Evolutionary Characteristics of the Innovation Cooperation Network Structure in China's Yangtze River Delta Urban Agglomeration

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Abstract:This paper will study the network of innovation cooperation in the Yangtze River Delta (YRD) Area and focus on the 27 selected nodal cities. Based on the co-filed patent application data from 2014 to 2025, an undirected graph with multiple values has been built, and then social network analysis (SNA) was used to study the structure and evolution of this network. The findings are as follows: (1) the horizontal cooperative ties are strong, but the vertical links are weak; most patent collaborations occur in Shanghai, Suzhou, Nanjing and Hefei, and together they form the core of the network. (2) The development of the innovation cooperation network is uneven across the YRD urban agglomeration, with disparities among node cities gradually widening and the network displaying increasing clustering, demonstrating notable small-world network characteristics. (3) Among the urban clusters in the Yangtze River Delta, Shanghai has become the top coordinating institution for cooperative innovation, and many other municipalities in Anhui as well as the peripheral areas of Zhejiang and Jiangsu have not yet joined such collaborations. To promote the coordinated development of the region, we should utilise the driving force provided by the major cities, at the same time foster characteristic innovative strengths in the peripheral areas, build open and flexible systems for sharing intellectual resources, continuously improve distribution, and thus create a more equitable network of urban innovation throughout YRD.

Keywords: Yangtze River Delta Urban Agglomeration; Regional Innovation Network; Patent Cooperation; Social Network Analysis; Network Dynamic Evolution

1. Introduction

Innovation serves as the engine of sustained global economic growth, with cities functioning as the spatial carriers of innovation activities [1]. With the rapid development of the knowledge-based economy and the growing societal demand for innovation, knowledge innovation, technological innovation, and institutional innovation have increasingly become essential urban functions, exerting profound influences on regional spatial development [2]. After the release of the Yangtze River Delta (YRD)Regional Integration Outline in 2019, cross-provincial cooperation has been promoted at the national level to build a modern economic system and achieve high-quality development [3]. The area of Shanghai, Jiangsu, Zhejiang and Anhui is relatively close to the mainland, has strong economic integration, rich research and development resources, and a large number of innovation drivers [4]. As the pace of unification increases, cooperation in science and technology has been strengthening steadily among all these areas, and now the role of urban areas as the main physical hubs for inventive activities is becoming increasingly prominent. In the era of rapid development of the knowledge economy and high demands from society for newness, all kinds of changes—in knowledge, technology, institutions, etc.—have become essential urban functions and have changed the spatial development of the region significantly. Therefore, to maintain both the newness and the fairness of development in the YRD area, we need to use the power of cross-regional connectivity and synergistic inventive progress.

Through continuous contact with all sorts of parties at various levels through formal and informal means, enterprises, universities, research institutions, governments, etc., in the YRD region have gradually built a cooperation network [5]. This network is a regional innovation system that shows the spatial distribution of intercity inventive activities, as well as the degree of influence of a city on innovation and the efficiency of knowledge dissemination and absorption. It is now generally known that it serves to promote cooperative innovation across the entire YRD area [6]. The networks formed by intercity innovation linkages represent the degree of regional innovation intensity and collaborative development. Given the increasing globalization and networking of economic development, intercity connections and innovation linkages have been steadily strengthening. Consequently, a growing number of scholars have examined urban innovation from a network perspective. Most research on innovation networks at the regional level can be divided into three main directions. One is interested in the spatial and structural characteristics of such networks in the YRD urban agglomeration; for example, Zhou, Zeng and others [7] have classified innovation types according to the aggregate capabilities of cities, and Bi and Tang [8] have studied the spatial distribution of patent transfers. Sun and Peng investigated the characteristics and developmental mechanisms of cohesive subgroups within the YRD innovation network [5]. Hu and Shi analyzed the network characteristics and spatial structure of urban innovation in the YRD urban agglomeration [9]. The second area focuses on the influencing factors of innovation networks. For example, Yuan and Han analyzed the effects of proximity factors on the innovation cooperation network of Chinese cities [10]. Su and Cao examined the factors influencing spatial transaction costs within collaborative innovation networks [11]. Su investigated the impact of cooperative innovation networks on innovation performance [12]. The third area addresses the evolutionary dynamics of network structures. Zhou and Qiu explored the structural evolution characteristics of innovation networks across 295 Chinese cities [13]. Wang and Wan conducted a visual analysis of the organizational framework and evolutionary process of the Chengdu–Chongqing urban agglomeration network [14]. Xu, Zhou, et al. investigated the resilience evolution of the collaborative innovation network in the YRD region [15]. It is evident that synergistic innovation in the YRD region has emerged as a prominent research topic in recent years. However, existing studies have largely been confined to cross-sectional analyses of network structural characteristics or formation mechanisms at specific points in time, with insufficient attention paid to the long-term historical evolutionary processes and macro-level dynamics of the YRD innovation network. Currently, the YRD region is characterized by increasingly close economic interactions and increasingly prominent advantages in scientific and technological innovation, both of which provide a solid foundation for the development of regional innovation networks. Research on urban innovation networks holds significant theoretical and practical value for revealing the spatial patterns of regional innovation in China, elucidating the evolutionary mechanisms of urban innovation development, and promoting the construction of innovative cities.

Based on graph theory and social network analysis of a large number of joint-filing patents over several years, we can quantify and visualize the development of the collaborative innovation network among the main cities in the Yangtze River Delta. The three main research questions are: what is the general structure of inter-city cooperative relationships, when do these links occur, and what are the different functions of individual cities? Therefore, this paper will provide all-encompassing analysis of the development process and interaction forms of regional innovation cooperation.

2. Data Sources and Methodology

2.1 Data Sources

Patent records are tangible results of research and development, and thus contain a large amount of data that can be used to study changes in technology and collaborations to explore the structure of innovation ecosystems [16].Owing to the inherent innovativeness of invention patents, the use of cooperative invention patent data to construct innovation networks has been widely recognized by scholars and has been extensively applied in studies on technology and innovation activities [17], technological development trends [18], R&D strategies [19], and innovation management [20]. Patents adequately reflect and effectively measure the economic returns of innovation, and patent outcomes are currently among the most commonly used and broadly accepted standards for measuring innovation output. By analyzing patent cooperation networks formed by joint applicants, it is possible to identify the extent to which applicants integrate or leverage external technological advantages during the R&D phase. Accordingly, this study employs data on jointly applied patents to characterize innovation linkages among cities in the YRD region.

Based on the patent search infrastructure of China's national intellectual property office, an analysis of the frequency of co-filed patent applications in the main urban areas of the YRD has been conducted over the past eleven years (2014-2025). In the patent applicant search field, we performed combined searches using the names of the 27 cities. Search results were defined as indicating a cooperative relationship between cities when the applicants included institutions, enterprises, or universities from more than two cities. Based on the search results, we compiled statistics on jointly applied patents among cities at yearly intervals from 2014 to 2025. After processing the statistical results, a total of 24,804 valid intercity innovation cooperation linkages were extracted, which were then used to construct a multi-valued undirected innovation network.

2.2 Research Methods

For social scientists, network theory represents a "gold mine" that offers rich explanations for social phenomena in economics [21]. Social network analysis (SNA), as an application and development of network theory within the field of sociology, is a method for investigating certain interdependencies among actors. It can systematically reflect the overall structural characteristics of an organization while also revealing the status and role differences of individual actors. By constructing and analyzing patent cooperation networks, researchers can examine how inter-organizational patent cooperation activities are conducted [22]. Inter-organizational patent cooperation involves multiple categories of actors and multi-level relationships. According to the annual patent cooperation data from 2014 to 2025, social network analysis will be employed to study the development of the structure of innovation links among key cities in the YRD region. Based on the above framework, each city that participated in the joint patenting was set up as a node, and the cooperation relationships among them were used to build a patent cooperation network for the YRD urban agglomeration. The annual networks are obtained from the corresponding cooperation matrices, and a set of indices is chosen to reflect changes in the structure of the innovation cooperation network over time; that is, network density, network centralisation, node centrality and core-periphery analysis.

2.2.1 Network density analysis

Network density measures the degree of interconnectedness among network members. For a fixed number of nodes, the greater the number of connections among them, the higher the network density, which in turn indicates closer ties among network members [23]. In the context of urban innovation cooperation networks, higher density signifies more active innovation cooperation among city nodes, stronger innovation linkages, and a greater influence of the network on the innovation behavior and capabilities of individual nodes. The density of a network is the ratio of the number of actual links in the network to the maximum number of links that can be formed in the network. The equation of this calculation is shown below.

$$D = \sum_{i=1}^{k}\sum_{j=1}^{k} m(n_i, n_j) \Big/ N(N-1) \quad (1)$$

where D denotes network density; N represents the number of nodes in the network; and $m(n_i, n_j)$ is the number of edges between node i and node j.

2.2.2 Overall network centralization analysis

One does not need to know how prominent a single vertex is in the graph; rather, one can also determine whether the whole network is likely to be pulled towards a common centre. Such an investigation [24] is based on the idea of network centralisation and measures the total centrality of the structure. This index shows how much all nodes are clustered around a single centre, and it has been divided into three types: degree centrality, betweenness centrality and closeness centrality.

Degree centralization quantitatively reflects the unevenness of the distribution of node centrality across the network by identifying the most central node within the network graph. It is calculated by measuring the differences between the centrality of a given node and that of other nodes in the network. A larger difference indicates a more uneven distribution of centrality among nodes, which in turn implies a higher degree of network centralization, suggesting that the network structure is likely organized around and radiating outward from the most central node. The calculation formula [25] is as follows:

$$C_{ad} = \sum_{i=1}^{n} (C_{ad}\max - C_{ad}i) \Big/ n^2 - 3n + 2 \quad (2)$$

where $C_{ad}i$ denotes the absolute degree centrality of node i, $C_{ad}\max$ represents the maximum value of absolute degree centrality among all nodes in the network, and n is the total number of nodes in the network.

In the analysis of the whole network, another index is betweenness centrality. A measure is obtained by comparing the betweenness centrality values of various nodes. There is a much larger difference etween the network's most central node and the others. A central structure is proposed, and it is connected to any other parts and thus depends on them. If too many nodes are used, then a number of small, ependent clusters will be formed. To transmit the links in all the sections, this component is needed to build the whole network. Centralisation of betweenness is expressed by the formula below.

$$C_b = \sum_{i=1}^{n} (C_{ab}\max - C_{ab}i) \Big/ n^3 - 4n^2 + 5n - 2 \quad (3)$$

Where $C_{ab}\max$ denotes the absolute betweenness centrality of the node with the highest value, $C_{ab}i$ represents the absolute betweenness centrality of node i, and n is the total number of nodes in the network.

Closeness Centralisation is an index of how spread out the nodes in a network are; a large index means that some nodes are far from others, and a small index indicates a more uniform distribution. The next is a formula for closeness centrality.

$$C_c = (2n-3)\sum_{i=1}^{n} (C'_{rc}\max - C'_{rc}i) \Big/ (n-2)(n-1) \quad (4)$$

where $C'_{rc}\max$ denotes the standardized absolute closeness centrality of the node with the highest value, $C'_{rc}i$ represents the standardized absolute closeness centrality of node i, and n is the total number of nodes in the network.

2.2.3 Network node centrality analysis

Centrality reflects the power and status of an individual node within the overall network. Centrality measures are important indicators for quantitatively assessing social network centrality, reflecting the magnitude of power held by a node in the network. Depending on the focus of analysis and the analytical perspective adopted, centrality measures can be further classified into several specific types, including degree centrality, betweenness centrality, and closeness centrality.

The total number of direct connections a particular node has in a network is referred to as the degree centrality of that node. Thus, one can determine the relative importance of a particular vertex in the local network by assessing how well it is positioned in its vicinity. The number of times a node appears in the shortest paths from other nodes is given by the betweenness centrality measure. A vertex is located between the two adjacent nodes and is called a bridge. Closeness centrality reflects how quickly one can reach all other nodes in the network. The extent of autonomy a network node has from outside influence is determined by how well it can form connections with other nodes. By adding up all the direct neighbours of a particular vertex, one can obtain its degree centrality value. Closeness centrality is determined by the distances from a node to all other nodes.

$$C_i = \sum_{j=1}^{n} d_{ij} \quad (5)$$

where Ci denotes the closeness centrality of node i, and d_{ij} represents the shortest path distance between node i and node j.

Betweenness centrality is calculated as follows:

$$M_i = \sum_{j}^{n}\sum_{k}^{n} F_{jk}(i) \Big/ F_{jk} \quad (6)$$

where M_i denotes the betweenness centrality of node i; $F_{jk}(i)$represents the number of shortest paths between node j and node k that pass through node i; and F_{jk} represents the total number of shortest paths between node j and node k, with $k \neq j \neq i$ and $j<k$.

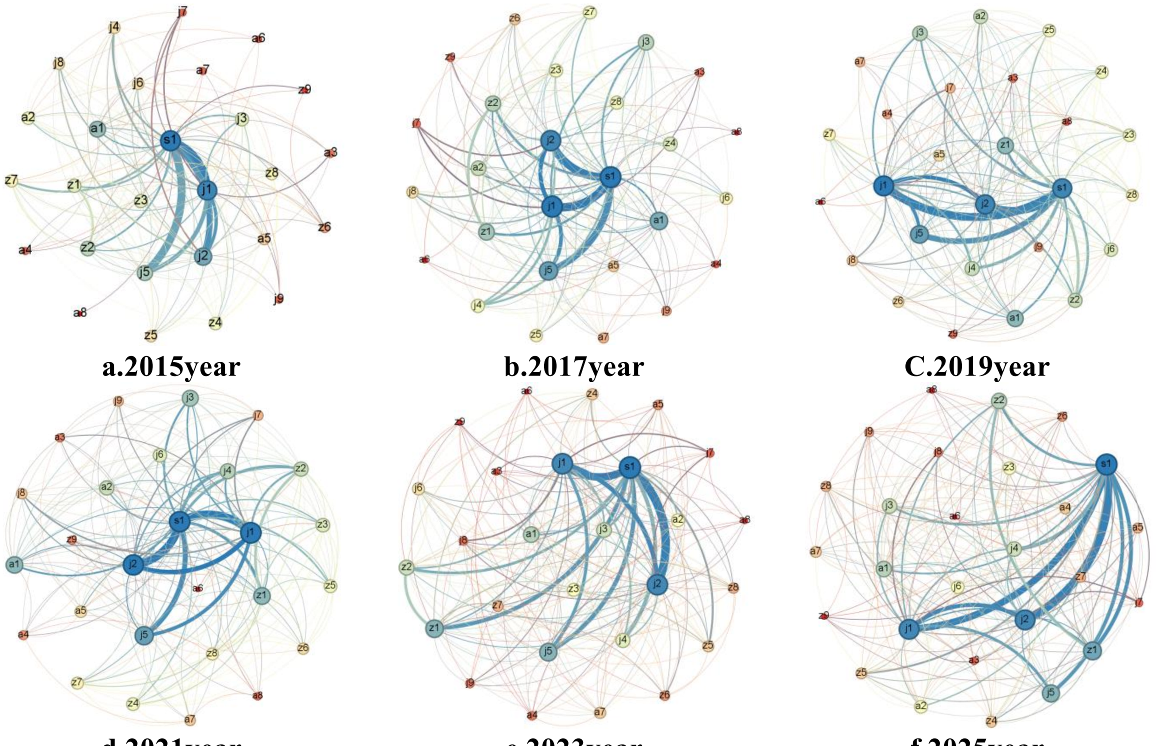
2.2.4 Core–periphery analysis

Based on the structure of a network, the core-periphery model can show the position of any specific node among the others. A node's position in the network is determined by how important it is and how often it is connected to other nodes; therefore, nodes near the centre of the network generally have more access or influence. Strengthen their bargaining power and exert better control over the good assets at hand. At the top and bottom are continuously added to obtain the coreness values for all nodes in the network. According to the collaborative innovation framework of the YRD metropolitan area, the contributions of all the cities are listed below. Analysis of the Clustering of Key Urban Nodes in the YRD Innovation System is shown below. The two types of membership in a partnership system are general and special.

3. Structural Evolution Characteristics of the Network

3.1 Overall Network Structure Evolution

Using the Network Science Service (NSS 2.2) software, we calculated the overall network structure characteristic values of the innovation cooperation network in the YRD urban agglomeration from 2014 to 2025. Visualization was performed using Gephi 0.9.2. The results are presented in Table 1 and Figure 1. In the Figure 1, each node city is labeled with an alphanumeric code (letter + number). Specifically, Shanghai is coded as s1; cities in Zhejiang Province are coded sequentially as z1 (Hangzhou), z2 (Ningbo), z3 (Wenzhou), z4 (Shaoxing), z5 (Jiaxing), z6 (Jinhua), z7 (Taizhou), z8 (Huzhou), and z9 (Zhoushan); cities in Jiangsu Province are coded as j1 (Nanjing), j2 (Suzhou), j3 (Wuxi), j4 (Nantong), j5 (Changzhou), j6 (Yangzhou), j7 (Yancheng), j8 (Taizhou), and j9 (Zhenjiang); and cities in Anhui Province are coded as a1 (Hefei), a2 (Wuhu), a3 (Chuzhou), a4 (Anqing), a5 (Ma'anshan), a6 (Xuancheng), a7 (Tongling), and a8 (Chizhou).



a.2015year b.2017year C.2019year

d.2021year e.2023year f.2025year

Figure 1. Structural Evolution of the Urban Innovation Network in the YRD, 2015–2025.

The urban innovation network of the YRD is modeled as an undirected weighted network (i.e., a multi-valued network) with a fixed set of 27 node cities. The general network structure in the six time steps can be described by the following three macro indicators: the total number of edges, the average degree of nodes, and graph density. Over the time period considered, the network's connectivity has been on the rise steadily, and the total number of links has increased from 306 to 438, up by about 43.1%, adding around 26.4 new links each period. A gradual increase shows that the relationship has been gradually strengthened, giving more chances for interaction among the people and adding new colour to the existing ties. The total interaction weight in 2021 was about the same as in 2019 (around 400-410), so there was little change between the two years. However, since 2021, the speed of development has increased substantially; the total strength has reached 428 from 410, an increase of 18 units, and although it briefly stagnated around 2021, it has been on the rise again in recent years. The average strength of the network increased from 11.333 to 16.222, and with the same number of nodes, the average weighted connection sum of each node rose by about 43%; therefore, the exchange of innovation resources and dissemination of information in the urban network has been enhanced to some extent. Increase it from 0.436 to 0.624, and the index of interconnectedness among urban nodes—which shows the overall strength of links—has reached a level where the mean of pairwise connections exceeds 60% of the theoretical upper bound; thus, it can be concluded that the whole system is highly connected and has a high degree of linkage.

Based on extended observation, it has been discovered that the total connectivity among the 27 nodes in the urban area network is constantly growing, and at the same time, the average strength of these nodes has increased by 43 per cent; therefore, the level of innovation collaboration in the YRD region has moved from "medium-strength ties" to "strong ties", leading to more frequent cross-city knowledge sharing and an intensification of cooperation among cities.

Table 1. Structural Characteristics of the Urban Innovation Network in the Yangtze River Delta

Network Indicator	2015	2017	2019	2021	2023	2025
Number of ties	149	153	153	151	141	136
Average degree	11.037	11.333	11.333	11.185	10.444	10.074
Network density	0.425	0.436	0.436	0.430	0.402	0.387
Degree centralization	0.539	0.485	0.485	0.532	0.605	0.662
Betweenness centralization	0.183	0.105	0.109	0.120	0.185	0.219
Closeness centralization	0.602	0.528	0.537	0.611	0.686	0.775

After 2016, the centralization index of the urban innovation network in the YRD rose from 0.485 to 0.662; this indicates that some cities have become more dominant, their links with other cities have strengthened, the spread of node importance has been increasingly uneven, and most urban areas are now centred around a few essential hubs.The betweenness centralization has also increased steadily since 2016, from 0.105 to 0.219, indicating that local clustering among node cities in the YRD urban innovation network has been intensifying, and the strategic importance of certain node cities has been growing over time. Similarly, the closeness centralization of the YRD urban innovation network has risen from 0.528 to 0.775 since 2016, reflecting growing differentiation among node cities and their increasing independence from one another.

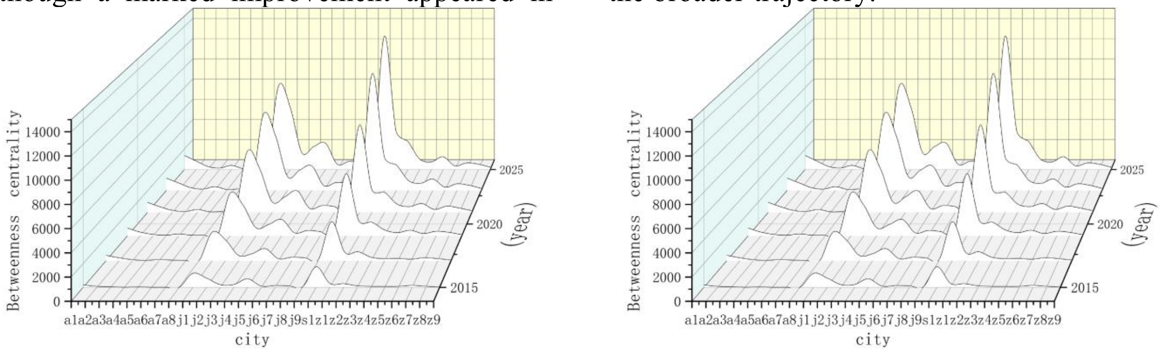
3.2 Ego-network Structure Evolution

NSS 2.2 is employed to conduct an analysis of the undirected network of innovation. The Yearly Pattern of Inter-City Cooperation in the Delta Region of the Yangtze River. Centrality measures for all vertices in the graph have been calculated over the period from 2014 to 2025.

3.2.1 Degree centrality

The degree centrality of the YRD urban innovation cooperation network is presented in Figure 2.

In terms of degree centrality of the innovation cooperation network in the YRD urban agglomeration, the total sum of node degrees increased steadily from 6,666 to 8,578 between 2015 and 2023, representing a growth of 28.7%. From 2015 to 2023, the aggregate connectivity of the network underwent steady expansion, as evidenced by the mean connections per node rising from 246.9 to 317.7—an average gain of roughly 71 new links for each vertex. Within this system, Shanghai consistently served as the dominant hub, exhibiting a nodal weight that surpassed all others by a factor of three to six relative to the average across Jiangsu Province's cities; it reached a maximum of 3,021 in 2023 before subsequently decreasing. For Jiangsu Province, the overall intensity of collaborative innovation remained comparatively high, with mean values clustering between 400 and 500, and with Nanjing and Suzhou demonstrating notably elevated levels. In Zhejiang Province, cooperation intensity was moderate (spanning 150 to 280) and followed an inverted-U pattern—first rising then falling. Anhui Province recorded the weakest innovation ties with other YRD cities (ranging from 50 to 90), although a marked improvement appeared in 2023. When examining degree centrality (vertex strength) across the entire network, total network strength exhibited continuous growth over the nine-year period, with Shanghai acting as the absolute focal point whose intensity fluctuations largely dictated the broader trajectory.



a. Single Year **b. Cumulative Network**

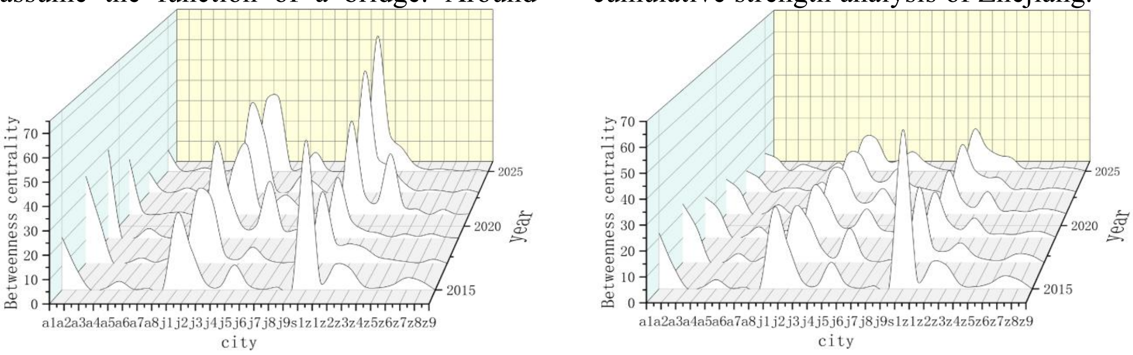
Figure 2. Degree Centrality of the Innovation Cooperation Network in the YRD Urban Agglomeration

According to the analysis of the innovation cooperation network, the total weighted connectivity (the sum of all node strengths) has been rising at an increasing rate, going from 6,666 to 54,853 and multiplying by 7.2. The annual contributions were 7,283, 8,760, 10,234, and 11,031 in consecutive years, and then dropped slightly to 10,879 in 2023-2025; thus, the overall level of participation peaked around 2023 and has been declining gradually since then, though it remains relatively high. The mean annual growth rate has risen from 3641 to 5515 (an increase of 51%), and thus the speed of total accumulation is also picking up pace. In light of the above, Shanghai will lead the country with 13,056 cases by 2025. Zhejiang had the highest relative expansion rate (774%); that is to say, its constituent cities became relatively more active later, but its absolute total did not exceed that of Jiangsu. Anhui started from a low base and has remained in the outer ranks. In short, the total connection weight of the network is an upwardly curved function, and the rate of increase is also rising.

3.2.2 Betweenness centrality

Betweenness centrality is a measure of how often a particular node appears on the shortest paths between all other pairs of nodes, and it indicates that node's capacity to distribute information or resources in a network. Figure 3 is the development and cumulative development of this index for individual cities in the urban innovation collaboration network of the YRD from 2015 to 2025.Therefore, the nodes with higher scores are given more weight in the coordination and control, and they appear more frequently in the essential intermediate links of these geodesic paths.

According to the analysis of the Yangtze River Delta's urban innovation cooperation network, both the aggregate betweenness centrality values and their arithmetic means showed little change over time and were always in the narrow range of 189 to 206. It did not change either way, so the total dependency of the system on the nodes acting as intermediaries was still the same. Although the overall amount of the cumulative sense of the network's total degree strength has increased, its proportion to the total strength of betweenness centrality has gradually fallen, from 0.0302 to 0.0036. Therefore, as the total connectivity of the nodes has grown, more direct links have been added, and thus the demand for intermediate bridge paths has decreased accordingly. Therefore, the network was relatively short and did not have many links. Throughout this time, Shanghai has maintained its position as the leading intermediary with a much higher betweenness centrality than all other countries; it was 62.57 in 2015 and has risen to 65.84 by 2025. Although there were fluctuations in the amount, the lowest points were in 2017 and 2019, and then it rose again; however, other cities did not take over Shanghai's role as an intermediary. Among the urban areas in Jiangsu Province, the average level of betweenness centrality was relatively high in 2019 at 12.04; however, it has since fallen to around 9-10 and is now lower than that in Anhui and Zhejiang. It can be seen that Nanjing and Suzhou have continued to function as important secondary links in the network. The values of the betweenness centrality for Anhui Province and Zhejiang Province were generally low, mostly less than 10. Anhui had a relatively high figure of 7.59 in the early years, 2015-2017, and then it dropped significantly in the following period. This pattern is characteristic of the early period when the network was sparse; at that time, only a few cities were connected, and thus they had to assume the function of a bridge. Around 2021, the cities in Zhejiang had seen an increase in their mean of betweenness centrality to about 5.94, and some of these municipalities began to take on additional connection functions at that time. Wenzhou was the clear exception; in 2021, it reached a high of 27.86, and the surrounding years were much lower, so it served as an interim link that year before being replaced by more direct links. Both Hangzhou and Ningbo have increased their betweenness centrality, and Hangzhou has risen significantly from 3.36 to 18.54; both cities are now becoming new, important intermediaries. It can be concluded that a "catch-up effect" has also occurred in the cumulative strength analysis of Zhejiang.



a.Single Year **b.Cumulative Network**

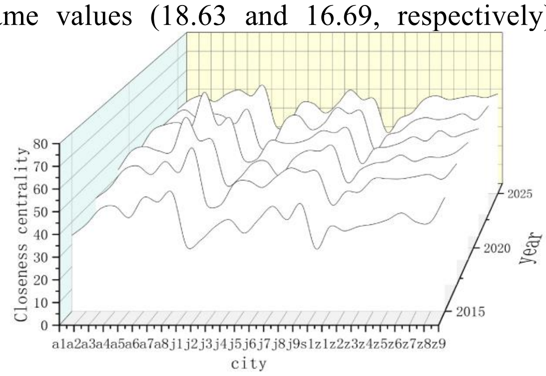
Figure 3. Betweenness Centrality of the Innovation Cooperation Network in the YRD Urban Agglomeration

By 2019, the mean of the betweenness centralities of urban areas in Zhejiang was 12.04, and high values were also achieved in Nanjing, Changzhou and Hefei. It was not the same as in 2015-2017; the network was less connected, bridge centrality was concentrated in only a few cities—Shanghai, Nanjing, Suzhou and Hefei—and surprisingly, Hefei had a relatively high degree of intermediacy and showed a dumbbell structure that depended on a small number of connecting links because it was located on the periphery. At the beginning, there was an increase in bridge functionality with many cities acting as relay stations; this stage reached its peak in 2021 when Wenzhou's centrality index was relatively high and that of Hefei fell; at this time, old bridging functions decreased and new, temporary ones began to appear. At this time, many relay stations were built to meet the demands of construction. The distribution of centrality has been relatively stable from 2023 to 2025; the top three core intermediaries are still Shanghai, Nanjing and Suzhou, and although Hangzhou and Ningbo have increased their ranks, Anhui and most cities in Zhejiang have dropped to a very low or negligible level. This development shows that the number of links has decreased, so fewer links are required; thus, it is no longer necessary to go through an intermediate city. Therefore, the flow of information is less dependent on a few control nodes, and the key bridging functions are highly concentrated and stable; thus, the network has become more direct overall.

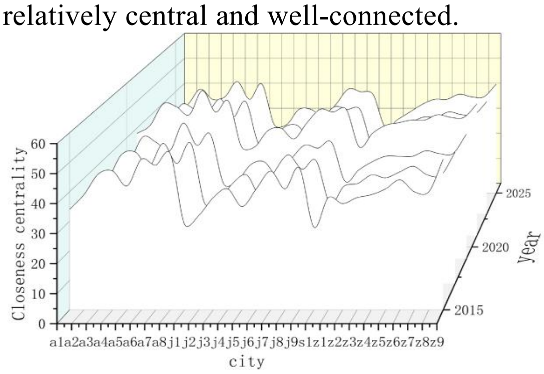
There was a continuous drop of 17.3% in the cumulative betweenness centrality aggregate; it fell from 201.2 to 166.5, and the annual value remained unchanged during this time. Therefore, with the continuous and extensive construction of networks in recent years, most data transmission no longer needs to pass through many intermediate nodes. At the same time, the total cumulative strength reached 54,853 from 6,666, and thus the betweenness-to-strength index dropped from 0.0302 to 0.0030; this change shows that the structure has moved away from a sparse, bridge-dependent type and is moving towards one with many direct links. Among the cities, Shanghai was one of those that saw a considerable decrease in total betweenness, dropping by roughly two-thirds from 62.57 to 19.19. Although it is still the highest in terms of betweenness centrality for the whole network (about 19 by 2025, well above the average of other groups), it is no longer a hub. The average betweenness of the cities in Jiangsu Province dropped only slightly from 7.48 to 6.29 (a decrease of 15.9%), and they remained in the 6-7.5 range; therefore, it can be concluded that these cities retained a relatively stable bridging function and were not entirely replaced. In contrast, the cities in Anhui Province did not continue to function as bridges for long after the initial expansion of the network. The mean betweenness centrality of Zhejiang Province fell from 4.31 to 3.55, but a small increase was observed between 2023 and 2025 (from 3.36 to 3.55). In the early cumulative period (2015-2017), Shanghai, Nanjing, Suzhou and Hefei had very high betweenness centrality; Hefei's fell sharply from 23.67 to 8.21, and thus lost its bridging advantage. Only one node had a prolonged and considerable increase in cumulative betweenness, which was Hangzhou; it rose from 3.36 to 10.97, and as the network gradually thickened, Hangzhou also assumed more positions of structural holes. Notably, from 2021 on, Nanjing and Suzhou had the same values (18.63 and 16.69, respectively) and had also reached full parity in the cumulative network. The first few are: With the increase in general network density, the total dependence on intermediate nodes has gradually decreased (the total betweenness dropped by 17%), and the structure of the network has changed from one centred around a few gatekeepers to one with many direct, multi-path connections. In addition, the correlation between cumulative degree centrality and cumulative betweenness centrality decreased over time; although the two were relatively close at the beginning (many active nodes also needed to be links), later on they started to diverge, for example, Hefei had a large degree and a small betweenness, while Hangzhou had a small degree but a considerable betweenness. The above divergence indicates that the general form has been changed from a central-radiating type to a multi-centre mesh.

3.2.3 Closeness centrality

Figure 4 is the development (annual and cumulative) of closeness centrality for municipalities in the joint innovation network of the YRD from 2015 to 2025. A measure of how central a city is and how quickly information can spread in a network is given by the inverse of the average shortest path distance from a node to all other nodes. Therefore, a high score shows that the city is relatively central and well-connected.



a. Single Year



b. Cumulative Network

Figure 4. Closeness Centrality of the Innovation Cooperation Network in the YRD Urban Agglomeration

Overall, the mean closeness centrality in the graph rose from 42.52 in 2015 to 49.22 in 2017 and then fluctuated between 48 and 50. The first reduction in the mean distance of the nodes was due to early compression, and then it did not change much. The highest closeness values, from 45 to 54, were always obtained for cities in Anhui Province, and these were closest to the centre of the network. The highest score for the interior node Xuancheng in 2021 was 71, and it was the main topological center at that time. At the same time, the mean closeness centrality of Jiangsu's cities rose from 38 to 47, the highest increase (plus 8.89) among all provinces.

According to the network data, it can be seen that over the course of the research, cities in Jiangsu Province have moved closer to the centre, but their recorded values have been lower than those in Anhui and Zhejiang. They are called "long-range hubs", so they have high strength and betweenness centrality but relatively low closeness centrality. Shanghai has the highest strength and betweenness centrality in the whole network, but it has the lowest closeness centrality, at 28 to 37. As it is in the periphery, it is expected to be a "power centre" of the system rather than a "geographic centre". At the same time, the urban areas of Zhejiang Province had moderate closeness centrality values (between 41 and 49) and an increase of 7.55 points; thus, these cities had improved their geometric centrality in the later period. When calculating the cumulative closeness centrality average, the result is a fluctuating path: it started at 42.52 in 2015, fell to 39.15 by 2019, rose to 43.81 in 2021, and then dropped significantly to 37.41 in 2025; that is to say, it decreased first, then increased, and finally fell sharply.

3.3 Core–Periphery Structure Evolution

A cluster of closely connected nodes is in the middle, and there is an outer fringe. Ucinet 6.0 was used to study a group of nodes that are not well connected to each other. Core-Periphery Analysis of the Collaborative Innovation Structure in the YRD was Conducted. Figure 5 shows the results of the analysis for the urban cluster in the period from 2014 to 2025.

Research has been carried out on the interaction of the central and peripheral areas and the network structure of the YRD in the collaborative innovation system. It has been observed that the main cluster of the YRD metropolitan area generally has 12 nodes and accounts for a certain proportion. After 2023, the number of nodes dropped to eleven, down from 115 in 2015-2021.

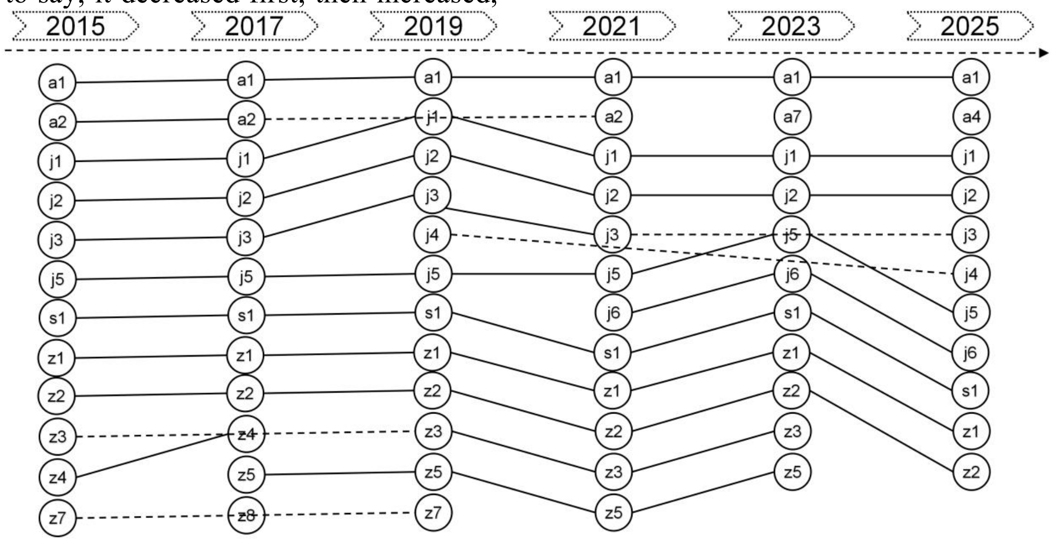


Figure 5. Core–Periphery Distribution of the Urban Innovation Network in the Yangtze River Delta

The core consistently comprised less than half of all nodes, indicating a clear core–periphery stratification within the network, though the core layer is not extremely exclusive. Shanghai was classified as a core member in all years, which is fully consistent with its cumulative eigenvector centrality remaining constant at 1.In Anhui Province, the core members shifted from Hefei and Wuhu in the early period to Hefei plus one additional node (either Tongling or Anqing) in the later period. Hefei is the only city in Anhui Province that remained a core member throughout the entire observation period. Jiangsu Province had the largest number of core members among all provinces, reaching six in both 2021 and 2025, accounting for two-thirds of the province's total.The number of core members in Zhejiang Province fell from five to two; only Hangzhou and Ningbo remained, and the early-stage participants Wenzhou, Shaoxing, Jiaxing, Taizhou and Huzhou were subsequently excluded. Based on the above, it can be concluded that Hangzhou and Ningbo have been improving over time, unlike other cities in Zhejiang. Changzhou's own centre had some considerable instability.

All six observed periods had the same set of seven cities in the inner ring: Hefei, Shanghai, Nanjing, Suzhou, Hangzhou, Ningbo and Wuxi.

The above urban areas can be regarded as the framework for the central area. On the other hand, a number of other cities joined this group at different times: Wuhu, Shaoxing, Taizhou, Huzhou, Jiaxing, Nantong, Yangzhou, Anqing, and Tongling each appeared at a specific time. At this time, four new participants have been added: Nantong (starting in 2019), Yangzhou (2021), Tongling (2023) and Anqing (2025), and some of the former peripheral nodes have been gradually included in the core. Conversely, some cities that were previously included have now been dropped; Wuhu, Shaoxing and Taizhou have all left after 2019, and Jiaxing and Wenzhou left in 2025. Therefore, the proportion of Zhejiang Province in the core is declining gradually, and eventually, only Hangzhou and Ningbo will remain. Based on the change in the composition of the membership, Jiangsu Province increased its share to six members in the later stage and accounted for more than half of the total core. Zhejiang, on the other hand, declined steadily and fell from the initial five to only two. Anhui Province had a small number of intermittent participants and was not well-supported by the organisation. Shanghai is a single-node province; therefore, it has never left its original place at any time.

The basic section is relatively stable over time, provides the foundation for the network, and can be seen in the table of core-periphery membership. Node assignment to the core or the periphery is based only on whether there is a binary connection and does not consider the weight of weighted ties or eigenvector centrality. Hefei has a relatively low strength in weighted ties but a high binary degree, meaning it is connected to many nodes; thus, it has been named a core member. Similarly, Wuxi has only moderate prestige (eigenvector centrality) but also shows a high degree in the binary network and is therefore considered a core member. Therefore, it can be seen that prestige and membership in a structural core are not in alignment; Shanghai is high in both, and Hefei is a representative case of a 'low-prestige but high-connectivity' topological core. Based on the above observations, it can be inferred that there is a "separation of power centres and connectivity centres". Furthermore, longitudinal analysis of the core-periphery membership table shows that the core layer is relatively stable and constitutes the structural basis of the network. In addition, the core-periphery division does not perfectly align with eigenvector centrality; for example, Hefei has low prestige but a high degree, so it can be included in the core, and Changzhou has high prestige but a relatively low degree, so it may be excluded from the core at a later time.

4. Conclusion and Discussion

4.1 Research Conclusions

Social network analysis will be employed in this paper to study changes in structure and space. Changes in the time of cooperative innovation links among the 27 urban areas in the YRD will be studied, and as thriving innovation ecosystems depend on the continuous participation of members, knowledge sharing and mutual development are also necessary; these interactions create a network of relationships that drives the whole group forward. Based on the above data, there is a clear pattern in the cooperation network of the YRD urban cluster: the horizontal connections are strong, but the vertical connections are relatively weak; that is to say, patent-based collaborations originating from Shanghai, Suzhou, Nanjing and Hefei form the structural core of this network. Second, although the network has been expanding steadily and is now quite large, the development of these collaborative relationships is not uniform; clustering around key node cities has increased significantly, and at the same time, the nodes themselves have grown more differentiated and independent, resulting in a pronounced small-world structure. Third, Shanghai has continuously taken the lead in regional innovation cooperation and has been a long-standing base for spreading knowledge and carrying out collaborative activities across the YRD. Fourth, cities in Anhui Province and some outlying municipalities in Jiangsu and Zhejiang have not been fully included in these cooperative networks and have made little contribution to the coordinated development of the region.

4.2 Policy Recommendations

To promote the development of a high-end and integrated innovation ecosystem in the Yangtze River Delta, the catalytic role of the first-tier cities, Shanghai, Suzhou, Nanjing and Hefei, needs to be strengthened systematically, and they should be developed as concentrated innovation bases to drive the entire network. Therefore, not only do we need to reconstruct the foundation of the knowledge-sharing network, but also carry out deep-rooted reforms in the institutional system for inter-city cooperation to achieve an all-weather, high-quality pattern of regional innovation integration. In line with the general direction of the country, the delta should make full use of its strengths in concentrated platforms, skilled personnel and technological resources to jointly build shared innovation platforms, carry out collaborative basic research and academic exchange, achieve technological breakthroughs, and strengthen collective problem-solving abilities. Open, synergistic and highly efficient resource-sharing mechanisms should be established to promote the healthy flow of innovation factors, awaken the dormant innovation potential in more distant and smaller municipalities, accelerate the dissemination of these factors, and achieve both horizontal and vertical diffusion of knowledge. Therefore, the central area will not be included in the stages of the delta innovation system. Increase the proportion of investment in research and development to strengthen the research and development capabilities of the cities, improve urban infrastructure, especially cross-city transportation and communication links, promote the flow of innovation resources, quickly solve market and institutional bottlenecks among municipalities, and reduce transaction costs for collaborative innovation. Increase the emphasis on strengthening the homegrown innovation strength of secondary and peripheral urban areas, build a diversified and high-quality regional innovation system, and promote more equitable distribution of innovation capacity in all areas of the Yangtze River Delta.

Acknowledgments
This study was funded by the 2021 Special Project for Science and Technology Innovation Strategy and Soft Science Research of Anhui Province (Grant No. 202106f01050046).

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