolution of urban networks.

Third, as a complex system, the growth of urban networks is affected by many factors. Taylor *et al.* maintained that the degree centrality and accessibility of urban networks are affected by the economy, industry, and infrastructure; developed capitalist countries have strong ''manipulation'' of global city networks, which determines the development trend of global city networks [26]. He also claimed that emerging economies, such as China and India, have become prominent in the global economy, industry, and trade and are reshaping the global city network structure [27]. Other scholars contend that the global city network does not unfold simultaneously but that the demographic dividends, market capacity, and price advantages of emerging economies have accelerated the integration of the global city network [28]–[30]. Moreover, geographic proximity, cognitive proximity, economic culture, and transportation are pivotal factors that affect the growth of urban networks [31]–[33].

The existing research has produced rich results in related fields, but some problems are worthy of further discussion. On the one hand, most scholars have only used data from listed companies to build urban networks. However, over 99% of enterprises in the YRD are small and medium-sized enterprises (SMEs; retrieved from https://www.qcc.com/). If only the data of listed companies are used to study the urban network, then the results may be distorted. On the other hand, existing research has primarily employed cross-sectional data

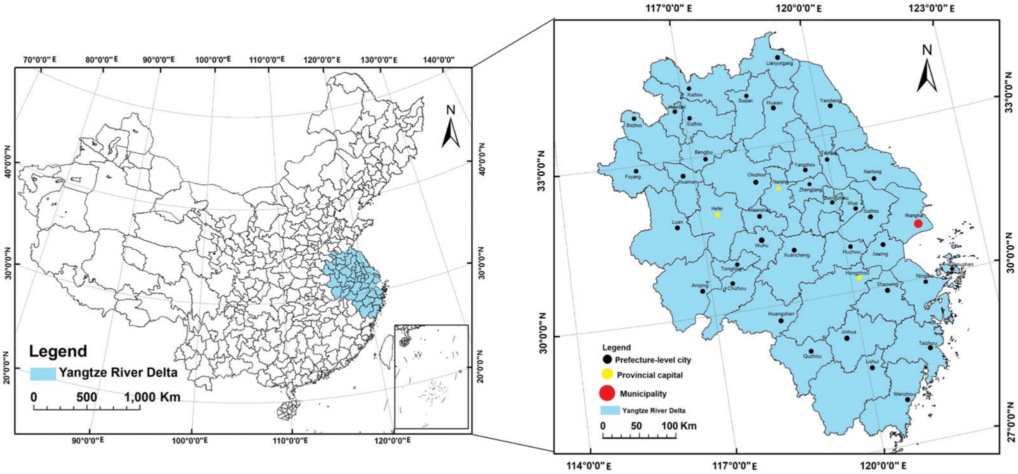

FIGURE 2. Location map of the YRD.

to construct urban networks and has seldom used panel data to compare and analyze urban networks in different years. Moreover, most studies have only created networks using corporate headquarters and their subsidiaries but have rarely attempted to form multilevel networks through corporate headquarters (*ch*), regional branches (*rb*), local branches (*lb*), or joint ventures (*jv*).

To fill these gaps, we first used Python to gather data on the headquarters of all financial companies in the YRD and their *rb, lb,* and *jv* from 1990 to 2017. Combining the interlocking network model and complex network analysis, we explored the evolutionary characteristics, modes, and influencing factors of urban networks. On the one hand, financial enterprises reflect the overall operations of social and economic growth and are a barometer for national economic development [34]. On the other hand, as important carriers of talent, capital and information, financial enterprises have penetrated into all walks of life and have become an increasingly momentous force in promoting the spread of urban networks [35].

This article deepens the understanding of the YRD urban network by attempting to answer three key questions. First, what is the pattern and evolutionary mode of the urban network? Second, can the radiation/agglomeration capacity and development status (contraction/expansion) of urban networks be measured? Third, what are the potential influencing factors of urban networks?

II. METHODOLOGY AND DATA

A. STUDY AREA

The YRD region includes 41 cities in Shanghai, Jiangsu, Zhejiang, and Anhui provinces (Figure 2). Shanghai is a municipality directly under the central government. Nanjing is the capital of Jiangsu Province. Hangzhou is the capital of Zhejiang Province, and Hefei is the capital of Anhui Province. The YRD is the region with the most active economic development, the highest degree of openness, and the strongest innovation capability in China [36]. As of 2019, the YRD had a population of 227 million, an area of 358,000 square kilometers, and a GDP of 3.6 trillion US dollars.

The YRD is one of the regions with the largest number of financial companies in China and has long occupied the core position of China's financial growth. However, due to historical, policy, and natural reasons, the financial development pattern of the YRD has strong spatial heterogeneity. The financial development levels of Shanghai, Jiangsu, and Zhejiang are significantly higher than that of Anhui Province. Hence, urban network research based on financial enterprises in the YRD is representative.

B. DATA

Qichacha (QCC) Technology Co., Ltd. is China's largest, most comprehensive website that provides information on enterprises (https://www.qcc.com/). According to the classification of financial enterprises in the "Classification of National Economic Industries (GB/T 4754-2017)" (*bank*, *securities*, *insurance*, *wealth management*, *funds*), we used Python to collect data on all types of financial enterprises on the QCC website. The specific steps were as follows:

Through keywords (*bank*, *securities*, *insurance*, *wealth management*, *funds*), we first used Python to gather data on all the financial companies in the YRD from 1990 to 2017 listed on the QCC website. Moreover, we filtered the data according to the conditions required to build the urban network: (1) The financial enterprise headquarters has one or more branches in the YRD. (2) During the study period, all the financial enterprises have clear registration times, a registered capital, registered addresses, and main businesses. (3) All the financial companies mentioned in this article are registered in prefecture-level cities. If some enterprises are registered in counties, cities, or districts, they are merged into prefecture-level cities. Based on these conditions, we identified 41 effective enterprises in 1990, 928 in 2000, 3,137 in 2008, and 8,061 in 2017 (Figure 3).

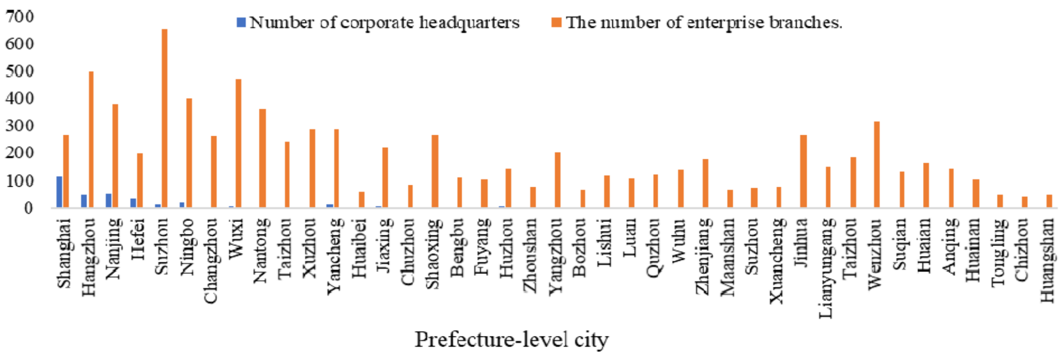

FIGURE 3. Number of corporate headquarters and branches.

C. METHODS

1) INTERLOCKING NETWORK MODEL

Effectively measuring the strength of connections between cities is the basis for constructing urban networks. Referring to Liu *et al.*, we assigned weights of 4, 3, 2, and 1 to the financial corporate headquarters (*ch*) and its regional branches (*rb*), local branches (*lb*), and joint ventures (*jv*), respectively [37]. We proposed an interlocking network model based on financial enterprise connections. The model is as follows:

$$R_{ij} = \sum^{n} 4(3C_{rb} + 2C_{lb} + C_{jv}) \tag{1-1}$$

$$DC_i = \sum_{k=1}^{n} R_{ij} (i \neq k) \tag{1-2}$$

where R_{ij} represents the connection strength between city i and city j, and the greater the value of R_{ij}, the greater the strength of the connection between city i and city j; n embodies the number of financial enterprise headquarters in city i; C_{rb}, C_{lb}, and C_{jv} represent the numbers of *rb, lb,* and *jv*, respectively, of the *k-th* financial enterprise whose corporate headquarters is located in city i; and the associated company is located in city j. DC_i is the degree centrality of city i, which signals the total strength of connections between city i and 40 other cities in the YRD.

2) CLUSTERING COEFFICIENT

Due to geographic proximity, the probability of connections between adjacent nodes in the urban network of the YRD is greater than the probability of random connections between two nodes [38]. The clustering coefficient can identify clusters that are more closely connected. The model is as follows:

$$C_{Di} = \frac{2E_i}{K_i(K_i - 1)} \tag{2}$$

where C_{Di} represents the clustering coefficient of city i, E_i represents the actual number of edges connected to city i, and K_i represents the maximum number of edges connected to city i. We used the clustering coefficient as one of the indicators to characterize the resilience of urban networks. The larger the value of C_{Di}, the stronger the network agglomeration effect within the region and the higher the risk resistance ability.

3) NETWORK DENSITY

Network density is the ratio of the number of edges that exist in the network to the number of edges that can be accommodated [39]. In this study, we used the network density model to reflect the closeness of urban network connections. The model is as follows:

$$D = \sum_{i=1}^{n} \sum_{j=1}^{n} d_i(c_i, c_j) \Big/ n(n-1), (i \neq j) \tag{3}$$

where n represents 41 cities in the YRD and $d_i(c_i, c_j)$ is the strength of the connection between city i and j. D represents the network density; the larger the value of D, the greater the urban network density.

4) RELATIVE NETWORK RELEVANCE

Relative network relevance refers to the ratio of the total connection strength of a city to the connection strength of all cities in the region [11]. By comparing the changes in the relative network relevance from t to $t+1$, we can determine the development status (expansion/contraction) of the urban network. For example, the total connection strength of city a in 2016 was 100, and its relative network relevance was 0.8. In 2017, the total connection strength of city a was 110, but its relative network relevance was 0.75. Although the network of city a expanded in 2017, its expansion speed was not as fast as the overall speed; hence, the network of city a contracted. The model is as follows:

$$D_{i[t-(t+1)]} = \frac{\sum_{j=1}^{41} R_{ij(t+1)} \Big/ \sum_{j=1}^{41} R_{ij(t+1)} \sum_{j=1}^{41} R_{ij(t+1)}}{\sum_{j=1}^{41} R_{ij(t)} \Big/ \sum_{j=1}^{41} R_{ij(t)} \sum_{j=1}^{41} R_{ij(t)}} \quad (i \neq j)(t \neq 0) \tag{4}$$

where $R_{ij(t)}$ represents the connection strength between city i and city j during t and $R_{ij(t+1)}$ represents the connection strength between city i and city j during $t+1$ (Model 1 shows the specific calculation method of R_{ij}). $D_{i[t-(t+1)]}$ represents the relative network relevance change value of city i

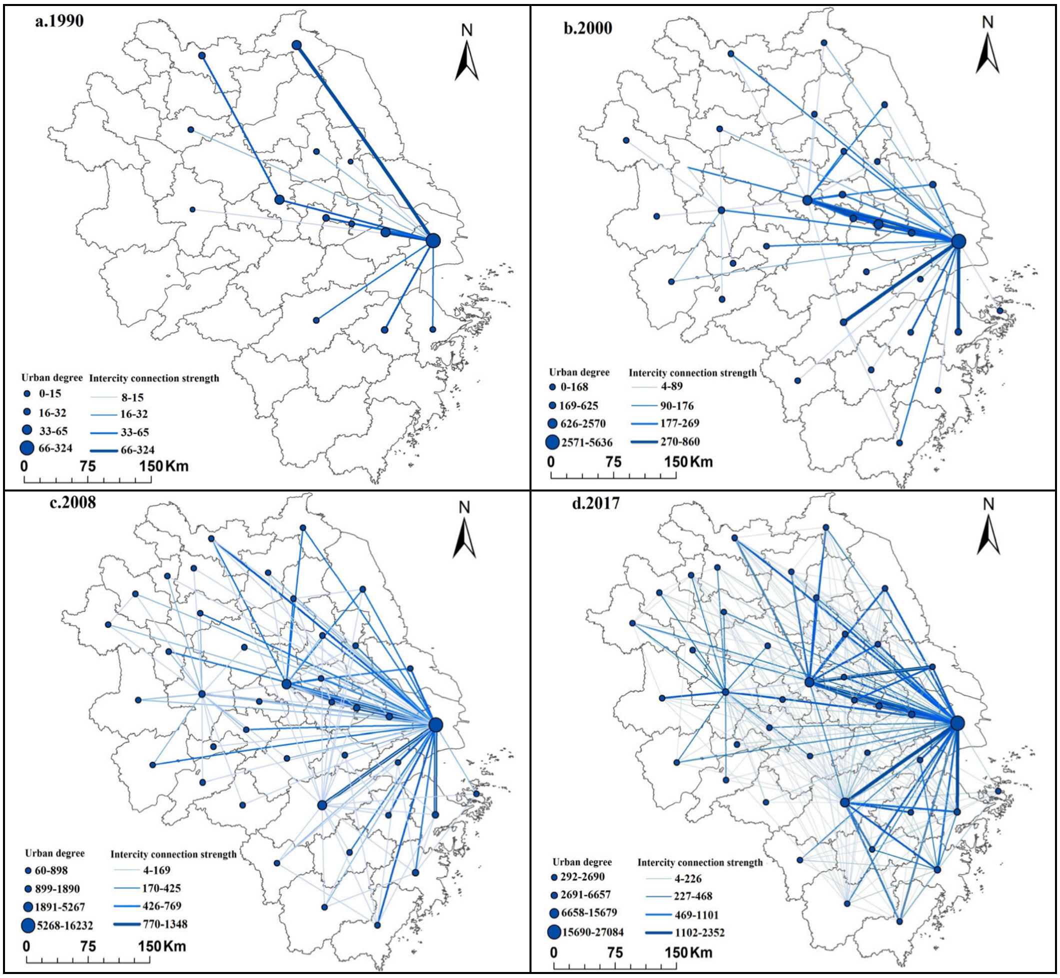

FIGURE 4. Temporal and spatial evolution of urban networks from 1990 to 2017.

during $t-(t+1)$, which is used to characterize the development status. If $D_{i[t-(t+1)]}>1$, then the urban network is relatively expanded; if $D_{i[t-(t+1)]}<1$, then the urban network is relatively contracted; and if $D_{i[t-(t+1)]}=1$, then no relative change has occurred in the urban network.

5) QUADRATIC ASSIGNMENT PROCEDURE (QAP)

Due to the unique nonparametric test function of the QAP regression model, it is widely used in social network analysis and complex network analysis and is considered to be one of the most effective models for evaluating the influencing factors of urban networks [40]. The principle of the QAP relational regression model is to compare the values between two matrices or one matrix and multiple matrices, which can avoid the principle of ‘‘collinearity.’’ This article used the interlocking network model to construct the 41×41 connection strength matrix of the YRD and used it as the dependent variable. In addition, referring to the relevant literature, we selected 7 independent variables, including the economy, technology, transportation, and geographic distance, and converted them into a 41×41 matrix [47]. Finally, we selected the appropriate number of permutations in Ucinet software to perform nonparametric tests on the independent and dependent variables.

III. RESULTS

A. URBAN NETWORK HIERACHY CHARACTERISTICS

To explore the evolution of the temporal and spatial patterns of the urban network, we used ArcGIS 10.2 spatial analysis tools and the natural break method to divide the urban network connections into 4 levels (Figure 4).

In 1990, limited by the level of transportation and economic development, Shanghai only established weak connections with as Lianyungang, Nanjing, and Suzhou. Since 2000, the frequency of the flow of various elements has gradually accelerated, and the intensity and scope of the connections between cities have continued to increase. For example, the connection strength between Shanghai–Hangzhou and Shanghai–Wu rose from 20 and 24 in 1990 to 420 and 860 in 2000, respectively. Moreover, connections between core and peripheral cities have slowly emerged, mainly because in the early stages of regional growth, geographic proximity

TABLE 1. Urban network resilience index.

Year	1990	2000	2008	2017
Average weight	25.42	226.56	2164.29	1452.28
Modularity	0.143	0.183	0.185	0.315
Average clustering coefficient	0.051	0.516	0.744	0.812
Network density	0.021	0.055	0.073	0.606

determines the direction and strength of urban network connections. On the one hand, neighboring cities have similar economic, cultural, and social concepts, which make the connections between neighboring cities frequent and stable. Further, geographic proximity helps cities learn from each other and thus obtain more external benefits. On the other hand, neighboring cities have less spatial friction, thereby making face-to-face information exchange and tacit knowledge transfer easy. However, the farther the distance between cities, the worse the spillover effect of knowledge and the more difficult the transfer of tacit knowledge.

In 2008, the urban network connection pattern underwent major changes. The "V" spatial pattern of Shanghai–Hangzhou (1,348), Shanghai–Nanjing (1,304), Shanghai–Suzhou (1,227), and Shanghai–Wuxi (1,008) constitutes the core framework of the urban network. This is mostly because with the acceleration of technological advancements and shifts in consumer behavioral demands, the complexity and risk of financial enterprise operations have progressively increased. It is difficult for financial companies to face the impact and uncertainty brought about by market style switching and rapid technological changes. However, the financial network facilitates professional knowledge exchange and a division of labor based on the common interests of its members, reduces transaction costs, and enhances corporate competitiveness. In 2017, a multicenter network development pattern with Shanghai, Nanjing, Hangzhou, and Hefei as the core basically took shape. As a result, the urban network connection is more balanced, and the connections between core and peripheral cities have gradually gotten stronger. This is primarily because as the degree of resource exchange between cities continues to increase, the core cities of the network have begun to break through spatial constraints to establish connections with peripheral cities.

B. URBAN NETWORK RESILIENCE

Network resilience refers to the ability of a system to maintain its own stability and core functions after external shocks [41], [42]. In the context of unilateralism and trade protectionism, external economic and industrial shocks have brought great challenges to the resilience of financial networks. Generally, cities with higher network resilience have stronger collaborations and complementary relationships in various fields, such as society, the economy, ecology, and industry, and thus have certain risk resistance capabilities. We comprehensively evaluated the resilience of urban networks based on the average weight, modularity, average clustering coefficient and network density in the complex network model (Table 1). The average weight, modularity, average clustering coefficient, and network density of the urban network increased from 25.429, 0.143, 0.051, and 0.021 in 1990 to 1,452.289, 0.351, 0.812, and 0.606 in 2017, respectively. From 1990 to 2017, the average weight of the urban network increased 57 times, which is one of the most sensitive indicators for testing the resilience of urban networks. In general, the indicators that characterize urban network resilience showed an upward trend from 1990 to 2017, which suggests that the operating level of urban networks has continuously improved and has certain potential risk resistance and self-repair capabilities. Similarly, Li et al. also affirmed that with the implementation of various reforms, the urban network resilience of the YRD is gradually improving. In fact, in order to enhance the resilience of urban networks and create a multicenter, networked development pattern, the YRD is reinforcing cooperation in the fields of healthcare, education, transportation, and finance among cities [43].

The model of Modularity is: $Q = \frac{1}{2m}\sum_{ij}\left[A_{ij} - \frac{k_i k_j}{2m}\right]\delta(c_i, c_j)$;

where A_{ij} represents the weight of the connection degree between nodes i and j;k_i represents the sum of the connection strength of all nodes connected to node i;m represents the number of edges; $\delta(c_i, c_j)$ is mainly used to judge whether nodes i and j are in the same community. Average weight refers to the average of the degree centrality of 41 cities in the YRD (see Model 1-2 for details).

C. RADIATION AND AGGLOMERATION

1) URBAN NETWORK RADIATION ABILITY

Core cities often have better location and policy advantages, which have a strong impact on the resource allocation capabilities of peripheral cities [44]. We combine Gephi tools and weighted in-degree and out-degree indexes to visualize the radiation and agglomeration capabilities of urban networks (Figure 5). If the weighted out-degree of a city is greater, its radiation capacity is stronger; otherwise, the opposite is true. If the weighted in-degree of a city is larger, its agglomeration ability is stronger; otherwise, the opposite is true.

The urban network radiation pattern of the YRD has strong temporal and spatial heterogeneity. In 1990 (Figure 5a), the weighted out-degrees of Shanghai and Nanjing were 234 and 32, respectively, but other cities had not yet formed network radiation capabilities, mostly because China's financial development was in a relatively blank stage before 1990, and the financial connections between cities

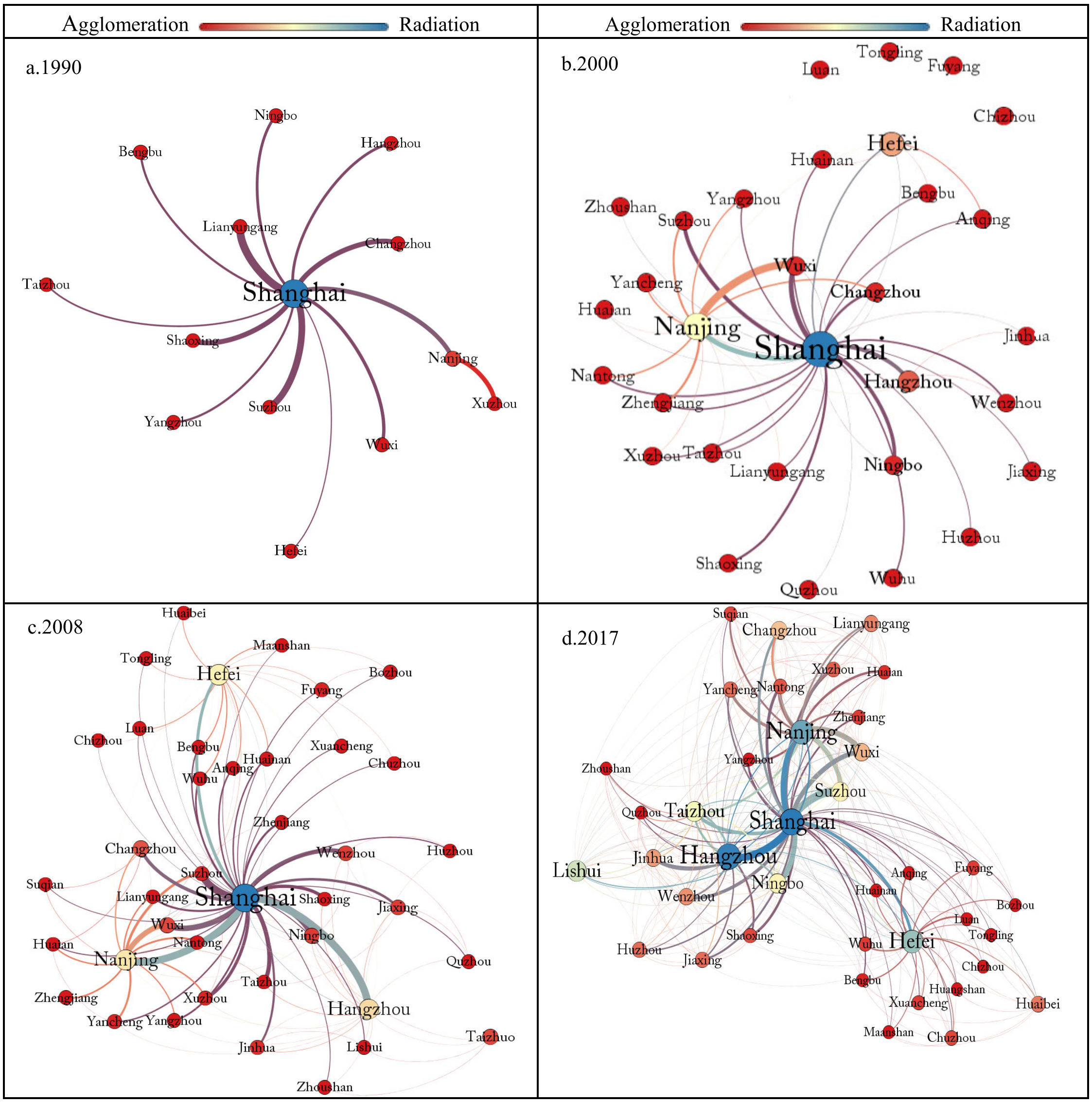

FIGURE 5. **Network radiation and agglomeration capabilities of cities in the YRD.**
Note: The clockwise lines represent the radiation capacity of cities, while the counterclockwise lines represent the agglomeration capacity of cities. The thicker the line, the stronger the radiation/agglomeration capacity. The node size indicates the total radiation and agglomeration capacity.

were weak. It was not until December 1990 that China established the Shanghai Stock Exchange, which was also China's first stock exchange. In 2000 (Figure 5b), the top five cities with network radiation capabilities were Shanghai (4,992), Nanjing (2,056), Hefei (160), Hangzhou (24), and Ningbo (12). Among them, Shanghai and Nanjing have strong network radiation capabilities, which can control the resources, capital, and technological development of other cities to a large extent. However, most peripheral cities, such as Fuyang and Lishui, have not yet formed network radiation capabilities. As the financial center of China and the world, Shanghai's unique location conditions and policy advantages have attracted a large number of financial corporate headquarters and branches. Moreover, financial activities are characterized by complexity, diversity, and high risk [45]. The development of financial centers must rely on good infrastructure and developed financial networks, which have a high development threshold for small and medium cities.

In 2008 (Figure 5c), Shanghai, Nanjing, Hefei, and Hangzhou did not change their rankings of network radiation capabilities, while Changzhou replaced Ningbo. Jiaxing, Wenzhou, and Jinhua have gradually formed network radiation capabilities, but their network radiation strength is relatively weak, and their radiation space is small. In 2017 (Figure 5d), Hangzhou's network radiation capabilities increased significantly and replaced Hefei in third place. To date, a multicenter network radiation pattern centered on Shanghai, Nanjing, Hefei and Hangzhou has taken shape.

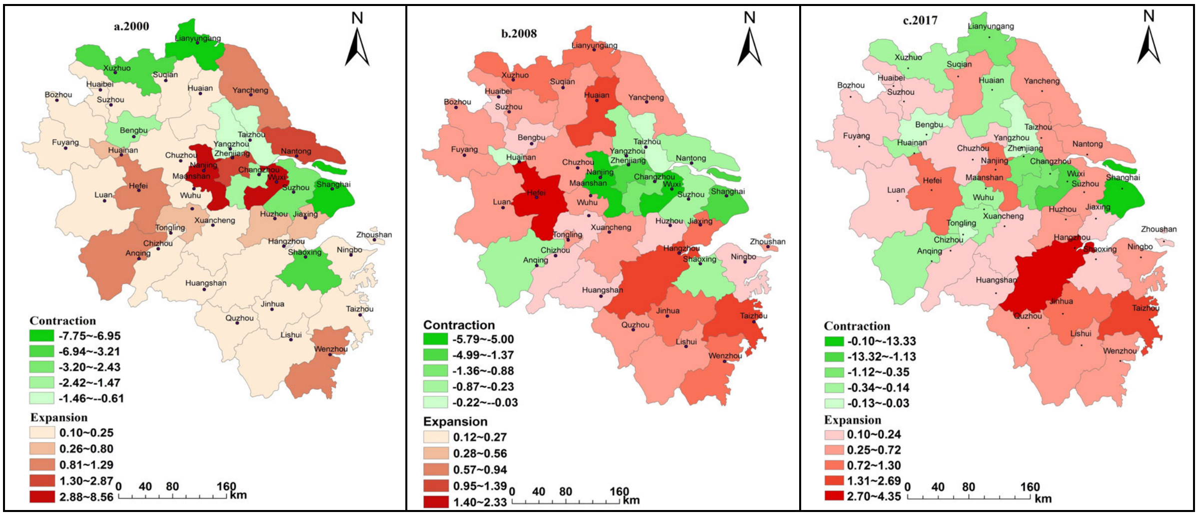

FIGURE 6. Degrees of contraction and expansion of the urban network.

In general, provincial capitals and subcentral cities have large weighted out-degrees and strong network radiation capabilities. By contrast, most peripheral cities have almost no network radiation capabilities, primarily because cities that generate network radiation capabilities must have financial enterprise headquarters; otherwise, they can only accept radiation from other cities. However, due to economic, industrial, transportation, and policy restrictions, the headquarters of Chinese financial companies are rarely established in peripheral cities.

2) URBAN NETWORK AGGLOMERATION CAPACITY

In terms of agglomeration capacity, 13 cities formed a network agglomeration capacity in 1990 (Figure 5a). Compared with other cities, Lianyungang (56) and Suzhou (48) have stronger network agglomeration capabilities. In 2000 (Figure 5b), the top five cities with network agglomeration capabilities were Wuxi (1,400), Suzhou (644), Nanjing (564), Changzhou (460), and Hangzhou (432). This is mostly because the southern Jiangsu region, represented by Suzhou, Wuxi, and Changzhou, has a solid economic foundation and obvious geographic advantages, which provides natural soil for the growth of financial enterprises. Other cities in the YRD have formed relatively weak network agglomeration capabilities. For example, although Chizhou, Lu'an, Fuyang, and Tongling in Anhui Province receive network radiation from the provincial capital of Hefei, the amount of radiation is small, which makes them drift at the edge of the network.

By 2008 (Figure 5c), all the cities in the YRD had formed network agglomeration capabilities. Among them, the top five cities with agglomeration capacity are Wuxi (1,972), Suzhou (1,736), Hangzhou (1,428), Nanjing (1,352) and Ningbo (1,312). Notably, Shanghai's network agglomeration capacity is only 1/22 of the network radiation capacity, which has strong asymmetry. This finding reflects that Shanghai has established many branches in other cities and acts as a bridge and intermediary in the connection of the urban network. In 2017 (Figure 5d), the network agglomeration capacity of most cities was significantly enhanced, and a network agglomeration pattern centered on Suzhou, Wuxi, Hangzhou and Nanjing was formed. However, cities in Anhui Province, such as Chizhou and Tongling, have relatively weak network agglomeration capabilities and have not yet formed a close network radiation pattern with the provincial capital of Hefei and other cities in the YRD. Hence, it is necessary to further optimize the spatial distribution pattern of resources such as talent and funds to enhance the rights and status of cities on the edge of the network.

D. CONTRACTION AND EXPANSION

Combining the relative network relevance model and using ArcGIS 10.2 spatial analysis tools, we explored the contraction and expansion trends of urban networks in the YRD (Figure 6).

Overall, the number of urban networks in contraction rose from 9 in 2000 to 14 in 2017. Among them, core cities, such as Shanghai and Changzhou, maintained a high degree of contraction, while peripheral cities, such as Suqian, Fuyang, and Lishui, continued to expand. The result may be that the financial development of core cities, such as Shanghai, Suzhou, Wuxi, and Changzhou, occurred earlier, and a relatively complete financial network system was established. Although a series of measures have been taken in recent years to promote financial reforms and capital flows, these actions are only optimizations and adjustments in the stock space. However, network peripheral cities, such as Suqian and Fuyang, were restricted by infrastructure and the business environment, leading to the slow growth of the financial industry. With the ongoing implementation of various financial reform measures, a large amount of incremental space for the development of the financial enterprises has been released, causing the financial network to expand. Similarly, Tseng *et al.* believe that strengthening the infrastructure construction of cities on the edge of the network and creating a good business environment are important ways to promote the development of urban networks [46].

IV. POTENTIAL INFLUENCING FACTORS OF THE URBAN NETWORK

A. INDEX SELECTION

Given that the urban network is a form of ''relational'' data, ordinary statistical methods can hardly avoid the principle of ''collinearity'' for statistical analysis. However, the QAP relational regression model can solve this problem by using ''grid value'' comparison between matrices [40]. The model is as follows:

$$Y_i = k_0 + k_1 q_1 + k_2 q_2 + k_3 q_3 \cdots + k_7 q_7 \tag{5}$$

where Y_i is the dependent variable, represented by the 41×41 city connection matrix; K_0 is a constant; k_1–k_7 are the regression coefficients of the impact factor; and q_1–q_7 are the impact factor matrix.

As a complex system, urban network development is affected by many factors. We follow the principles of theoretical analysis, QAP correlation analysis, R^2 and explanatory variable significance testing to select explanatory variables. First, referring to the research of Ji, Chong, and Xu, and combining the actual situation of urban network development in the Yangtze River Delta, we construct the explanatory variables of the urban network from the following seven aspects [47]–[49]: (1) Economic Development (*ED*): Economic development promotes the cross-regional flow of various resource elements and is a key support for the urban network. We chose GDP per capita to measure economic development. (2) Technological progress (*TP*): Technological progress can improve the production efficiency of enterprises, and expanding marginal income is an important factor in promoting economic development and social progress. We select the per capita scientific research expenditure of cities to measure technological progress. (3) Financial development (*FD*): The financial-related ratio refers to the degree of economic monetization and is a critical indicator of financial development. We used the financial-related ratio (financial assets/GDP) to represent financial development. (4) Transportation development (*TD*): Transportation development can reduce transportation costs, expand the market radius, and increase regional accessibility. Based on the availability of data, we use the area of urban paved roads (10,000 square meters) to reflect the level of transportation development. (5) Geographic distance (*GD*): Geographic distance mainly considers the influence of administrative divisions on the urban network. We set 2 cities in the same province to 1, otherwise 0, and constructed a 41*41 administrative relationship matrix. (6) Industrial structure (*IS*): The financial industry belongs to the tertiary industry, and cities with more developed tertiary industries tend to produce more financial services. Therefore, we chose the ratio of the added value of the tertiary industry to gross domestic product (GDP) to measure financial development. (7) Fixed investment (*FI*): Generally, the greater the fixed investment, the better the infrastructure and business environment of a city, which are conducive to economic and industrial development. We used the city's annual fixed investment amount to express *FI*. The above data come from the China City Statistical Yearbook and the Shanghai, Jiangsu Province, and Anhui Province Statistical Yearbooks.

Second, to test the rationality of the selected variables, we performed QAP correlation analysis on the 7 explanatory variable matrices and the explained variable matrices. We found most of the variables to have relatively good correlations, which indicates that they are suitable for QAP regression analysis. Finally, we input the above explanatory variable matrix and explained variable matrix into Unicet software for regression analysis and examined the significance level of R^2 and each explanatory variable. We found that the R^2 of the QAP regression analysis was 0.824 and that most of the explanatory variables had good significance, which implied that the variables we selected were appropriate.

B. REGRESSION RESULTS

To compare the differences between the QAP model and the traditional OLS regression model, we converted the above 7 explanatory variables from the $n \times n$ matrix form to the $n \times 1$ form. The explained variable in the QAP model represents the matrix of the connection strength between cities. However, OLS regression cannot identify the explained variables in matrix form, so we used the degree centrality (the degree centrality calculation method is introduced in Model 1) of the city as the explained variable of OLS regression. In addition, geographic distance is presented in the form of a 0-1 matrix in the QAP model, but in OLS regression, we used the distance from the city's administrative center to the economic center of the YRD to characterize it. Before performing OLS regression analysis, we tested the variables for multicollinearity, heteroskedasticity and autocorrelation. The test results are as follows:

According to the test outcomes, the maximum value of the variance inflation factor (VIF) was 7.089 (Table 2), the minimum value was 1.884, and the average value was 4.526, which suggest no collinearity between the variables. The correlation test results revealed that the explanatory variable and the explained variable had a certain correlation (Table 3). The statistic F in the heteroscedasticity test accepted the null hypothesis to indicate no heteroscedasticity (Table 4). Overall, the variables selected in this article met the basic conditions of OLS regression analysis. We performed QAP and OLS regression analyses for the above variables. The findings are displayed in Table 5.

Our research focuses on the analysis of influencing factors of urban networks. Although the outcomes of the OLS regression analysis were relatively good, they can only reflect the impact of explanatory variables on the degree centrality of cities. Hence, we focused on examining the results of the

TABLE 2. Multicollinearity test.

Variable	*ED*	*TP*	*TD*	*FX*	*FD*	*GD*	*IS*	*Average*
VIF	1.884	6.227	6.133	5.267	7.089	2.911	2.177	4.526

Note: * means passing the test at the significance level of 0.1, ** means passing the test at the significance level of 0.05, *** means passing the test at the significance level of 0.01.

TABLE 3. Autocorrelation test.

Variable	*CON*	*ED*	*TP*	*TD*	*FX*	*FD*	*DIS*	*IS*
CON	1.000	0.706***	0.758***	0.799***	0.774***	0.965***	-0.537***	0.589***
ED	0.706***	1.000	0.506***	0.581***	0.616***	0.653***	-0.323**	0.380***
TP	0.758***	0.506***	1.000	0.500***	0.645***	0.794***	-0.787***	0.578***
TD	0.799***	0.581***	0.500***	1.000	0.839***	0.812***	-0.394***	0.452***
FX	0.774***	0.616***	0.645***	0.839***	1.000	0.812***	-0.499***	0.311**
FD	0.965***	0.653***	0.794***	0.812***	0.812***	1.000	-0.649***	0.568***
GD	-0.537***	-0.323***	-0.787***	-0.394***	-0.499***	-0.649***	1.000	-0.361***
IS	0.589***	0.380***	0.578***	0.452***	0.311**	0.568***	-0.361***	1.000

Note: * means passing the test at the significance level of 0.1, ** means passing the test at the significance level of 0.05, *** means passing the test at the significance level of 0.01.

TABLE 4. Heteroscedasticity test.

F-statistic	0.47480	Prob. F (35,5)	0.9121
Obs*R-squared	31.5172	Prob. Chi-Square (35)	0.6370
Scaled explained SS	21.5461	Prob. Chi-Square (35)	0.9637
R-squared	0.768	Mean dependent var	0.064
Log likelihood	86.436	Hannan-Quinn criter	-1.919

Note: * means passing the test at the significance level of 0.1, ** means passing the test at the significance level of 0.05, *** means passing the test at the significance level of 0.01.

QAP regression model and comparing the similarities and differences with the outcomes of the OLS model.

(1) The coefficient of *ED* was 0.086 and passed the significance test. Economic development is the basis for the flow of capital and talent. The more developed an economy is, the better the infrastructure and business environment and the higher the efficiency of resource flow. (2) The regression coefficient of *TP* was 0.137 and passed the significance test. This finding may imply that technological progress has a strong spillover effect, which can reduce the repetitive work of network members, enhance the information complementation and resource sharing capabilities between enterprises, and thus promote the development of urban networks. (3) The regression coefficient of *TD* was 0.122, but it failed the significance test. Although the essence of finance is flow, finance does not need to use a certain mode of transportation to flow like other commodities, which makes its flow less restricted by traffic. In addition, China's mobile payment and e-commerce systems have developed rapidly in recent years, which has to some extent eliminated the constraints of transportation development and geographic location on financial growth. (4) The coefficient of *FI* was significantly positive in the QAP model but negative and not significant in the OLS model. This may be because the narrowing of the fixed investment gap between cities can speed up the flow of resources and improve the connection efficiency of the overall network, but it has little effect on the connection strength of a single city. (5) The regression coefficient of *FD* was 0.064 and passed the significance test, which signals that cities with similar financial development may conduct more financial business transactions. (6) The coefficient of *GD* was negative in the QAP model and failed the significance test but was significantly positive in the OLS model. This may be because in the early stages of regional growth, geographic proximity has a greater impact on the range and strength of urban network connections. With the continuous deepening of resource agglomeration and diffusion, the connections between cities have gradually broken through spatial restrictions, making them increasingly less affected by administrative divisions. However, the explained variable in OLS is the degree centrality of the city. Generally, the closer to the economic center, the greater the strength of the connection between cities, and the higher the degree centrality. (7) The regression coefficient of *IS* was 0.17 and passed the significance test, which means that a significant positive correlation exists between the industrial structure and the urban network. On the one hand, cities with similar

TABLE 5. QAP regression analysis.

Explanatory variables	OLS regression analysis		QAP correlation analysis		QAP regression analysis	
	Correlation coefficient	P value	Correlation coefficient	P value	Regression coefficients	P value
ED	0.039**	0.029	0.165**	0.032	0.086*	0.074
TP	0.347*	0.097	0.352**	0.026	0.137**	0.026
TD	0.090	0.414	0.073	0.179	0.122	0.198
FI	-0.126	0.206	-0.055*	0.070	-0.066**	0.043
FD	0.910***	0.008	0.085*	0.063	0.064***	0.002
GD	0.366***	0.003	-0.370	0.421	-0.158	0.361
IS	0.026	0.936	0.086**	0.033	0.117**	0.037
R^2	0.843		0.732**	0.013	0.824***	0.004

Note: * means passing the test at the significance level of 0.1, ** means passing the test at the significance level of 0.05, *** means passing the test at the significance level of 0.01.

TABLE 6. Stepwise regression analysis.

Explanatory variables	QAP regression analysis	
	Regression coefficients	P value
ED	0.088**	0.037
TP	0.183***	0.008
FI	-0.063***	0.000
FD	0.062**	0.024
IS	0.134**	0.034
R^2	0.837***	0.000

Note: * means passing the test at the significance level of 0.1, ** means passing the test at the significance level of 0.05, *** means passing the test at the significance level of 0.01.

economic and industrial structures have extensive economic and technological links, which will promote economic cooperation and resource exchange between cities and reduce transaction costs. On the other hand, with the spread of economic globalization, the phenomenon of production segmentation is becoming common, and the division of labor and cooperation networks based on the industrial chain is becoming an important engine for the expansion of urban networks.

To further observe the influence of explanatory variables on the urban network, we eliminated insignificant variables such as *GD* and *TD* for the second regression (Table 6). The results show that the coefficients and significance levels of ED, TP and FI have increased. The coefficient of FD has decreased, but the level of significance has further increased. The coefficient of IS has improved, but the level of significance remains the same. Overall, the second QAP regression analysis performed better and further verified the above conclusions.

C. RECOMMENDATIONS

Based on the above conclusions and actual requirements, we propose the following recommendations for the integration and network development of the YRD.

(1) Create a multicenter network development pattern and foster the balanced and coordinated development of urban networks in the YRD. In the context of economic globalization, the competition among cities for talent, capital, and industries is extremely fierce, and uneven development within the region is becoming increasingly serious. Compared with the traditional central place system, the concept of "multicenter balanced development" and "multilevel governance" encouraged by the urban network is a response to the progressive expansion of development contradictions between regions. We found that Shanghai occupies an absolute core position in the urban network, while other peripheral cities are not fully integrated into it. This polarized development method not only is not conducive to the balanced and coordinated development of urban networks, but also triggers certain social contradictions and conflicts. In the future, it will be necessary to reinforce the connections and cooperation between cities to construct a multicenter network development pattern with a rational division of labor and complementary advantages.

(2) Transform the functions of local governments and enhance the efficiency of resource allocation. The urban network is a critical manifestation of the cross-regional flow of various resource elements. Reducing the cost of factor flow, expanding the market space of enterprises, and realizing the free flow of production factors are prerequisites for regional integration and networked development. Since local government protectionism not only failed to form an economic and industrial layout with complementary advantages and a reasonable structure, it also reduced the efficiency of resource allocation and expanded vicious competition between cities.

The key to breaking local protectionism lies in government reform. The functions of local governments should be transformed into public services, social management and the maintenance of social order and gradually bring into play the decisive role of the market in resource allocation. In addition, it is necessary to continue to relax the government's intervention in business activities to create a good external environment for business development.

(3) Explore differentiated and characteristic growth models, and strengthen competition and cooperation between cities. The integrated development of the YRD is not meant to create a homogeneous space but rather to pursue differentiated and characteristic development. The most obvious advantages of the network are the exchange of resources and complementary advantages. Based on the actual situation, Shanghai, Nanjing, and Hangzhou are rich in talent and funds; Chizhou and Huangshan are rich in tourism resources; and Huainan, Huaibei, and Tongling are rich in natural resources. These features provide the basis for the differentiated and characteristic development of the YRD. Therefore, in the future, we must clearly recognize the comparative advantages and development potential of each city, clarify the urban development goals, strengthen the competition and cooperation between cities, and realize the sustainable development of the economy and industry.

(4) Promote the interconnections of infrastructure and build a three-dimensional transportation network. Building a comprehensive transportation system is the foundation and guarantee for the integrated development of the YRD. On the one hand, it is difficult for cities with a backward transportation infrastructure to introduce advanced technology and high-quality talent and may even lead to the loss of population and industries. On the other hand, backward transportation will also increase the cost of factor flow and lower cooperation and exchanges between cities, which is not conducive to the development of urban networks. However, due to historical, natural and policy reasons, the growth of transportation in the YRD is extremely uneven, which has become an important factor in restricting the development of peripheral cities. In the future, it will be necessary to give appropriate preferential policies to areas with backward transportation infrastructure, such as southern and northern Anhui; to reinforce the construction of three-dimensional transportation networks, such as highways, railways, and shipping; and to facilitate and liberalize resource flows.

V. CONCLUSION

In the context of regional integration development, research on the urban network in the YRD has received extensive attention from policymakers and scholars. In this article, we constructed the urban network by using financial enterprise data and an interlocking network model, and combined the complex network and QAP relation regression model to explore the evolutionary characteristics, modes, and influencing factors of urban networks.

From 1990 to 2017, the urban network connection strength and network resilience increased significantly. For example, the average weight, modularity, average clustering coefficient, and network density of the urban network rose from 25.429, 0.143, 0.051, and 0.021 in 1990 to 1,452.289, 0.351, 0.812, and 0.606 in 2017, respectively. These outcomes suggest that urban networks have certain potential risk resistance and self-repair ability. Moreover, the urban network connection form has shifted from adjacent connections to jump connections. This may be because in the early stages of regional growth, geographic proximity determines the development direction of urban networks. With the rapid development of the economy and industry, core cities gradually broke through spatial constraints to link with neighboring cities and network edge cities. As a result, the urban network density and the connections between cities have been continuously strengthened, and the urban network spatial structure has developed towards multiple centers.

Second, the radiation and agglomeration capabilities of urban networks have strong asymmetry. Among them, Shanghai's network agglomeration capacity is only 1/22 of its radiation capacity, which signals that Shanghai is continuously exporting financial resources to other cities in the YRD region and acts as a bridge in network connections. In sharp contrast, the network agglomeration capacity of Suzhou, Wuxi, and Changzhou is significantly greater than their radiation capacity. This is not surprising as the southern Jiangsu region, represented by Suzhou, has a solid economic foundation and evident geographic advantages, which provide fertile ground for the growth of the financial industry. Most cities in Anhui Province have weak network radiation and agglomeration capabilities and have been floating on the edge of the network. This is primarily because the development of financial centers must rely on good infrastructure and robust financial networks, which have a high threshold for small and medium cities. Notably, the network of some peripheral cities was in a state of expansion from 1990 to 2017, while Shanghai was in a state of contraction, which means that the urban network in the YRD was moving in a balanced and coordinated direction. This is also consistent with the concept of "multicenter balanced development" advocated by the urban network.

Finally, the QAP regression model reveals that economic development is a crucial source of support for urban networks, and technological progress may improve the management level of enterprises and promote cooperation and exchanges between cities. Furthermore, cities with similar industrial structures may have certain industrial synergy or complementary relationships, and are more likely to establish spatial connections, which is consistent with the research by Yi *et al.* [34]. Therefore, strengthening urban economic and industrial development, accelerating technological progress, and enhancing exchanges and cooperation between companies are important measures to advance the development of urban networks.

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