Recognition of Value of International Aviation Hub Air Shuttle on Hub Route Network

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DOI: https://doi.org/10.30210/JMSO.202503.001

Submitted: Dec. 09, 2024 Accepted: Feb. 01, 2025

ABSTRACT

To improve the strategic architecture of the air shuttle network, it is crucial to conduct a scientific evaluation of the value of the air shuttle line connecting international aviation hubs. In light of the blocking of 31 international inter-hub shuttle routes, this study computes the changes in the indicators of the inter-hub route network based on inter-hub route statistics. Changes in transit characteristics and node accessibility were further investigated based on changes in betweenness and closeness. The findings demonstrate the following: (1) the influence of international inter-hub shuttle lines on the inter-hub route network is categorized into three levels, with the routes connecting Beijing, Shanghai, and Guangzhou constituting the highest tier; (2) the obstruction of the shuttle line between international hubs has the greatest effect on the accessibility of Beijing, Shanghai, and Guangzhou as well as the transit performance of Lhasa, Fuzhou, and Changchun; and (3) Wuhan, Zhengzhou, and Changsha demonstrate noteworthy resilience in terms of accessibility and transit capacity. These findings provide insights for enhancing the main routes of air shuttle networks and boosting the competitiveness of important hubs. They also provide stakeholders in the aviation sector, including airlines, airports, and legislators, a basis on which to make decisions.

Keywords: Aviation hub; Air shuttle; Complex network

1. Introduction

The air transport industry is based on the aviation network, which is constructed with airports as nodes and routes as edges. It is a space carrier for medium- and long-distance passenger transportation as well as high-value cargo transportation. [1]. With the continuous development of the route network, regional accessibility and spatial coverage have been significantly enhanced, providing strong support for the construction of a modern comprehensive transportation system [2].

Within the aviation network, air shuttle services with hubs serving as nodes represent the backbone of the system. These shuttle lines have played a pivotal role in shaping the air transport market by driving their development. Also referred to as shuttle flights, this route mode has emerged in response to evolving market demands and competitive pressures from other modes of transportation. Characterized by high-frequency daily flights (often exceeding ten per day), point-to-point operations, balanced flight schedules, efficient processes, seamless transfer services, flexible rebooking options, and distinctive branding, air shuttles are designed to maximize passenger convenience. Additionally, operational coordination between airports and airlines ensures a high flight release rate and improved service quality [3]. *The 14th Five-Year Plan for Civil Aviation Development* emphasizes the importance of ‘promoting the use of shuttle services to establish a high-frequency, high-quality backbone network.’ The establishment of high-quality shuttle routes enhances passenger throughput at both terminals, strengthening the hub's ability to efficiently collect and distribute passengers and cargo while seamlessly integrating with other transportation modes. This not only improves connectivity, but also serves as a catalyst for urban growth and economic development [4]. Air shuttle services have become a key response to the growing competition from high-speed rail, owing to their convenient travel process, long-distance regional accessibility, and substantial passenger benefits [5,6].

In the air shuttle line, the shuttle line with the international hub as the node has a relatively longer operation time and larger operation scale, which is more representative of the air shuttle line. First, international aviation hubs serve as "lead geese" in the development and construction of China's air shuttle routes. From the perspective of connecting points, air shuttle routes with international aviation hubs as their nodes are not only the longest-established and highest-value routes but also serve as priority connecting points for regional aviation hubs and non-hub airports in building air shuttle services. These routes play a crucial "lead goose" and "demonstration effect" role in cultivating and establishing the air shuttle market in China. Second, air shuttle routes between international aviation hubs have the highest market value. The average daily frequency of "international-to-international" air shuttle routes increased from 27.86 in 2008 to 40.95 in 2019, while annual passenger traffic rose from 1,385,217 in 2008 to 2,613,652 in 2019. These figures significantly outperform the "international-to-regional" air shuttle routes and other types of air shuttle routes during the same period in terms of market value. Third, different types of air shuttle routes exhibit different market development prospects. A comparison reveals that air shuttle lines with international aviation hubs as connecting points typically exhibit a strong foundation for development, a large potential for growth, and substantial market value. These routes represent a "star market" and should therefore become the primary focus in the cultivation and construction of China’s air transportation market. Therefore, a scientifically based evaluation of the value of international hub air shuttle routes, along with a quantitative assessment of their importance in the overall route network, provides valuable reference points for stabilizing the domestic air transport market [7], improving air transport efficiency, and guiding scientific planning of the route network [8].

Several scholars have discussed the strategic value of route networks from their perspective. For instance, Zhang et al. constructed a passenger transport network model for airport group routes based on complex network analysis methods and found that four major airport clusters play a significant role as hubs within the national route network [9]. Cheung et al. proposed the Global Airport Connectivity Index (GACI) to analyze the evolution of the global air transport network and discovered that different regions focus on distinct types of service routes [10]. Sunny B et al. assessed the route network of India's second-tier cities and identified potential for the development of feeder routes [11]. In terms of analyzing dynamic changes in network structural characteristics under route disruptions, much of the research has focused on evaluating network resilience or robustness, with less emphasis placed on assessing the importance of edges in complex networks. Başpınar et al. used tools from network science and control theory to characterize the relationship between interconnectivity and the robustness of air transportation systems. Their study revealed that greater interconnectivity in the United States makes the system more vulnerable to the impact of rapidly spreading disruptions [12]. Ding, J.L. et al. evaluated the robustness of the network based on edge weights and agglomeration coefficients, and employed various attack methods to verify it [13]. Wong et al. evaluated the value of new routes from a global aviation network perspective by analyzing changes in indicators, such as connectivity potential after adding new routes [14].

The existing body of research demonstrates that route network evaluations are conducted from multiple perspectives, such as accessibility and connectivity. However, the focus has mainly been on national or urban aviation networks [9, 10, 11], airport group networks [15, 16], and airline route networks [17], with limited attention paid to the evaluation of air shuttle networks. Therefore, this study adopted a dynamic network evaluation method to assess the value of the air shuttle network and effectively identify and scientifically evaluate the importance of air shuttle routes.

2. Empirical Design

2.1 Network Model Construction

In this study, we propose a framework for measuring the dependence of an air shuttle network (Figure 1). First, based on the definitions of international hubs and regional hubs provided in the 14th Five-Year Plan for Civil Aviation Development, we constructed an undirected weighted network with 10 international hub cities and 29 regional hub cities as the basic units. Transit routes were excluded from this analysis and the data were sourced from the China Civil Aviation Statistical Yearbook. Routes with more than ten flights were classified as shuttle routes. Given the extreme impact of COVID-19 on the data, which makes it difficult to accurately reflect the real situation, this study defined the research time point as 2019. Next, we calculated the network feature indices before and after the removal of international inter-hub air shuttle routes. We then measured the dependence of the entire network and individual hub nodes on the remaining routes using both global and local indices.

Figure 2 illustrates the network construction method. First, based on *the 14th Five-Year Plan for Civil Aviation Development*, 10 international hubs, such as Beijing, and 29 regional hubs, such as

Tianjin, were identified. Then, according to the 2019 route data of *the China Civil Aviation Statistical Yearbook*, an undirected route network $G=(V,E,W)$ among the 39 hubs was constructed, as shown in Figure 2a. Passenger traffic was used as a weight, and the scenario of multiple airports within a city was considered, as shown in Figure 2b. $V=\{v_1,v_2,v_3...,v_n\}$ represents the set of hub nodes, where n denotes the total number of hubs and $E=\{e_1,e_2,e_3\cdots, e_s\}$ indicates the set of relationships between hubs. If there is a connection between hubs v_i and v_j, then e_i=1; otherwise, e_i=0; W represents the weight of the connecting edge between hubs v_i and v_j, which is described in terms of passenger traffic.

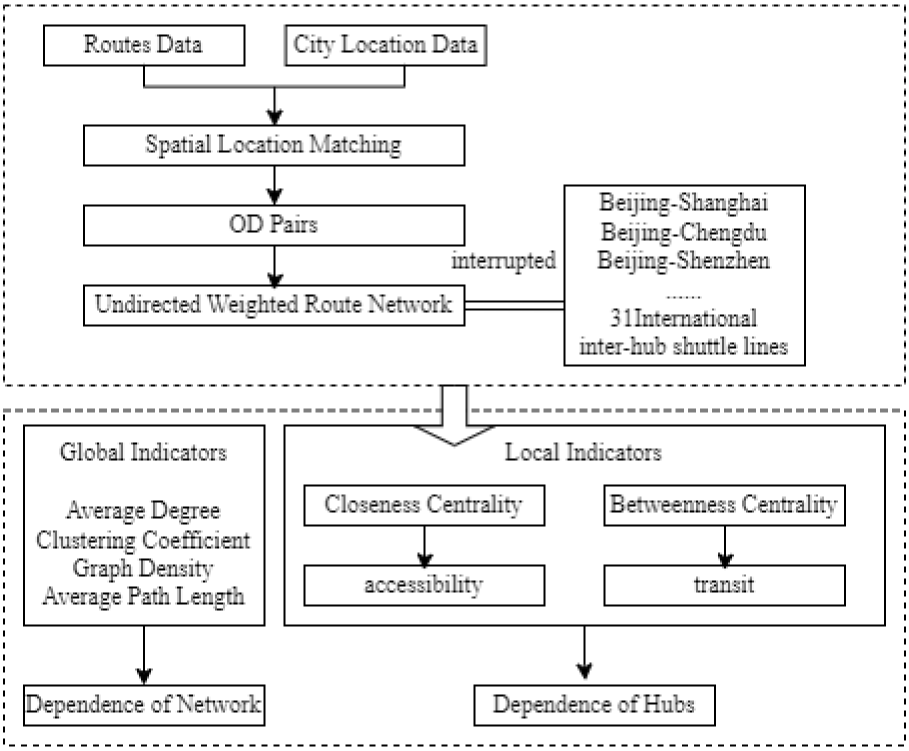

Figure 1. Research framework

Source: By authors.

This study explored the dependence of the inter-hub shuttle network on the international inter-hub shuttle line by simulating the interruption of these shuttle routes. Figure 3 illustrates the simulation process when a shuttle line is interrupted (Figure 3a represents the original network and Figure 3b shows the interrupted network). In Figure 3b, when the shuttle line between hubs A and B is interrupted, the advantages of the shuttle route are lost, and passengers no longer choose the shuttle service. As a result, shuttle routes connecting A and B were also suspended.

Figure 4 shows the spatial distribution and passenger traffic of China's hub routes. Passenger traffic volume serves as a key indicator of the quality of these routes and is an important service for enhancing the rights and interests of air passengers. As shown in the figure, the shuttle routes connecting Beijing, Chengdu, Chongqing, Guangzhou, Shanghai, Hangzhou, and other hubs carry a higher volume of passenger traffic, which aligns with the role of these cities as international aviation hub. Table 1 lists the administrative districts to which each hub is located. From the perspective of administrative regional distribution, East China has the largest number of hubs, with 11 hubs accounting for 28.21%. This was followed by the central and southern regions, which had nine hubs, accounting for 23.08%. The northeast, northwest, and southwest regions had five hubs each, accounting for 12.82%. North China has the fewest hubs, with only four hubs in Beijing, Tianjin, Taiyuan, and Shijiazhuang accounting for 10.26%.

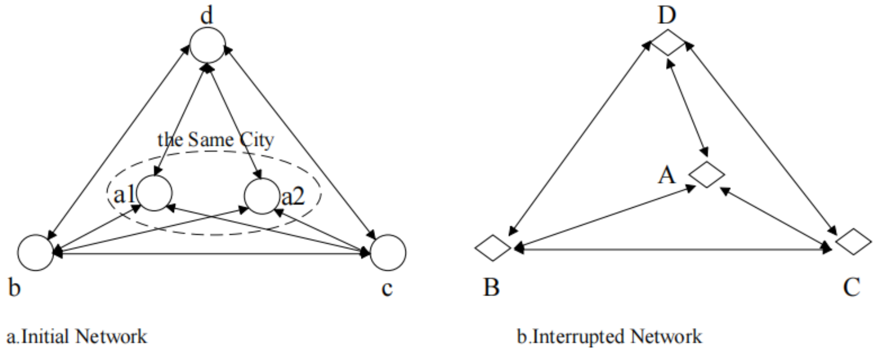

Figure 2. Network model construction

Note: A, B, C, D represent different hub cities; a1、a2、b、c、d represent the airport in a hub city

Source: By authors.

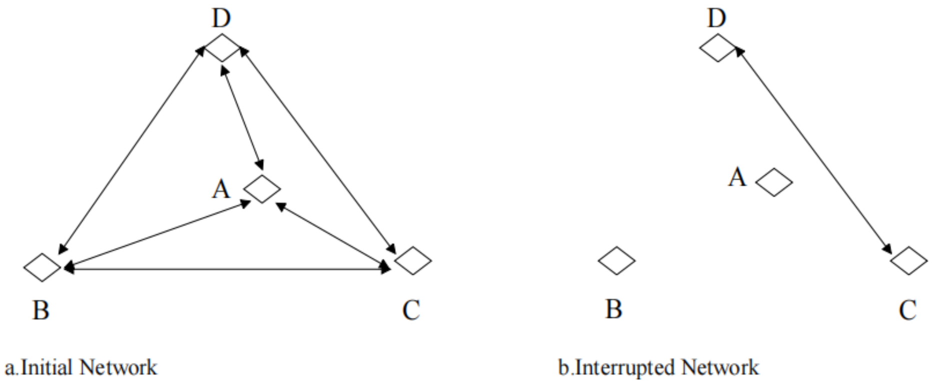

Figure 3. Changes in the structure of the aviation network due to route disruptions

Source: By authors.

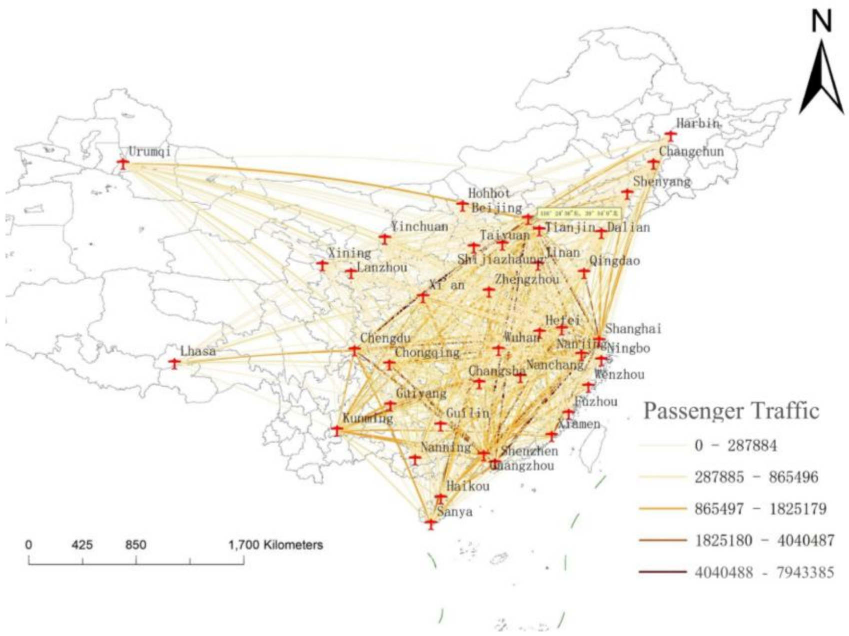

Figure 4. Spatial distribution pattern of routes between hubs

Source: By authors.

Note: This map was based on the standard map of *the National Geomatics Center of China*(map content approval number: GS(2024)0650).

Table 1. Distribution of hub cities

District	Number	Percentage	Hub Cities
East China	11	28.21%	Shanghai, Nanjing, Xiamen, Qingdao, Jinan, Hangzhou, Wenzhou, Nanchang, Hefei, Ningbo, Fuzhou
Central South China	9	23.08%	Zhengzhou, Guangzhou, Wuhan, Shenzhen, Sanya, Changsha, Haikou, Nanning, Guilin
Northeast China	5	12.82%	Hohhot, Shenyang, Harbin, Changchun, Dalian
Northwest China	5	12.82%	Yinchuan, Xi'an, Lanzhou, Xining, Urumqi
Southwest China	5	12.82%	Chengdu, Chongqing, Kunming, Guiyang, Lhasa
North China	4	10.26%	Beijing, Tianjin, Taiyuan, Shijiazhuang

Source: By authors.

2.2 Measurement Method of Dependence of International Hub Shuttle Line

In this study, we selected the average node degree, network clustering coefficient, graph density, average path length, closeness centrality, and betweenness centrality to measure both global and local changes in the network [19]. The average node degree, clustering coefficient, graph density, and average path length are global indicators used to assess the compactness and efficiency of the network. Closeness and betweenness centralities are local indicators employed to evaluate the accessibility and transit of nodes within the network [20].

When an air shuttle route is blocked, the removal of the route alters the weight distribution of the other routes, thereby changing the overall structure of the air network. Consequently, the transfer function and accessibility of nodes within the network are also affected. In this study, the absolute values of changes in the average node degree, network clustering coefficient, graph density, and average path length were used to reflect the dependence of the inter-hub route network on the international inter-hub air shuttle. Absolute changes in closeness centrality and betweenness centrality were used to assess the dependence of individual nodes on the air shuttle network. A larger range of changes in these indices indicates stronger dependence.

2.2.1. Overall indicators

1. Average Degree

The average degree is the average number of nodes in a network.

$$K = \frac{1}{N}\sum_{i=1}^{N} k_i \cdots\cdots \text{[Formular 1]}$$

$$\Delta K = \left(1 - \frac{K'}{K}\right) \times 100\% \cdots\cdots \text{[Formular 2]}$$

K: Average degree before the route was blocked.

k_i: node degree value of node i

where N is the total number of nodes in the network.

K': Average degree after the route was blocked.

△K: rate of change in the average degree when the route is blocked.

2.Network Clustering Coefficient

The network clustering coefficient is the average value of the clustering coefficient of all nodes in the network, and refers to the probability that two nodes adjacent to a node are also connected to each other.

$$C = \frac{1}{N}\sum_{i=1}^{N} C_i \cdots\cdots \text{[Formular 3]}$$

$$C_i = \frac{2E_i}{k_i(k_i-1)} \cdots\cdots \text{[Formular 4]}$$

$$\Delta C = \left(1 - \frac{C'}{C}\right) \times 100\% \cdots\cdots \text{[Formular 5]}$$

C: Network clustering coefficient before the route is blocked.

C_i: clustering coefficient of node i

E_i: number of edges that exist between k_i neighbors of node *i*.

C': Network clustering coefficient after the route is blocked.

△C: Rate of change in the network clustering coefficient before and after the route is blocked.

3.Graph Density

Graph density is the proportion of the actual number of edges in the entire network to the maximum number of possible edges, and is used to measure the closeness of the connections between nodes in the graph.

$$D = \frac{2E}{N(N-1)} \cdots\cdots \text{[Formular 6]}$$

$$\Delta D = \left(1 - \frac{D'}{D}\right) \times 100\% \cdots\cdots \text{[Formular 7]}$$

D: Graph density before the route is blocked.

D': Graph density after route blockage.

E: Number of edges in the graph.

△D is the rate of change in the graph density of the network before and after the route is blocked.

4.Average Shortest path Length

The average shortest path length is the average number of steps in a path multiplied by the weight in the network, to reflect the global connection characteristics of the network.

$$L = \frac{2}{N(N-1)} \sum_{i=1}^{N} \sum_{j=i+1}^{N} d_{ij}^{w} \cdots\cdots\cdots\cdots \text{[Formular 7]}$$

$$\Delta L = \left(1 - \frac{L}{L'}\right) \times 100\% \cdots\cdots\cdots\cdots \text{[Formular 8]}$$

L: average shortest path length of the network before the route is blocked.

L'' *is* the average shortest path length of the network after the route is blocked.

d_{ij}^{w}: weighted shortest path length of nodes i and j [21].

⊿L: rate of change of the average weighted path length before and after the route is blocked.

2.2.2. Local indicators

1. Closeness Centrality

Closeness centrality refers to the reciprocal of the sum of the shortest path distances from one node to all other nodes [22]. This reflects the proximity of a node to other nodes in the network,whose change reflects the influence of the route on the "centrality" of the node.

$$WCC_i = \frac{1}{\sum_{j}^{N} d_{ij}^{w}} \cdots\cdots\cdots\cdots \text{[Formular 9]}$$

$$\Delta WCC_i = \left(1 - \frac{WCC_i'}{WCC_i}\right) \times 100\% \cdots\cdots\cdots\cdots \text{[Formular 10]}$$

WCC_i: closeness centrality of node i before route blockage.

WCC_i': The closeness centrality of node i after the route is blocked.

ΔWCC_i: rate of change in closeness centrality before and after the route is blocked.

2. Betweenness Centrality

betweenness centrality is the ratio of the shortest weighted path in the network that passes through a point and connects the two points to the total number of shortest weighted path lines between the two points.The magnitude of the rate of change reflects the capacity of the attacked shuttle line to carry the network.

$$WBC_i = \sum_{i \neq s, i \neq t, s \neq t} g_{st}^{w}(i) / g_{st}^{w} \cdots\cdots\cdots\cdots \text{[Formular 11]}$$

$$\Delta WBC_i = \left(1 - \frac{WBC_i}{WBC_i'}\right) \times 100\% \cdots\cdots\cdots\cdots \text{[Formular 12]}$$

WBC_i: betweenness centrality of node i before the route is blocked.

g_{st}^{w} : total number of shortest weighted paths from node *s* to node *t*

WBC_i': Betweenness centrality of node i after the route is blocked.

ΔWBC_i: rate of change in betweenness centrality before and after the route is blocked.

2.3 Experimental Data

This study is based on data from China's civil aviation routes in 2019. According to statistics, there were 649 direct routes between 39 hubs in 2019, constructed according to the model outlined in Section 2.2. A network map for these 39 inter-hub routes was generated, excluding routes with zero passenger traffic. The final result included 603 direct routes, comprising 139 air shuttle routes and 31 international inter-hub air shuttle routes. Figure 5 illustrates the interhub air shuttle network. As shown in Table 2, international inter-hub air shuttle routes account for 58.56% of passenger traffic, despite representing only 21.09% of the total route volume. Domestic air shuttle routes connecting international hub cities have established a "star market" within the air shuttle network, becoming the dominant segment of the domestic air shuttle network.

Table 2. Comparison of air shuttle routes between different types of hubs

	International - international	Percentage	International-regional	Percentage	Regional-regional	Percentage
Number	31	21.09%	96	65.31%	20	13.61%
Passenger Traffic	2613652.97	58.56%	1069492.63	23.96%	780143.40	17.48%

Source: By authors.

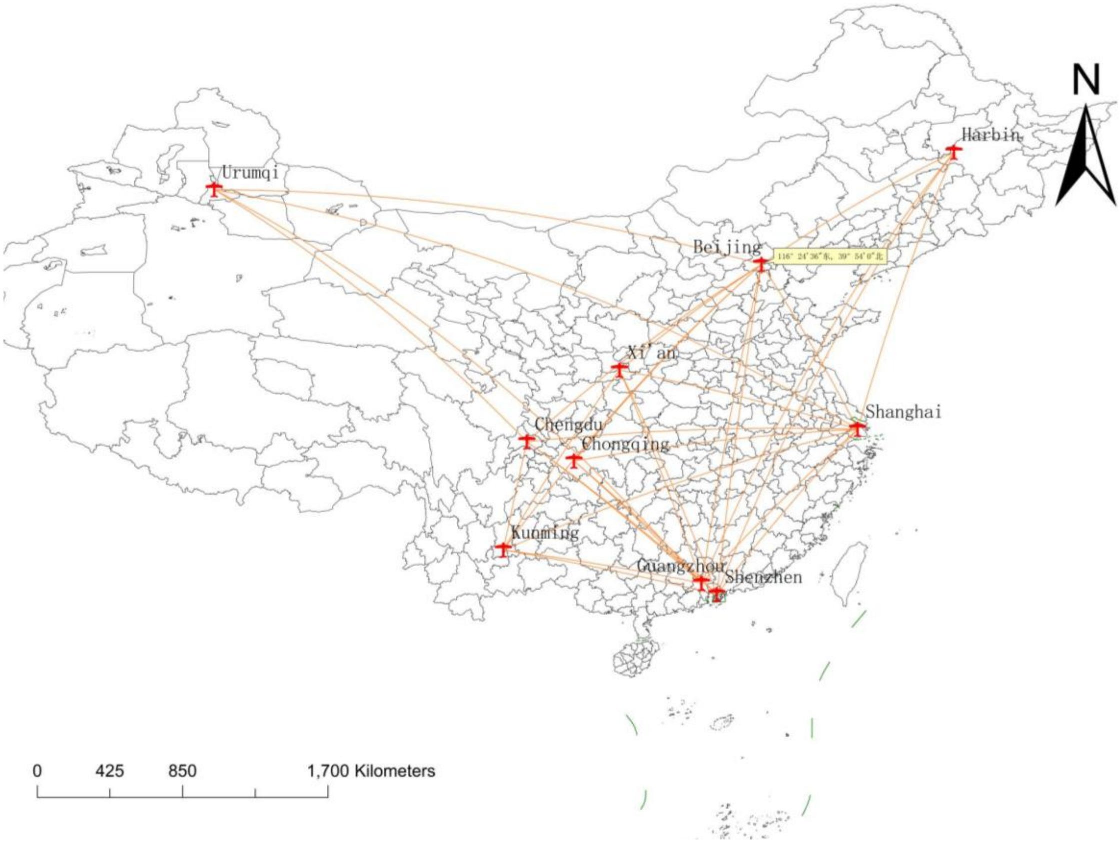

Figure 5. Spatial distribution pattern of shuttle lines between international hubs

Note: This map was based on the standard map of *the National Geomatics Center of China*(map content approval number: GS(2024)0650).

Source: By authors.

3. Experimental Results

3.1 Analysis of Aviation Network Characteristics

According to statistics, the degree value of all nodes in the network is $k\in[12,38]$, with the average degree of the network being approximately 31. This means that, on average, each city was connected to 31 other cities, indicating strong connectivity within the air network. Table 3 lists the degree values for each node. Among the 39 hub cities, Chengdu and Chongqing have the highest degree value of 38, meaning they are connected by direct air shuttle routes to all the other 38 hubs. Hubs connected to Beijing, Shanghai, and Xi'an accounted for 97.4%, 94.7%, and 94.7% of the total number of hubs, respectively, demonstrating their wide reach and strong connectivity. The number of nodes with degree values between 24 and 36 accounts for 87.18% of the total, whereas only Lhasa, with a degree value of 12, has a significantly lower degree of accessibility. The limited connectivity of Lhasa can be attributed to its unique geographical condition. Located in the middle of the Tibetan Plateau, with high terrain in the north and lower elevations in the south, Lhasa's transportation accessibility is constrained by these physical factors, which impose stringent requirements on the type of aircraft required. Additionally, Lhasa's geographical isolation and uneven distribution of economic resources and population further limit the expansion of its aviation market[23].

Table 3. Degree values of each node in the network

Node	Degree	Node	Degree	Node	Degree	Node	Degree
Chengdu	38	Changsha	34	Hangzhou	31	Changchun	28
Chongqing	38	Yinchuan	34	Nanning	31	Ningbo	28
Beijing	37	Nanjing	33	Sanya	30	Dalian	27
Shanghai	36	Shenyang	33	Taiyuan	30	Fuzhou	27
Xi'an	36	Haikou	33	Lanzhou	30	Nanchang	27
Kunming	36	Guiyang	33	Wenzhou	29	Urumqi	24
Wuhan	36	Jinan	33	Hohhot	29	Guilin	24
Guangzhou	35	Xiamen	32	Hefei	29	Xining	23
Zhengzhou	35	Qingdao	32	Shijiazhuang	29	Lhasa	12
Shenzhen	34	Tianjin	32	Harbin	28		

Source: By authors.

3.2 The Dependence of the Overall Route Network on the International Shuttle Line

Table 4 presents the characteristic indicators of the route network and the rate of change in the event of a shuttle line interruption. As shown in Table 4, when routes are blocked, the average degree, average clustering coefficient, graph density, and average path length of the network change, indicating that a reduction in the number of routes leads to structural changes in the route network. When all shuttle routes were removed, the average degree, average clustering coefficient, and graph density of the entire route network decreased by 5.14%, 5.16%, and 6.74%, respectively, while the average path length increased by 3.54%. The decrease in the average node degree was attributed to the reduced accessibility of the route network caused by route disruptions. The decline in the average clustering coefficient was due to the reduced level of aggregation between hub nodes when the routes were blocked. The decrease in graph density resulted from the loosening of the network connectivity after disruption. The increase in the average path length occurs because more transfers are required between hub nodes in the network after the shuttle line is interrupted, thereby reducing transportation efficiency.

Table 4. Dependence of the overall route network on international shuttle routes

Route	Average Degree		Average Clustering Coefficient,		Graph Density		Average Path Length	
	Value	Rate	Value	Rate	Value	Rate	Value	Rate
Initial Route	30.923	-	0.814	-	0.846	-	1.186	-
Shuttle Removed	29.333	-5.14%	0.772	-5.16%	0.789	-6.74%	1.228	3.54%

Source: By authors.

Figure 7 shows the change in the average degree of the route network when 31 international hub shuttle lines are disrupted. As shown in the figure, the average degree of the shuttle network remains at approximately 30 after any route is attacked, indicating that each node in the network is connected to 30 other nodes following the interruption of a shuttle line. The natural discontinuity method is applied to categorize the routes based on the rate of change in the average degree. Routes with an impact range of 2.32%–2.82% include those between Beijing, Shanghai, Guangzhou, and Shenzhen. These are followed by routes between Beijing and Shanghai, Chengdu, and Kunming, which have an impact range of 1.99%–2.16%. Most of the routes, with an impact range of 1.49%–1.82%, are between Guangzhou and Shenzhen and the three southwest regions of Kunming, Chengdu, and Chongqing.

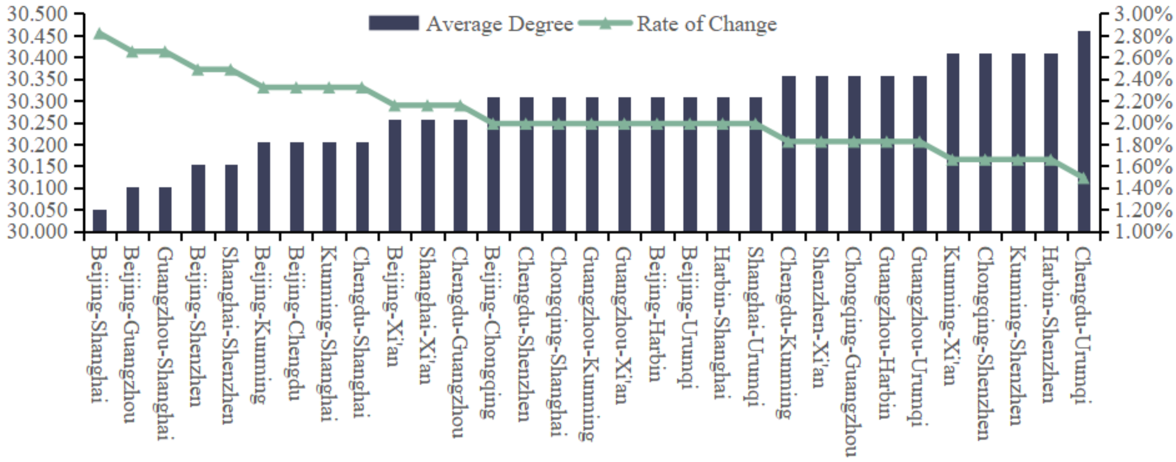

Figure 7. Change in average degree of the route network when routes are attacked

Source: By authors.

From the perspective of the clustering coefficient, when a shuttle line is disrupted, the original network is fragmented, leading to a decrease in network agglomeration and a reduction in the average clustering coefficient. Figure 8 shows the change in the clustering coefficient of each shuttle route after disruption, with the remaining routes classified into three categories based on the average change rate of the clustering coefficient using the natural discontinuity method. Air routes with an impact range of 2.70%–2.83% include those connecting Beijing, Shanghai, and Guangzhou. Routes with an impact range of 2.21%–2.46% are mostly between the hubs of Beijing and Shanghai, as well as the three hubs of Kunming, Chengdu, and Xi'an. Routes with an impact range of 1.47%–1.97% are primarily between Beijing, Shanghai, and Harbin and Urumqi, followed by routes between Guangzhou and Chongqing, Harbin and Urumqi, and finally between Shenzhen and Chongqing, Harbin, and Urumqi.

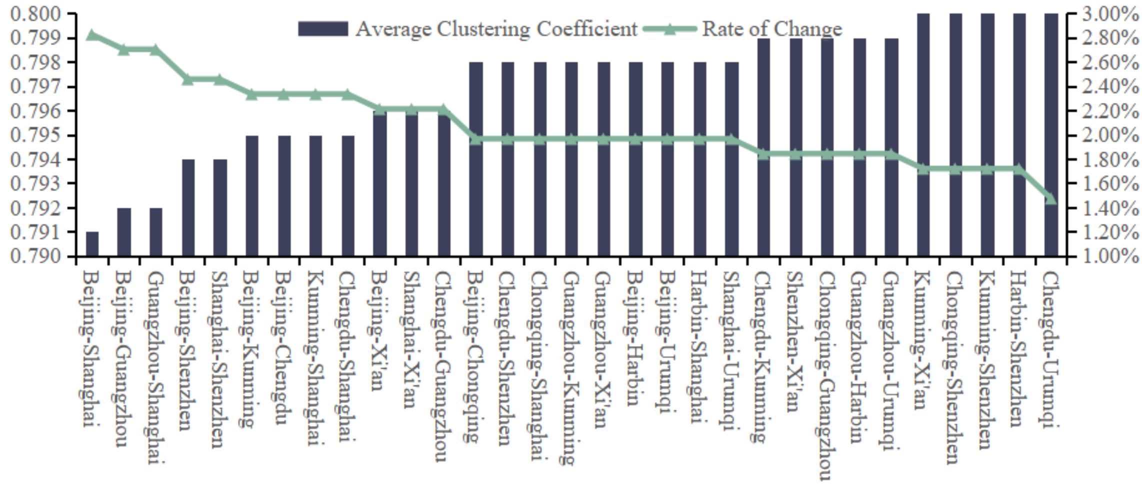

Figure 8. Changes in average clustering coefficients of route networks when routes are attacked
Source: By authors.

From the perspective of graph density, when a shuttle line is disrupted, the connectivity of the route network decreases, leading to a reduction in graph density. Figure 9 shows the change in graph density for each shuttle route after disruption, with the routes categorized into three groups based on the change rate in graph density using the natural discontinuity method. Routes with an impact range of 2.96%–3.66% include those between Beijing, Shanghai, Guangzhou, and Shenzhen. These are followed by routes connecting Beijing, Shanghai, and Xi'an, with an impact range of 2.36%–2.84%. Routes affected by a range of 2.36%–2.84% are primarily between Beijing, Shanghai, Guangzhou, and Chengdu, Kunming, and Xi'an, followed by routes between Guangzhou and Shenzhen and between Chengdu and Xi'an. The routes with an impact range of 1.77%–2.25% are primarily between Shanghai, Guangzhou, Shenzhen, and Harbin, and Urumqi.

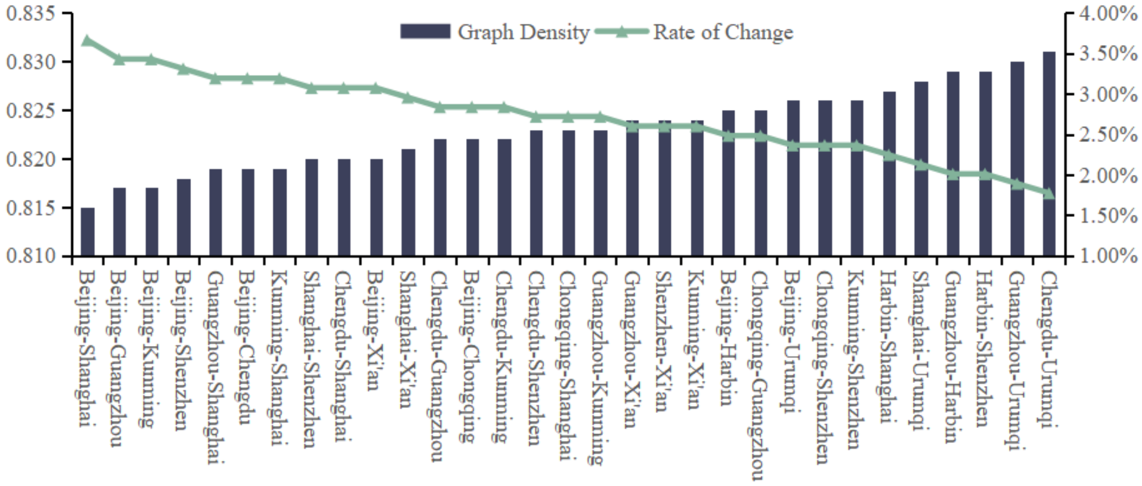

Figure 9. Changes in density of route network diagrams when routes are attacked

Source: By authors.

The average path length measures the average shortest distance between all node pairs, which represents the minimum number of transfers required between two hubs, rather than a physical distance. When a shuttle line is disrupted, the degree of separation within the network increases, causing the average path length to rise. Figure 10 illustrates the change in the average path length of the network when each shuttle line is blocked. The routes are categorized into three groups based on the change rate in average path length using the natural discontinuity method. Routes with an impact range of 1.85%–1.94% include those between Beijing, Shanghai, and Guangzhou. Routes with an impact range of 1.52%–1.69% are between Beijing, Shanghai, and Shenzhen, followed by routes between Beijing, Shanghai, Kunming, Chengdu, and Xi'an. Routes with an impact range of 1.01%–1.35% are between Shenzhen and Chengdu, Guangzhou and Kunming, followed by routes between Beijing, Shanghai, Guangzhou, and the three northern regions of Xi'an, Harbin, and Urumqi. Finally, routes between Shenzhen, Chongqing, and Kunming, and Harbin are also included.

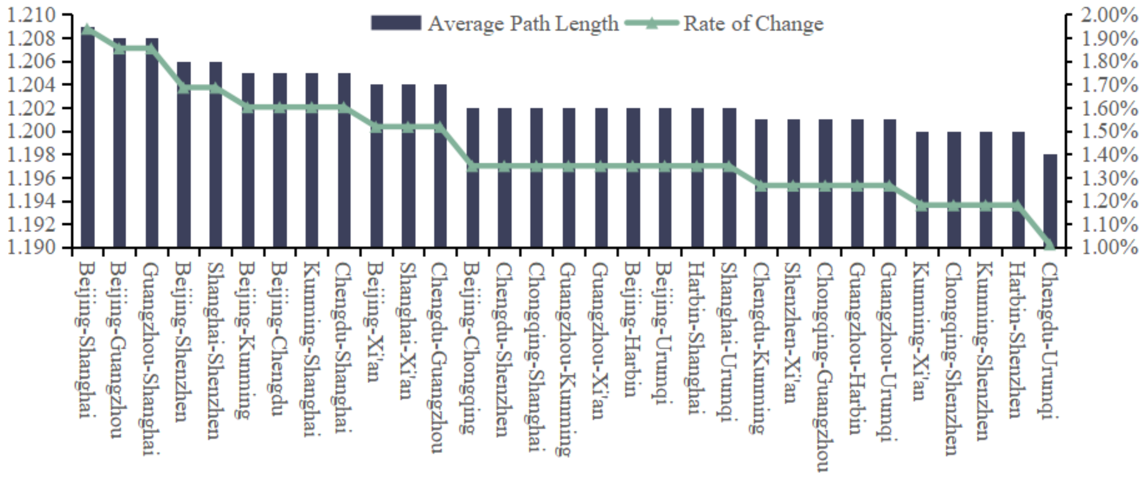

Figure10. Change in average path length of the route network when routes are attacked

Source: By authors.

From the perspective of the change range of each index, the routes between Beijing, Shanghai, and Guangzhou fall into the first echelon. These cities, with their positioning as "Comprehensive Gateway Composite International Aviation Hubs," play a crucial role in connecting the entire country, radiating outward, and linking the domestic air transport network with international channels [24]. They are characterized by a well-developed economy, large populations, and have consistently ranked at the top of the aviation hub system. According to 2019 data, the passenger traffic on the three routes connecting Beijing, Shanghai, and Guangzhou accounted for 7.26% of all 604 routes. The routes between the four nodes of Beijing, Shanghai, Guangzhou, Shenzhen, and the western regions, such as Kunming, Chengdu, and Xi'an, fall into the second echelon. The southwest region, represented by Kunming, Chengdu, and Chongqing, has developed into a new district-level agglomeration center, with routes connecting the western region playing a key role in both internal and external exchanges [25]. The routes between the four nodes of Beijing, Shanghai, Guangzhou, Shenzhen, and the northern regions, such as Urumqi and Harbin, belong to the third echelon. Due to factors such as administrative level, tourism development, and economic foundation [26], there is a lack of large-scale, comprehensive central cities in Northeast and Northwest China, and the radiation effect of nodes on these regions is weak. Consequently, the supporting role of air routes in these areas is less pronounced than that of routes between megacities and agglomeration centers.

3.3 Dependence of Nodes on the International Hub shuttle

3.3.1. Impact of the obstruction of the international hub shuttle network on the accessibility

Closeness centrality measures how central a node is in the network; the higher the value, the closer the node is to the center of the network, and the faster it can reach other nodes. Figure 12 shows the change in the closeness centrality of international hub nodes when the inter-international hub shuttle routes are disrupted. The natural discontinuity method was used to categorize the closeness centrality of nodes into three levels: high, medium, and low, as shown in Table 5. Beijing (18.75%), Shanghai (18.37%), and Guangzhou (16.33%) experienced the largest changes, while Shenzhen (14.29%), Chengdu (13.64%), Kunming (13.04%), and Xi'an (11.11%) saw moderate changes. Chongqing (9.52%), Harbin (7.69%), and Urumqi (7.14%) exhibited the smallest changes..

There are two reasons why Beijing, Shanghai and Guangzhou are the most sensitive in terms of accessibility. First, regarding their base status, China's three major airlines, Air China,China Eastern Airlines, and China Southern Airlines, are headquartered in Beijing, Shanghai, and Guangzhou respectively, and will therefore rely on their main bases to develop air shuttle routes as an important means of optimizing their innovative route networks [27]. Second, from the construction of the shuttle line, according to the official websites of each airline, Air China will launch six "*Air China shuttle*" in 2022: Beijing-Shanghai, Beijing-Hangzhou, Beijing-Chengdu, Beijing-Chongqing, Beijing-Guangzhou, and Beijing- Shenzhen. In 2023, the Beijing-Xiamen shuttle will be added. By the winter and spring season of 2023, China Eastern Airlines will operate 41 "*Sky Shuttle*". By the end of 2023, China Southern Airlines has launched 16 "*China Southern Airlines shuttle Lines*". Shenzhen's rapid rise in the manufacturing sector, particularly in high-tech industries, has bolstered its status as a transportation hub, thanks to the convergence of people, logistics, capital flows, and information flows [28]. As a key node connecting the world-class airport cluster in the Guangdong-Hong Kong-Macao Greater Bay Area, Shenzhen is playing an increasingly significant role in the development of the air shuttle network. Chengdu, Kunming, Xi'an, and Chongqing—the four major cities in the western region—have historically faced challenges in land transportation due to topographical constraints. However, with the advancement of the western development strategy and the growth of regional aviation, the status of these cities as hubs is steadily increasing[29].

In addition, closeness centrality ranking of Wuhan (0.95), Zhengzhou (0.93), Changsha (0.90) increases rapidly after the attack on the route . As a traditional railway hub city, affected by alternative transportation railways and highways [30], Wuhan, Zhengzhou, and Changsha present to be relatively low level of hubs [28].The results prove that the establishment and optimization of the air shuttle network has changed the route network pattern, which can cope with the challenges brought by alternative modes of transportation to a certain extent.

Table 5. Disruption of the hub accessibility function

Level	Range	Number	Hub Cities
High	14.29%~18.75%	3	Beijing, Shanghai, Guangzhou
Medium	9.52%~14.29%	4	Shenzhen, Chengdu, Kunming, Xi'an
Low	7.14%~9.52%	3	Chongqing, Harbin, Urumqi

Source: By authors.

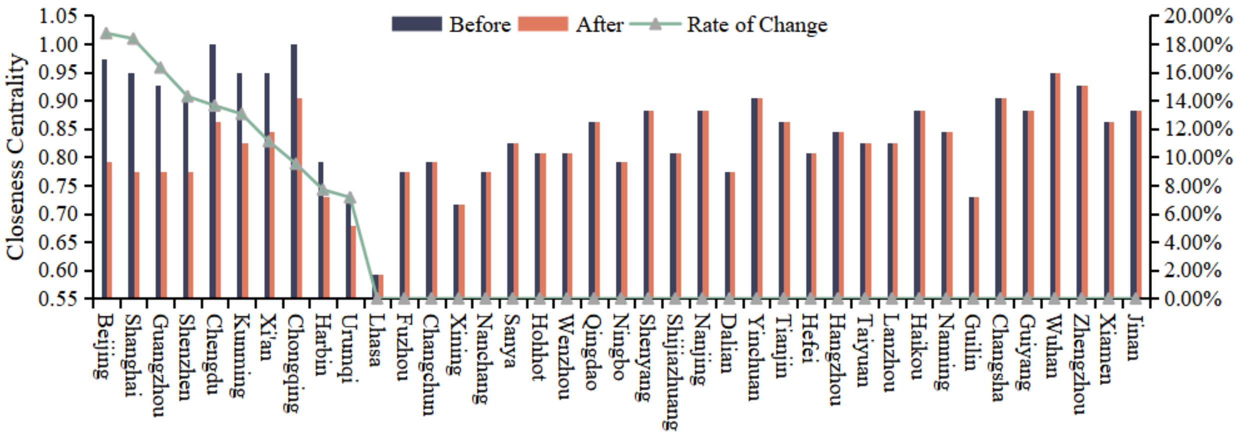

Figure12. Changes of accessibility of removing all international hub shuttle

Source: By authors.

3.3.2. The mpact of the obstruction of the international hub shuttle network on the transit

Betweenness centrality measures the importance of nodes in the network. In the aviation hub network, the betweenness centrality of a hub node reflects its ability to act as an "intermediary" within the network. Figure 13 illustrates the change in betweenness centrality for each hub when the shuttle line between international hubs is disrupted. When the shuttle line network is blocked, the intermediary role of the international hub node decreases. However, hubs that are not part of the shuttle line network take on an alternative intermediary role, increasing their importance within the entire route network. Using the natural discontinuity method, the absolute rate of change in node intermediary centrality is classified into three categories, as shown in Table 6. After the disruption of the shuttle line, 8 hubs experienced significant changes in their transit function: Lhasa (102.50%), Fuzhou (84.41%), Changchun (81.77%), Xining (81.39%), Nanchang (80.18%), Sanya (67.30%), Hohhot (62.28%), and Wenzhou (61.71%). These hubs had relatively low betweenness centrality before the disruption, but their transit capacity increased significantly after the route was blocked, resulting in larger changes. There are 24 hubs with moderate changes, and 7 hubs with small changes. Among the international hubs, Shanghai, Guangzhou, and Beijing showed moderate changes in their intermediary centrality, while the remaining seven international hubs experienced small changes. Regional aviation hubs play an irreplaceable role in the development of regional markets, the opening of trunk and regional networks, and facilitating the transit of passengers, cargo, and mail within a specific region, capitalizing on their inherent advantages [31]. In the case of disruption to international shuttle lines, the transit role of regional aviation hubs is more pronounced. Except for Urumqi, the intermediary centrality of other international hub nodes has decreased. As a key hub for external connections in the region, Urumqi not only maintains close ties with nodes outside the province but also connects provincial nodes. With the expansion of interconnection routes between smaller nodes in Xinjiang Province and deeper connections with inland and coastal cities, Urumqi's status as a hub has been challenged to some extent [32].

From the perspective of the betweenness centrality of nodes after the shuttle line is blocked, Zhengzhou (8.20), Wuhan (8.10) and Changsha (7.14) rapidly improved the betweenness centrality ranking after routes are attacked. Zhengzhou, Wuhan, and Changsha are located in the core area of central China, with good airspace conditions, a vast economic hinterland, a large radiation radius, a low detour rate, and a high transfer ratio [33]. As non-international hubs, the intermediary centrality ranks high after the shuttle is blocked, indicating that these hubs have great potential to become important intermediaries in the aviation network, and at the same time, they also give the existing international hubs a certain competitive reference.

Table 6. Impact on the transitory function of the hub

Level	Range	Number	Hub Cities
High	56.3%~102.5%	8	Lhasa, Fuzhou, Changchun, Xi ning, Nanchang, Sanya, Hohhot, Wenzhou
Medium	16.14%~56.3%	24	Qingdao, Ningbo, Shenyang, Shijiazhuang, Nanjing, Dalian, Yinchuan, Tianjin, Hefei, Hangzhou, Taiyuan, Lanzhou, Haikou, Nanning, Guilin, Changsha, Guiyang, Wuhan, Zhengzhou, Shanghai, Xiamen, Guangzhou, Jinan, Beijing
Low	0.46%~16.14%	7	Chengdu, Shenzhen, Urumqi, Kunming, Xi'an, Chongqing, Harbin

Source: By authors.

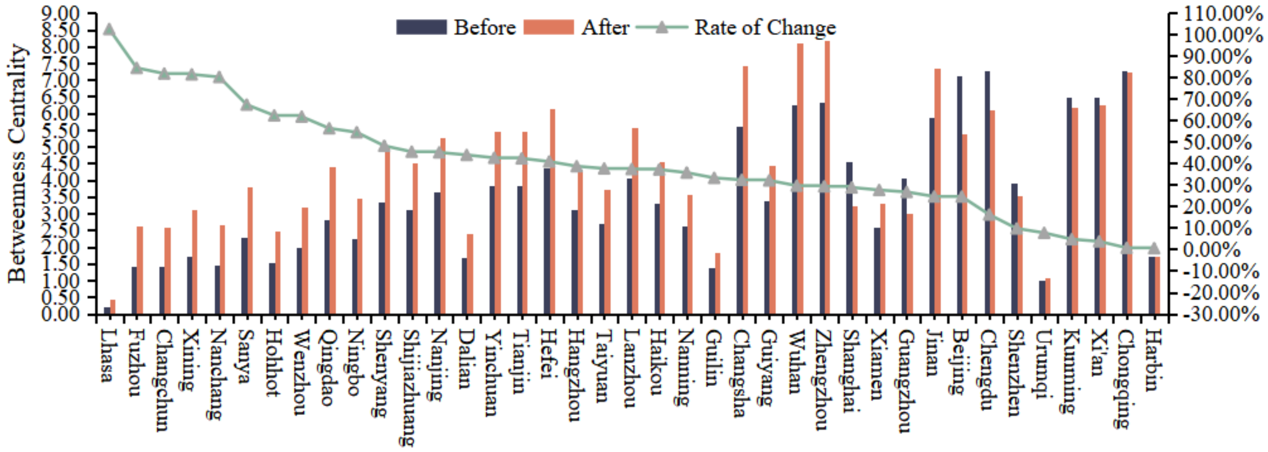

Figure 13. Changes of transitivity of removing all international hubs

Source: By authors.

4. Conclusions and Recommendations

This paper uses the complex network analysis to study the impact of the air shuttle network between international hubs on the hub route network, and obtains the following conclusions:

(1) The international inter-hub shuttle lines play a crucial role in enhancing the accessibility, aggregation, connectivity, and efficiency of the entire hub route network. These lines can be categorized into three echelons based on their importance: the shuttle lines between Beijing, Shanghai, Guangzhou and Shenzhen are the first echelon, shuttle lines between Beijing, Shanghai, Guangzhou and Shenzhen and the southwest region are the second echelon, and shuttle lines between Beijing, Shanghai, Guangzhou and Shenzhen and the cities in northwest and northeast are the third echelon.

(2) There are significant differences in the impact of shuttle line network disruption on node accessibility and transit. The disruption has the greatest impact on the accessibility of Beijing, Shanghai, and Guangzhou, while it most severely affects the transit of Lhasa, Fuzhou, and Changchun.

(3) Cities in central China, such as Wuhan, Zhengzhou, and Changsha, have demonstrated strong resilience in terms of accessibility and transit, challenging the status of existing hubs within the shuttle network.

Key routes in the shuttle network, such as the Beijing–Shanghai, Beijing–Guangzhou, and Shanghai–Guangzhou shuttles, serve as benchmarks in the route network. Each shuttle route offers valuable insights, setting the highest standards for the network. By conducting horizontal and vertical comparative analyses, these routes can enhance the overall competitive advantage of the network. For international hub nodes, the existing international hub shuttle network has certainly improved transit and accessibility. However, to further strengthen the network, differentiated strategies should be pursued on this foundation. This includes overall planning, such as defining the roles of individual cities and coordinating airport clusters, to effectively address the competitive pressure from regional hub nodes and even other modes of transportation.

For airlines, identifying high-value routes enables them to allocate resources more effectively towards these key routes, thereby increasing the output-to-input ratio. This enhances operational efficiency and profitability, allowing airlines to secure a competitive edge in the highly competitive aviation market. For airports, identifying high-value routes allows for the optimization of flight schedules and slot allocation, increasing the commercial value of the airport, improving passenger satisfaction, and attracting more carriers. This, in turn, supports regional economic development. For policymakers, route value identification provides a critical basis for decision-making. By understanding the value and potential of different routes, policymakers can prioritize investments in infrastructure, such as airport expansions, runway upgrades, and terminal renovations. This enables more accurate assessments of the economic and social benefits of infrastructure projects, helping to avoid blind investments and resource waste, and promoting the sustainable growth of the aviation industry. Additionally, in the context of high-speed rail expansion and an increasingly optimized network layout, identifying high-value routes offers a strategic approach to managing competitive pressures.

5. Limitations and Future Work

The data for 2020-2022 show anomalies that are not fully representative due to the impact of the COVID-19 pandemic. Therefore, relying solely on the 2019 data may introduce potential bias. The results of this study are regionally specific, and the generalization to other geopolitical contexts is somewhat limited. This study offers a new perspective on evaluating air shuttle lines, but it only constructs a hub route network and analyzes the position of shuttle lines between international hubs. Future research should expand on this by exploring the role of multiple types of shuttle lines within a broader route network.

Acknowledgements

We are grateful for the financial support from the National Natural Science Foundation of China (U2333206); the Major Project of Key Research Base of Humanities and Social Sciences of the Ministry of Education of China (22JJD630006); the Civil Aviation Safety Capacity Building Project of 2024 "Domestic Air Shuttle Safety Supervision"; and the Major Project of Social Sciences of Tianjin Municipal Commission of Education (2018JWZD52); Civil Aviation University of China Graduate Student Research Innovation Program (No. [2023YJSKC07006]).

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