Characterisation of the homogeneous development of hub airports in the Yangtze River Delta airport cluster

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ABSTRACT

To reasonably analyze and position the development pattern of the Yangtze River Delta Airport Cluster, and to form a differentiated development with reasonable allocation of resources, a similarity coefficient calculation model is constructed. This model considers the factors of the cities where the airports are located and the airport route networks to analyze the homogeneous development characteristics among the hub airports of the Yangtze River Delta airport cluster. Firstly, a similarity coefficient evaluation index system is constructed. Then, the similarity coefficient method is used to analyze the similarity coefficient between airports under each measurement index. Finally, the comprehensive similarity coefficient is calculated by the comprehensive empowerment evaluation method to comprehensively evaluate the degree of homogenization of the development of airports. The results show that: 1. The flight frequency factor between airports, i.e. the number of flights on routes with the same destination, has the greatest influence on the homogeneity between airports. 2. Hangzhou and Ningbo have the greatest degree of homogeneity due to the proximity of their airports and their comparable airport sizes. 3. The airports of Hefei and Wenzhou do not constitute an undeniable homogeneous competitive relationship. The research results provide a reference basis for promoting the high-quality development of civil aviation and the differentiated and linked development of the Yangtze River Delta airport cluster.

Keywords: Hub airports, Airport clusters, Route networks, Similarity coefficients, Homogenisation

1. Introduction

With the continuous development of China's city clusters, the scale of airport clusters has been increasing, and airport clusters formed on the basis of city clusters have become an important research topic in China [1]. As an important transport hub of the country [2], the Yangtze River Delta (YRD) airport cluster has an important impact on the promotion of domestic and international trade, investment, and tourism. At the policy level, the 2020 Plan for Higher Quality and Integrated Development of Transport in the Yangtze River Delta Region explicitly proposes to build a synergistic and connected world-class airport cluster. The 2022 "14th Five-Year Plan for the Development of a Modern Comprehensive Transportation System" re-emphasizes the importance of promoting the synergistic development of regional airport clusters, and the construction of a world-class airport cluster such as the Yangtze River Delta. In 2022, the "14th Five-Year" Modern Comprehensive Transport System Development Plan again emphasized the promotion of the synergistic development of regional airport clusters and the construction of world-class airport clusters such as the Yangtze River Delta. However, despite increasing policy support, the YRD airport cluster still faces a number of challenges in achieving its ambitious goals. Optimizing the route network structure is the basis for building a world-class airport cluster. Compared with mature international airport clusters, the YRD Airport Cluster has a big gap in terms of hierarchical structure and synergy [3], and the internal competition of the YRD Airport Cluster is fierce, with the isomorphism of the route network remaining high among the four major airport clusters [4]. This is mainly due to the high duplication rate of the route networks of the hub airports, resulting in the phenomenon of serious homogenization of routes [5]. This situation not only affects the ability of the whole YRD airport cluster to form synergies [6] but also reveals the insufficiency of the structural complementarity of the route network, which needs to be further optimized.

Each airport cluster is likely to be highly homogeneous in terms of airport capacity, level of operations, and route network. Therefore, there will be intense competition in the aviation market and it is important to assess the level of homogeneity of airport clusters [7]. Identifying the homogenization problems among the hub airports of the Yangtze River Delta airport cluster will lead to a more scientific and reasonable promotion of their coordinated development [8]. In recent years, many researches have been started about airport clusters.

(1) From the perspective of factors affecting competition among airports: by studying airports geographically located within airport clusters, the key factors of airport competition (fares, connectivity characteristics, punctuality) [9,10] were identified or the interrelationships between airport clusters and airports were measured [11,12].

(2) From the perspective of coordinated development of airport clusters: studying the homogeneous aviation market [13] and network competition [14,15] of regional airports within airport clusters is of great significance to the coordinated development of airport clusters. Suggestions for the development of Beijing Daxing Airport in the Beijing-Tianjin-Hebei Airport Cluster are put forward in terms of using shared data to promote law enforcement coordination and improving the legal management of airport management agencies [16]. The positioning of airports in the Yangtze

River Delta airport cluster is distinguished from the perspective of passenger throughput to promote the coordinated development of airports [17]. Taking California's world-class airport cluster as an example, its hub airports are reasonably differentiated according to the four circles to achieve the coordinated development of the airport cluster [18].

Although there has been some research on the degree of development homogeneity between airports in airport clusters, there are fewer homogeneity evaluations focusing on the homogeneity between hub airports. In this paper, we take the seven Yangtze River Delta airport clusters from the perspective of hub airports within regional airport clusters and improve the calculation of spatial coefficients with the minimum threshold method by drawing on the research results of Jiang Yonglei [19]. Considering the factors of the airport city aspect and route network aspect, calculates the comprehensive similarity coefficient of the homogeneous development of airports within the regional airport cluster and constructs the homogeneous network of regional hub airports based on the derived comprehensive similarity coefficient, and carries out the analysis of the structural characteristics of the homogeneous network of regional airports with the complex network theory to derive the homogeneous features of hub airports of the Yangtze River Delta airport cluster.

2. Research Methodology

In order to study the degree of homogeneity of the development of airports in the region, firstly, the similarity coefficients of cities and routes are calculated, and the similarity coefficient method [20] is used to analyze the degree of similarity of the development of the two airports under each index;

secondly, the comprehensive empowerment evaluation method [21] is used to assign weights to each index, and a comprehensive similarity coefficient is derived, thus reflecting the degree of homogeneity between airports; then, the airport homogeneity network between hub airports in the Yangtze River Delta is constructed according to the derived comprehensive similarity coefficient. The homogeneity coefficient between airports is then used to construct the airport homogeneity network between hub airports in the Yangtze River Delta airport cluster; finally, the homogeneous development characteristics between airports in the entire Yangtze River Delta region are analyzed according to the complex network theory [22].

2.1 Objects of Study and Selection of Indicators

(1) research object

In recent years, due to the impact of the pandemic, China's civil aviation sector has faced significant challenges. The civil aviation data post-2020 do not accurately reflect the normal development level of homogeneity among the Yangtze River Delta Airport Group's hub airports. Therefore, this paper selects the 2019 data for analysis. According to the 14th Five-Year Plan for Civil Aviation Development, excluding Hong Kong, Macao, and Taiwan, there are 40 hub airports in China, with 39 located in hub airport cities (Shanghai has two hub airports). As of 2021, according to the Outline of the Yangtze River Delta Regional Integration and Development Plan issued by the State Council, the Yangtze River Delta airport group comprises 23 airports, including 7 hub airports:

Shanghai Pudong Airport, Shanghai Hongqiao Airport, Hangzhou Xiaoshan Airport, Nanjing Lukou Airport, Ningbo Lishe Airport, Hefei Xinqiao Airport, and Wenzhou Longwan Airport. In 2019, the passenger throughput of the 7 hub airports in Shanghai, Hangzhou, Nanjing, Ningbo, Wenzhou, and Hefei accounted for 86.4% of the total in the Yangtze River Delta region, with the remaining 16 airports accounting for only 13.6%. Therefore, these 7 hub airports are sufficiently representative for a homogeneity evaluation study, making them the focus of this research.

(2) system of indicators

This study focuses on seven hub airports in the Yangtze River Delta airport cluster, with a specific focus on the airports in Shanghai. Following a hierarchical analysis approach, two primary indicators and six sub-indicators are used to calculate the homogeneity coefficient of the hub airports, namely, the primary level is the overall similarity coefficient among the hub airports (W). The criteria include the airport's host city factor (C1) and base scale (C2), and the indicators consist of the city's GDP (S1), population size (S2), economic outward orientation (S3), total flights (S4), total passenger traffic (S5), and total cargo and mail traffic (S6) as illustrated in Figure 1.

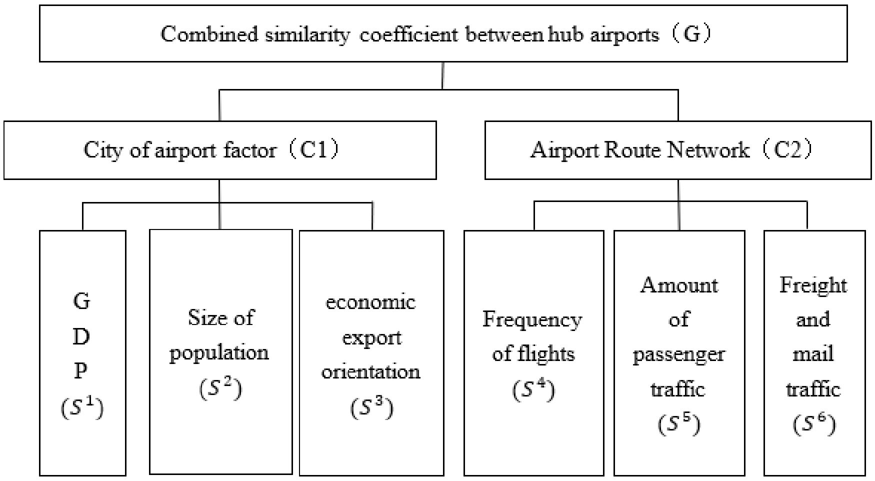

Figure 1. Indicator system map

Source: By authors.

1) Airport city factors, airport development, and the level of development of the hinterland city are closely related [23], the airport cluster system is also often accompanied by urban agglomerations, and the level of development and resources of the airport city plays a great role in the development of the airport, so the airport city factors have a great impact on the homogenization of airports. The level of city development is measured from three aspects: economic development level, social environment level, and foreign exchange level -- city GDP is chosen as an indicator to reflect the level of economic development of the city, and the resident population of the city is chosen as an indicator to reflect the level of social environment, and the degree of economic outward orientation of the city is chosen as an indicator to reflect the level of foreign exchange.

2) Airport route network, the development level of airports is mostly measured from the two aspects of airport output and operation scale [24], and the similarity of these two aspects is an important judgment factor of airport homogeneity. Therefore, the number of flights on navigable

routes is selected as an indicator reflecting the level of airport output, and the number of passengers transported on navigable routes and the amount of freight transported are selected as indicators reflecting the scale of airport operation. As of 2019, the Yangtze River Delta airport cluster has 177 domestic navigable cities, connecting most of China's provincial capitals and important provinces and cities [25]. This study collects route data between the 39 hub airport cities and evaluates the level of homogeneity between these seven airports by analyzing the route data from each of the seven hub airports in the Yangtze River Delta airport cluster to other hub airports.

2.2 Similarity coefficient based on spatial distance

The development of hub airports in a region is not only related to the current status of socio-economic development of the city in which they are located and the route scale of the airport but also closely related to the spatial distance between the hub cities [26]. Therefore, on the basis of the similarity coefficient, the spatial distance between hub airports is taken into account to calculate the spatial distance weighting coefficient between hub airports and airports, so as to further measure the degree of homogeneity of airport development. The formula for the spatial distance weight coefficient is calculated using the minimum threshold method, as shown in equation (1):

$$\delta_{ij} = \frac{d_{min}}{d_{ij}} \tag{1}$$

δ_{ij}: denotes the spatial distance weighting factor between hub airport i and hub airport j in the region;

d_{ij}: denotes the segment mileage between hub airports i and j, measured using the Great Circle Mapper tool;

d_{Min}: Indicates the furthest and closest segment mileage between the hub airport and the hub airport.

Considering the economic development of the cities where the hub airports are located and the air routes served by the airports in the YRD region, two similarity coefficients are used for the calculation of the city aspect and the air route aspect, respectively, and the formulas are shown in Eq. (2) and Eq. (3):

$$S_{ij}^{v} = \delta_{ij} \times \left[1 - \frac{\left|g_i^v - g_j^v\right|}{g_i^v + g_j^v}\right] \tag{2}$$

$$S_{ij}^{m} = \delta_{ij} \times \frac{\sum_{k=1}^{n} \left(X_{ik}^{m} \times X_{jk}^{m}\right)}{\sqrt{\sum_{k=1}^{n}(X_{ik}^{m})^2 \times \sum_{k=1}^{n}\left(X_{jk}^{m}\right)^2}} \tag{3}$$

S_{ij}^{v}: denotes the similarity coefficient between hub i airport cities and hub j airport cities under the v indicator in the region;

S_{ij}^{m}: denotes the similarity coefficient between hub i and hub j airports under m metrics in the region;

X_{ik}^{m} , X_{jk}^{m}: denotes the share of m-indicator values for the kth sector of the i(j) hub airport.

S_{ij}^{v} , S_{ij}^{m}: Takes values between 0 and 1. Larger values indicate a higher degree of similarity between the two airpors. S_{ij}^{v}, S_{ij}^{m}=0, the development of the two airports under the m indicator is not similar at all; S_{ij}^{v}, S_{ij}^{m}>0.3, there is homogenization between the two airports.

2.3 Comprehensive Empowerment Approach

The results of similarity coefficients calculated under different indicators selected in terms of cities and routes are different, so it is necessary to use the comprehensive weighting method to calculate the corresponding weights of each indicator, so as to accurately analyze the degree of homogeneous development among hub airports in the airport cluster region. The steps of the comprehensive assignment method are as follows:

(1) The difference-driven method is used to calculate the weight of indicator m for the similar system of hub airports i and j:

$$W_{ij}^{m,\ c} = t_{ij}^{m} \Big/ \sum_{k=1}^{m} t_{ij}^{k} \tag{4}$$

$t_{ij}^{m} = \sqrt{\frac{1}{m-1}\sum_{k=1}^{m}\left(S_{ij}^{k} - \bar{S}_{ij}\right)^2}$, $\bar{S}_{ij} = \frac{1}{m}\sum_{k=1}^{m} S_{ij}^{k}$ are the standard deviation and mean of the similarity coefficients for airports i and j, respectively.

(2) The function-driven approach is then used to calculate the weight of indicator m for similar systems at airports i and j:

$$W_{ij}^{m,\ g} = S_{ij}^{m} \Big/ \sum_{k=1}^{m} S_{ij}^{\bar{k}} \tag{5}$$

(3) Solve the following equation to determine the composite weight $w_{ij}^{m} = k_1 w_{ij}^{m,\ c} + k_2 w_{ij}^{m,\ g}$, and finally calculate the composite similarity coefficient between two two airports $S_{ij} = \sum_{ij}^{m}(w_{ij}^{k} \times S_{ij}^{k})$:

$$max \sum_{k=1}^{m}\left(k_1 w_{ij}^{k,\ c} \times k_2 S_{ij}^{k,\ g}\right) S_{ij}^{k}$$

$$s.t.\begin{cases} k_1 > 0,\ \ k_2 > 0 \\ k_1 + k_2 = 1 \\ k_1 = \left(\sum_{k=1}^{m} W_{ij}^{k,\ c} S_{ij}^{k}\right)^2 \Big/ \left[\left(\sum_{k=1}^{m} W_{ij}^{k,\ c} S_{ij}^{k}\right)^2 + \left(\sum_{k=1}^{m} W_{ij}^{k,\ g} S_{ij}^{k}\right)^2\right] \\ k_2 = 1 - k_1 \end{cases} \tag{6}$$

Eqs. (4)-(6) are then used to calculate the corresponding weights under the combined assignment method to obtain the combined similarity coefficients.

2.4 Indicators of Structural Characteristics of Complex Networks

(1) Node degree: node degree k indicates the number of connecting lines connected to node v_i, which is a basic parameter for studying the topology of complex networks, and the standardised node degree index can be calculated by the following two formulas:

$$k(v_i) = \sum_{j=1}^{N} \mu_{ij} \tag{7}$$

$$\overline{k(v_i)} = \frac{k(v_i) - k_{min}}{k_{max} - k_{min}} = \frac{k(v_i)}{N} \tag{8}$$

μ_{ij}: Whether node v_i and node v_j are connected or not, if they are connected then μ_{ij}=1 and vice versa μ_{ij}=0;

N: Total number of nodes.

The node degree indicator indicates the number of airports with which there is homogeneous development, the larger the node degree, the more airports with which there is homogeneous development.

(2) Proximity to centrality: refers to the average shortest distance between any point in the network to each other node (the distance here in this study is expressed by the minimum number of nodes in the network passing between two points), the calculation formula is as follows:

$$Cc(v_i) = \frac{1}{\sum_{j=1}^{N} d(v_i, v_j)} \tag{9}$$

$$\overline{Cc(v_i)} = \frac{(N-1)}{\sum_{j=1}^{N} d(v_i, v_j)} \tag{10}$$

$d(v_i, v_j)$: The shortest path from node v_i to v_j, i.e., the minimum number of nodes through which two nodes are connected.

This indicator further describes the proximity of the node to nodes that are not directly connected. A larger value of the indicator indicates that the node has a larger sphere of influence, implying that airports with greater proximity centrality are more indirectly homogeneous with other airports throughout the region. (3) Intermediary centrality: In the airport homogenization network, the intermediary centrality indicator reflects the degree to which an airport acts as an intermediary airport that must be passed through for homogenisation between two other airports in the whole homogenisation network. The formula is as follows:

$$C_B(v_i) = \sum_{j=1}^{N} \sum_{k=j}^{N} \frac{p_{jik}}{p_{jk}} \tag{11}$$

$$\overline{C_B(v_i)} = \frac{C_B(v_i)}{(N-1)(N-2)/2} \tag{12}$$

p_{jk}: denotes the number of shortest paths from node j to node k;

p_{jik}: denotes the number of shortest paths from node j to node k through node i.

This metric also reflects the importance of the node in the network, similar to the role of the proximity centrality metric above, where the node with the highest number of shortest path traversals in the network is considered to have the highest degree of mediated centrality.

3. Analysis of The Degree of Homogeneity of Hub Airports in The Yangtze River Delta Airport Cluster

3.1 Indicator Data Collection

(1) Factors of the city where the airport is located

Data were collected for the six hub airport cities corresponding to the seven hub airports in the Yangtze River Delta airport cluster in 2019 as shown in Table 2.

Table 2. Hub airport city aspect indicators for Yangtze River Delta airport cluster, 2019

Cities	GDP（billions of yuan）	Population size (10,000)	Economic export orientation
Shanghai	38156	1466	89.23%
Hangzhou	15373	785	33.77%
Nanjing	14031	703	34.41%
Ningbo	11985	606	76.52%
Hefei	9409	764	23.61%
Wenzhou	6606	831	28.79%

Source: By authors.

(2) Airport route network

The total number of flights, total passenger traffic, and total cargo traffic from the six hub airports of the Yangtze River Delta airport cluster to other domestic hub airports in 2019 were collected as shown in Table 3.

Table 3. Indicators in terms of hub airports in the Yangtze River Delta airport cluster, 2019

Cities	Total number of flights (frequency)	Total passenger traffic (persons)	Total cargo and mail traffic (tonnes)
Shanghai	375607	62345484	648914.6
Hangzhou	180489	27360737	553704.4
Nanjing	141184	21011055	286857.3
Ningbo	54030	9289952	75001.6
Hefei	51815	9095310	72673.5
Wenzhou	6606	9908445	82429.4

Source: By authors.

A total of 430 flight routes from the six hub airports in the Yangtze River Delta airport cluster to other domestic hub airports in 2019 were selected, of which 190 were direct routes and 240 were transit routes, and the collected route data are shown in Figure 2. Based on the 190 direct routes, 39 direct segments were counted, and based on the 240 transit routes, 165 transit segments were counted, finally, the percentage of flights, passengers transported, and cargo transported in each segment relative to the total flights, passengers transported, and cargo and mail transported were outlined in Table 3, so as to calculate the degree of homogenization of the route network.

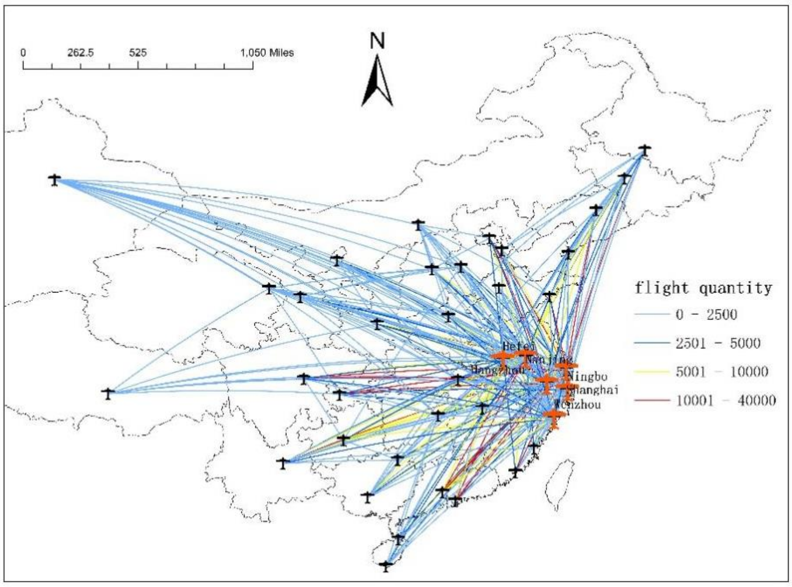

Figure 2. Air routes from the six hub airports of the Yangtze River Delta Airport Group to other domestic hub airports

Source: By authors.

3.2 Homogenisation Analysis Between Hub Airports

Firstly, the spatial distance weighting coefficient of the two airports between the hub airports of the Yangtze River Delta airport cluster can be calculated by adopting equation (1), and then the similarity coefficient under the 3 indicators between city and the other cities can be calculated by equation (2) according to the GDP, population size and economic outward orientation of the cities where the hub airports of the Yangtze River Delta airport cluster are located in 2019, and then according to the number of flights of each airline route, the passenger traffic volume, the cargo traffic volume. The similarity coefficients under 3 indicators between airports and other airports can be calculated through equation (3), and the calculated spatial weight coefficients and the similarity coefficients under 6 indicators after considering the spatial weights are shown in Table 4.

Table 4. Spatial distance weighting coefficients and similarity coefficients under six indicators

Airport Cities	Spatial distance weighting factor	GDP	Size of population	Economic export orientation	Frequency of flights	Amount of passenger traffic	Freight and mail traffic
Shanghai-Hangzhou	0.7195	0.4133	0.5018	0.3951	0.6861	0.6844	0.6868
Shanghai-Nanjing	0.4121	0.2216	0.2671	0.2294	0.3782	0.3578	0.3877
Shanghai-Ningbo	0.7219	0.3451	0.4222	0.6665	0.5965	0.5609	0.6046
Shanghai-Hefei	0.2449	0.0969	0.1678	0.1025	0.2006	0.1826	0.2041

Shanghai-Wenzhou	0.2958	0.0873	0.2140	0.1443	0.2255	0.2213	0.2405
Hangzhou-Nanjing	0.4844	0.4623	0.4577	0.4799	0.4543	0.4375	0.4436
Hangzhou-Ningbo	1.0000	0.8762	0.8713	0.6124	0.8719	0.8091	0.7620
Hangzhou-Hefei	0.2846	0.2161	0.2807	0.2342	0.2455	0.2266	0.2265
Hangzhou-Wenzhou	0.4192	0.2520	0.4073	0.3859	0.3476	0.3395	0.3346
Nanjing-Ningbo	0.3333	0.3071	0.3086	0.2068	0.2843	0.2541	0.2728
Nanjing-Hefei	0.6022	0.4835	0.5772	0.4901	0.5449	0.5007	0.5141
Nanjing-Wenzhou	0.2339	0.1497	0.2144	0.2131	0.1943	0.1807	0.1958
Ningbo-Hefei	0.2220	0.1953	0.1964	0.1047	0.1663	0.1437	0.1677
Ningbo-Wenzhou	0.4955	0.3521	0.4179	0.2709	0.4246	0.3972	0.3797
Hefei-Wenzhou	0.1857	0.1532	0.1779	0.1673	0.1404	0.1264	0.1399

Source: By authors.

Finally, the corresponding weights (0.15, 0.17, 0.16, 0.18, 0.17, 0.17) of the six indicators under the comprehensive assignment method are obtained through Eqs. (4)-(6), thus obtaining the comprehensive similarity coefficients between hub airports of the Yangtze River Delta airport cluster. The calculated results are shown in Table 5.

Table 5. Combined similarity coefficients (from highest to lowest)

Airport Cities	Composite similarity coefficient
Hangzhou-Ningbo	0.8061
Shanghai-Hangzhou	0.5695
Shanghai-Ningbo	0.5346
Nanjing-Hefei	0.5208
Hangzhou-Nanjing	0.4565
Ningbo-Wenzhou	0.3775
Hangzhou-Wenzhou	0.3455
Shanghai-Nanjing	0.3113
Nanjing-Ningbo	0.2739
Hangzhou-Hefei	0.2392

Nanjing-Wenzhou	0.1918
Shanghai-Wenzhou	0.1917
Ningbo-Hefei	0.1634
Shanghai-Hefei	0.1618
Hefei-Wenzhou	0.1507

Source: By authors.

According to the composite similarity coefficients between two of the six YRD hub airports obtained from Table 5, a composite similarity coefficient diagram can be drawn by connecting the two airports with a straight line as shown in Fig. 3, in which the thickness of the connecting line represents the degree of homogenization.

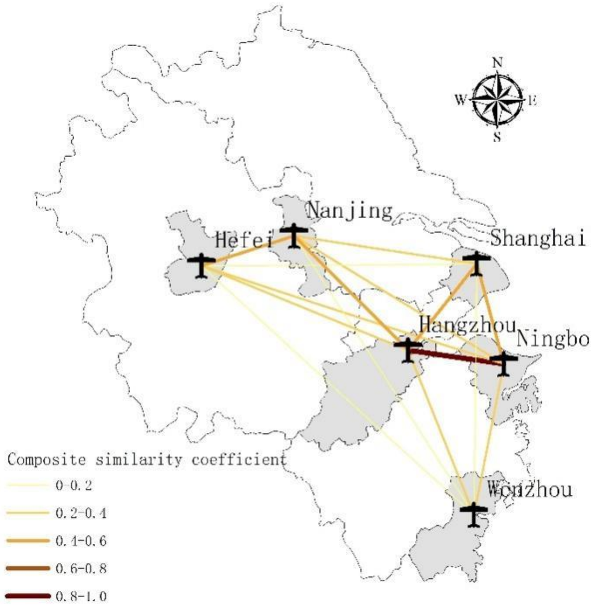

Figure 3. Composite similarity coefficient of hub airports in the Yangtze River Delta airport cluster in 2019

Source: By authors.

As shown by the comprehensive similarity coefficient, among the six hub airport cities in the Yangtze River Delta airport cluster:

(1) Hangzhou, the regional hub airport, has the most obvious homogeneity with other cities' airports. Due to its central location in the YRD airport cluster, there is homogeneity with neighboring airports in Ningbo, Shanghai, Nanjing, Wenzhou, etc.: Hangzhou and Ningbo (0.8061) have the most serious homogeneity, because the cities in which the two airports are located are very similar in terms of their GDP, population size and degree of openness to the outside world, and both regional hub airports, Hangzhou Xiaoshan and Ningbo Lishe, can provide relatively perfect airports. Hangzhou Xiaoshan and Ningbo Lishe, can provide a relatively complete level of airport services, with a high degree of similarity in the number of routes opened and the scale of operation. The main reason for the homogeneity between Hangzhou and Nanjing (0.4565) is that the two hub airports are located in cities with a similar degree of development, and there is a high degree of similarity in the opening of

air routes and the scale of operation.

(2) As the most developed city in the Yangtze River Delta region, Shanghai's highly developed socio-economic level has also contributed to the development of the two airports, Shanghai Pudong and Shanghai Hongqiao. In addition to the homogeneity with Hangzhou Airport (0.5695), the degree of homogeneity with Ningbo Airport (0.5346) is also not low, mainly due to the proximity and high similarity in terms of the city's economic outward orientation and the volume of cargo and mail transport, while the degree of homogeneity with Nanjing Airport (0.3113), Wenzhou Airport (0.1917), and Hefei Airport (0.1618) is not particularly serious.

(3) The combined similarity coefficient of Nanjing and Hefei (0.5208) is also higher, mainly because these two airports are located in cities that are not only similar in their degree of development, but also very close in terms of spatial distance, so it is easier to constitute a homogeneous competitive relationship, and therefore the weighting coefficient of the spatial distance is higher, which leads to the existence of a higher degree of homogeneity. On the other hand, Hefei and Wenzhou (0.1507) have the lowest combined similarity coefficients because they are the furthest apart in terms of spatial distance and have lower spatial distance weighting coefficients, so it is considered that it is not very obvious that these two airports constitute a competitive relationship with each other.

3.3 Complex Network Analysis of Homogenization at Hub Airports

According to the similarity coefficients between hub airports in the Yangtze River Delta airport cluster in Table 3, taking the airports with homogeneous development trends (comprehensive similarity coefficient value > 0.3) as nodes, and the similarity coefficients between airports and airports as arcs, the homogeneous network diagram of hub airports in the Yangtze River Delta airport cluster is constructed as in Fig. 4, and the standard node degree, the standard proximity centrality and the standard intermediary centrality are derived from the computation for evaluating complex networks. The three characteristic indexes are shown in Table 6 for the characterization of the homogeneous network of hub airports in the Yangtze River Delta airport cluster.

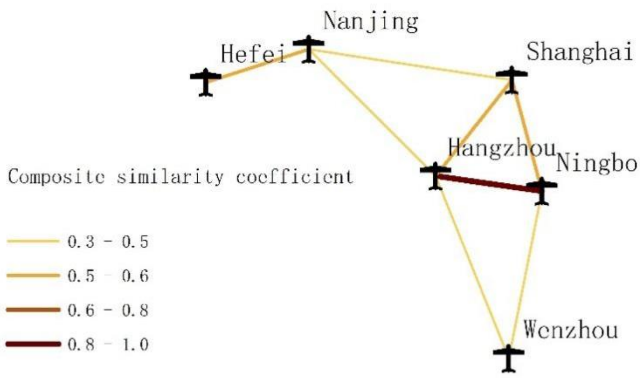

Fig. 4. Homogenised network of hub airports in YRD airport cluster
Source: By authors.

Table 6. Values of indicators characterizing the structure of complex networks

Airport Cities	Standard Nodal Degree	Standard Closeness Centrality	Standard Betweenness Centrality
Shanghai	0.600	0.714	0.100
Hangzhou	0.800	0.833	0.350
Nanjing	0.600	0.714	0.400
Ningbo	0.600	0.625	0.050
Hefei	0.200	0.455	0.000
Wenzhou	0.400	0.556	0.000
Shanghai	0.600	0.714	0.100

Source: By authors.

(1) **Nodal Degree**. According to equations (6) and (7), the node degree of the 6 hub airports in the Yangtze River Delta airport cluster can be calculated. As can be seen from Table 6, Hangzhou has the largest node degree (0.800), which indicates that Hangzhou airport has the most homogeneous situation with other airports among the 6 hub airports, implying that Hangzhou airport will face the situation that the surrounding airports are competing for passengers and cargo sources for the sake of development. This is followed by Shanghai (0.600), Nanjing (0.600), and Ningbo (0.600).

(2) **Closeness Centrality**. The indirect homogeneity between an airport and other airports in the whole region is reflected by proximity to the center. As can be seen from the standard proximity centrality data in Table 6, it is also Hangzhou (0.8330) that has the greatest proximity centrality, which indicates that Hangzhou Xiaoshan Airport not only has to face competition with neighboring airports for passenger and cargo traffic but also has to consider competition with other hub airports for transit passenger and cargo traffic. The proximity centrality of Shanghai (0.714) and Nanjing (0.714) is higher than average. This suggests that larger airports provide better services, enhancing their influence on surrounding cities. In response, neighboring cities improve their own airports to support development and enhance service quality. This creates a trend where airports in the region learn from each other, leading to a convergence of airport services.

(3) **Betweenness Centrality**. The standard intermediary centrality in Table 6 shows that Nanjing (0.400) has the highest degree of intermediary centrality, which is mainly due to the fact that the indirect homogenization of all other airports with Hefei uses Nanjing Lukou Airport as the intermediary node. Hangzhou (0.350) has the second highest mediated centrality after Nanjing. Because of its strategic location and developmental scale, other airports, primarily Wenzhou, are indirectly influenced through Hangzhou as a central node. This means Hangzhou plays a crucial role in harmonizing airport services across the region.

4. Main Conclusions and Recommendations

In order to analyze the homogeneous development characteristics between the hub airports of the Yangtze River Delta airport cluster in China, this paper proposes the similarity coefficient as a measurement index by considering the economic development status of the cities where the airports are located as well as the service scale of the airports and then calculates the similarity coefficients between the two airports under each index. Then the weights of the six selected indicators are given by the comprehensive assignment method to calculate the comprehensive similarity coefficient between the two airports. At the same time, the two airports with integrated similarity coefficients greater than 0.3 between hub airports are taken as nodes, and the integrated similarity coefficients of the two airports are taken as arcs to construct a homogeneous network between the hub airports of Yangtze River Delta airport cluster, and finally, the homogeneous network of hub airports is evaluated by using the complex network theory. Taking the hub airports of the Yangtze River Delta airport cluster as an example for empirical research, the following conclusions are drawn:

(1) Among the hub airports of the Yangtze River Delta airport cluster, Hangzhou Xiaoshan Airport and Ningbo Lishe Airport have the most serious level of homogeneity. Since the distance between the two airports in Great Circle Mapper is only 109km, they are the two closest airports among the hub airports of the Yangtze River Delta airport group, so their spatial weight coefficients are also the highest, which means that hinterland competition is inevitable between these two airports. At the same time, the cities where the two airports are located have similar economic development, and in terms of the scale of airport services, the routes opened and the scale of the airports are also very similar, so they have the highest overall similarity coefficient.

(2) From the perspective of the hub airport cities of the entire Yangtze River Delta airport cluster, the level of homogeneity among the airports in the three centrally located cities of Hangzhou, Shanghai, and Ningbo is at a high level (>0.5), and the competition between Nanjing and Hefei is also relatively intense (0.5208). In addition, the standard nodal degree of the four cities of Shanghai, Nanjing, Hangzhou, and Ningbo are all at a high level (⩾0.600), which further reveals that there is a homogenization problem between hub airports in the Yangtze River Delta airport cluster and that the competition between hub airports is relatively intense, mainly due to the high route overlap.

(3) The airports of Hefei and Wenzhou are located far away from the center, and the route (mileage) distance between them is the farthest among the hub airports, so they do not constitute a competitive relationship, so the spatial weighting coefficient is lower, which leads to the lowest overall similarity coefficient between them.

In view of the homogenization of hub airports in the Yangtze River Delta (YRD), this study proposes the following three sustainable development recommendations to avoid the waste of capacity due to over-competition in the YRD airports as a result of the overly serious homogenization of the YRD hub airports:

1) Carry out differentiated development and create a unique brand experience by combining airport characteristics. Each airport has its unique geographical location, cultural background, and development history. Airports should fully explore these characteristic resources to create a brand experience with unique charm.

2) Further optimize the route network, further integrate the routes and airspace between

Hangzhou and Ningbo, Nanjing and Hefei, and enhance the comprehensiveness and service efficiency of air transport operations;

3) Continuously innovate service models to meet the diverse needs of travelers. Develop smart airport systems and services such as unmanned check-in and self-check-in to enhance travel efficiency and convenience for passengers. Meanwhile, cooperation with airlines and tourism organizations can also be strengthened to jointly develop new travel products and services to provide travelers with richer choices.

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