Optimization of Urban Air Route Networks for China's Four World-Class Airport Clusters Based on Air Accessibility

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ABSTRACT

Measuring and analyzing the air accessibility of each airport city in world-class airport clusters is a prerequisite for optimizing the design of the route network and contributing to the function of high-quality power sources such as Beijing-Tianjin-Hebei. This paper calculates the air accessibility of 42 cities located in China's four world-class airport clusters using the weighted frequency air accessibility model, and finds that the air accessibility of each airport city shows a pattern of vertically steady improvement and horizontal polarization. The accessibility of international hubs, regional hubs, and non-hub cities shows a significant gradient decline. This implies that international aviation hub cities have significant comparative advantages in terms of aviation accessibility, owing to their robust economic foundation, large population size, and high frequency of flight operations. In the future, airport cities within China's four world-class airport clusters should further enhance flight connectivity between international aviation hubs, thereby establishing a primary backbone channel for domestic air transportation while fostering local economic development and attracting more residents. Meanwhile, it is crucial to effectively promote coordinated development among international aviation hubs, regional aviation hubs, and non-hub airports through strategic linkages in order to fully leverage the carrier role played by world-class airport clusters as catalysts for urban clusters. This paper presents a new exploration for more objective measurement of urban airport aviation accessibility and also provides an important reference for optimizing the design of air route networks among China’s four world-class airport clusters.

Keywords: World-class airport cluster, Air accessibility, Air route network.

1. Introduction

As the main engine of Chinese-style modernization, urban clusters are the main platform to support China's high-quality economic development [1]. City clusters such as Beijing-Tianjin-Hebei, Yangtze River Delta and Guangdong-Hong Kong-Macao Greater Bay Area, as regions of superior economic development, play an important role as a power source in driving the overall improvement of the national economic efficiency, and are important strategic spatial vectors for socio-economic development [2]. Transportation serves as the skeleton of interconnection between cities [3], the synergistic development of city clusters relies on world-class airport clusters [4]. The integration and development of airport clusters and city clusters has become an important trend in global economic development [5,6]. Therefore, world-class airport clusters such as Beijing-Tianjin-Hebei, the Yangtze River Delta, Guangdong-Hong Kong-Macao Great Bay Area and Chengdu-Chongqing airport clusters become the important carriers to support the function of power source of economic development of city clusters [7].

Studies have shown that air transportation between airport clusters is an important link for economic exchanges and interactions among city clusters [8,9,10,11,12] and the quality of its route network has a significant impact on the economic development of the city [13]. *The Guidelines on developing comprehensive transport network* points out that "the four poles of Beijing-Tianjin-Hebei, Yangtze River Delta, Guangdong-Hong Kong-Macao Greater Bay Area, and Chengdu-Chongqing Twin-city Economic Circle" are the important parts of the transportation "aorta" between urban clusters in China. The expansion of the four poles radiating space and transportation resource allocation capacity is important for building China's comprehensive transportation network. Resource allocation capacity to build China's comprehensive three-dimensional transportation synergistic development and domestic and international transportation convergence and transformation of the key platform is of great significance. As an important part of the modern comprehensive transportation system, air transportation plays an indispensable role in the transportation links among the 4 poles of Beijing-Tianjin-Hebei, Yangtze River Delta, Guangdong-Hong Kong-Macao Greater Bay Area, and Chengdu-Chongqing Twin Cities Economic Circle [14], and the main backbone of the air transportation channel formed among the hub airports of the world-class airport clusters is an important support for building China's air express network and consolidating the basic plate of the route network.

Related studies have shown that the high or low level of airport accessibility in the four world-class airport clusters is a key basis for determining the design of inter-airport route network connectivity [15,16]. Accessibility is one of the hot issues in human geography, urban and rural planning, transportation economics and other disciplines [17], which refers to the degree of convenience in using a specific transportation system to reach the activity location from a given location [18]. Thus, it is an important indicator to measure the degree of transportation network development [19], and is the key indicator to measure the development level of the world-class airport clusters level [20]. The effect and influence of transportation modes on urban and regional space stems from changes in accessibility. At present, the research of accessibility in the field of urban transportation mainly has the following aspects: to evaluate the existing transportation network by accessibility [21,22] and optimize the transportation network and its existing layout based on spatial accessibility [23,24,25,26] and some scholars have studied the effect of transportation development on regional accessibility [27,28], and accessibility is also used to measure the rationality of the spatial allocation of urban public service resources [30] . Research on world-class airport clusters has mostly focused on the evaluation of efficiency and synergistic development within airport clusters [31,32,33,34], and the design of inter-airport routing networks has not yet been systematically studied.

However, at present, Chinese scholars still use traditional models to evaluate airport accessibility, which fails to fully consider the heterogeneity of airport traffic flow. Moreover, the research samples mostly focus on a single airport, while lack of systematic research at the airport cluster level. Therefore, this paper focuses on the four world-class airport clusters proposed in *the "14th Five-Year Plan" for Civil Aviation Development*. Based on the accessibility of the cities where the airport clusters are located, it utilizes the evaluation indexes in the field of civil aviation, such as flight frequency, and relies on indicators related to airport development, including the resident population and GDP of the cities to calculate the air accessibility between the cities of the four world-class airport clusters so as to analyze the current development of air transportation networks with an aim to providing a theoretical basis for the future scientific design of air transportation networks and the smooth flow of the main air backbone corridors, and giving full play to the role of the four world-class airport clusters as a support for the economic power houses of Beijing-Tianjin-Hebei, the Yangtze River Delta, and Guangdong-Hong Kong-Macao Greater Bay Area, so as to promote the collaborative development of the region.

2. Data Sources and Research Methods

2.1 Description of Research Objectives / Sample Selection

This paper focuses on the 42 cities where airports within the four world-class airport clusters outlined in the *14th Five-Year Plan for Civil Aviation Development* in China， Beijing-Tianjin-Hebei, Yangtze River Delta, Guangdong-Hong Kong-Macao Greater Bay Area (Hong Kong and Macao airports are not taken into account during data processing due to factors such as data availability and policy) and Chengdu-Chongqing Airport cluster.

2.2 Evaluation Model for the Air Accessibility of Airport Cities

Accessibility is closely related to many factors such as the geographical location of the city, the level of economic development and the size of the city. Considering the heterogeneity of airport traffic flow, based on the traditional weighted average travel time, this paper draws on the existing studies [35,36], and uses frequency weighted average travel time to measure airport urban air accessibility taking into account the factor of flight frequency.

The larger the value of the index, the lower the level of accessibility of the city. The specific model is as follows:

$$N_i = \frac{M_i}{n_i} \times \frac{\sum_{j=1}^{n} T_{ij} \times P_j}{\sum_{j=1}^{n} P_j}$$ [Formular 1]

$$M_i = \frac{\sum_{j=1}^{n} T_{ij} \times P_j}{\sum_{j=1}^{n} P_j}$$ [Formular 2]

$$P_j = \sqrt{GDP \times POP}$$ [Formular 3]

N_i : represents the frequency-weighted average travel time (min/trip) for city i.

n_i : represents the daily frequency of flights at city i's airport as the sum of the daily frequency of flights for the three scenarios of departures from, stopovers at, and arrivals to city i.

M_i : represents the average air travel time of city i.

T_{ij}: represents the average air travel time from i to j (min).

P_j : represents the city quality of city j.

n: the number of nodes in the network.

The geometric mean of the gross regional product GDP (billion yuan) and the number of resident population POP (10,000 people) is used as the weights to construct the city quality according to Formula 3.

2.3 Data Sources

The Civil Aviation Administration of China (CAAC) proposed the concept of the three world-class airport clusters of Beijing-Tianjin-Hebei, the Yangtze River Delta and the Pearl River Delta for the first time around 2015, so the starting year of the data statistics in this paper is 2015. The COVID-19 pandemic had a big impact on the air transportation industry, and the data during the COVID-19 pandemic period can hardly reflect the normalized development of domestic civil aviation, so the data is counted up to the pre-pandemic period 2019. The data of resident population and GDP are obtained from *China Urban Statistical Yearbook (2016-2020).* The data of flight frequency study are obtained from *China Civil Aviation Statistical Yearbook (2016-2020).* The shortest flight time of direct routes is calculated by Boeing 737-800 with an average speed of 800km/h through the Great Circle Mapper website. The shortest flight time of transit routes is calculated by Boeing 737-800 with an average speed of 800km/h through the Great Circle Mapper website. The shortest flight time of transit routes was obtained by MATLAB by searching the shortest distance transit points of all cities of direct routes.

3. Empirical Analysis of the Evaluation Results of Air Accessibility of Airport Cities in China’s Four World-Class Airport Clusters

3.1 Empirical Results of Air Accessibility to Each Airport City in China;s Four World-Class Airport Clusters

Table 1 shows the results of the air accessibility of the cities in China's four world-class airport clusters from 2015 to 2019, from which it can be seen that the air accessibility of hub cities such as Beijing, Shanghai, Guangzhou, and Shenzhen is significantly better than that of non-hub cities such as Chengde, Zhangjiakou, Tangshan, and Quzhou.

Table 1 Air accessibility to cities in China's four world-class airport clusters from 2015 to 2019

Year / City	2015	2016	2017	2018	2019	Year / City	2015	2016	2017	2018	2019
Shanghai	5.78	5.52	5.23	5.61	5.86	Lianyungang	673.01	519.13	409.13	385.74	375.63
Beijing	6.42	6.37	6.82	7.90	6.89	Luzhou	984.96	940.63	2521.38	5625.67	441.27
Guangzhou	10.79	10.17	9.89	9.74	9.33	Xuzhou	891.00	714.53	703.78	878.41	450.36
Shenzhen	14.00	12.93	11.74	12.04	11.16	Yangzhou	1253.16	1041.15	704.77	645.67	506.95
Chongqing	16.30	14.45	13.13	12.39	11.26	Zhoushan	2683.78	856.38	819.89	701.75	630.92
Chengdu	22.59	17.60	15.55	15.42	14.92	Jinhua	1066.66	805.42	1042.21	848.98	661.43
Hangzhou	18.42	14.59	12.55	12.40	16.60	Huangshan	1054.30	1030.64	618.94	669.76	675.19
Nanjing	25.34	23.56	19.28	16.09	16.66	Fuyang	1426.83	1528.57	966.66	877.68	762.68
Tianjin	39.76	37.37	26.42	28.51	26.78	Taizhou	2424.79	1773.91	1265.49	973.36	822.25
Wenzhou	78.31	63.99	53.69	45.88	36.22	Handan	3553.74	2797.20	1622.01	1206.10	998.13
Shijiazhuang	94.62	65.64	51.94	70.04	46.39	Chizhou	1958.50	5461.44	1102.29	1293.48	1200.30
Hefei	88.84	75.71	64.91	50.17	47.52	Nanchong	2395.46	2025.15	1572.23	1595.37	1277.57
Ningbo	102.03	89.46	63.85	58.43	53.60	Dazhou	2384.18	2772.86	626.48	1640.21	1440.58
Zhuhai	244.13	113.13	112.89	53.83	67.65	Yibin	1758.58	1785.68	823.03	1537.73	1484.85
Wuxi	297.56	274.13	213.02	186.96	160.62	Foshan	3839.85	4227.10	3306.21	14943.90	1875.41
Changzhou	675.55	698.31	546.10	487.42	238.35	Anqing	2719.70	2389.96	1703.17	2223.36	1912.87
Nantong	773.04	500.55	359.98	285.20	244.20	Qinhuangdao	4332.06	2924.17	2273.56	2993.60	2164.10
Yancheng	1170.60	586.16	639.93	321.97	294.63	Chengde	\	\	7785.73	4228.58	2454.33
Huaian	1015.61	769.87	472.09	431.24	296.61	Zhangjikou	3550.34	2316.31	1094.98	2631.44	3054.32
Mianyang	878.23	693.39	389.37	343.71	310.63	Tangshan	3373.55	3303.29	2899.14	2979.32	3161.85
Huizhou	2795.21	2010.80	1108.41	487.75	342.76	Quzhou	7054.72	7303.73	7322.84	5975.87	3861.79

Source: By authors.

In conjunction with the air express, the cities with higher frequency of air express access are generally consistent with those with better air access in Table 1, all of which are international hubs in the airport clusters. But there is still much room for further development of air access and express construction in these cities. Table 2 shows the average daily frequency of air express routes between international aviation hubs within the four world-class airport clusters from 2015 to 2019. The frequency of flights between the six international aviation hubs has increased from 729 flights in 2015 to 835 flights in 2019, an increase of only 14.54%, whereas the national frequency has increased by as much as 35.03% in the same period. Figure 1 visualizes the average daily frequency of air express flights between Beijing, Shanghai, Guangzhou, Shenzhen, Chengdu and Chongqing in 2019, showing that there is a serious imbalance in the efficiency of air operations between the six international aviation hubs within the world-class airport clusters. Air operation frequency of Beijing-Shanghai is much higher than that of Beijing-Guangzhou, Beijing-Shenzhen, Beijing-Chongqing and Beijing-Chengdu, while air operation frequencies of Shanghai-Beijing, Shanghai-Guangzhou, and Shanghai-Shenzhen are much higher than that of Shanghai-Chongqing and Shanghai-Chengdu.

Table 2. Daily average frequency of air express routes between international aviation hubs

within the four major airport clusters from 2015 to 2019.

Source: By authors.

(Notes: Air express routes are defined in the table as direct routes with a daily average frequency of

		Beijing	Shanghai	Guangzhou	Shenzhen	Chengdu	Chongqing
2015	Beijing	0	96	56	65	61	37
	Shanghai	96	0	72	88	49	45
	Guangzhou	56	72	0	0	47	38
	Shenzhen	65	88	0	0	36	39
	Chengdu	61	49	47	36	0	0
	Chongqing	37	45	38	39	0	0
2016	Beijing	0	100	59	63	65	40
	Shanghai	100	0	76	90	52	46
	Guangzhou	59	76	0	0	49	40
	Shenzhen	63	90	0	0	39	41
	Chengdu	65	52	49	39	0	0
	Chongqing	40	46	40	41	0	0
2017	Beijing	0	98	60	62	64	38
	Shanghai	98	0	78	93	54	49
	Guangzhou	60	78	0	0	50	43
	Shenzhen	62	93	0	0	45	42
	Chengdu	64	54	50	45	0	0
	Chongqing	38	49	43	42	0	0
2018	Beijing	0	100	62	67	67	39
	Shanghai	100	0	86	96	58	53
	Guangzhou	62	86	0	0	52	42
	Shenzhen	67	96	0	0	49	47
	Chengdu	67	58	52	49	0	0
	Chongqing	39	53	42	47	0	0
2019	Beijing	0	101	65	67	66	41
	Shanghai	101	0	89	99	62	56
	Guangzhou	65	89	0	0	52	41
	Shenzhen	67	99	0	0	49	47
	Chengdu	66	62	52	49	0	0
	Chongqing	41	56	41	47	0	0

10 or more)

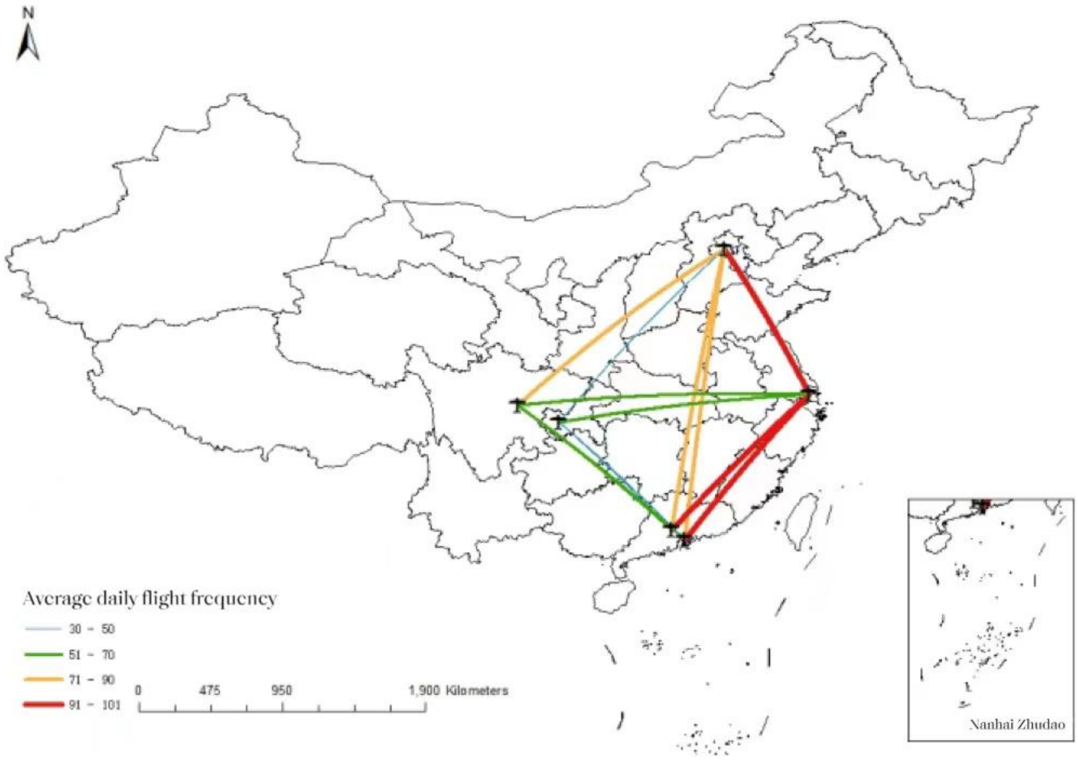

Figure 1. Daily average frequency of air express routes to international hubs in the four major airport clusters

Source: By authors.

3.2 Analysis of Evaluation Results of the Overall Air Accessibility of the Cities Within the Four World-Class Airport Clusters

The overall air accessibility of the cities within the airport clusters is generally turning for better, showing a pattern of "vertically steady improvement and horizontal polarization". Table 3 shows the results of the statistical description of the air accessibility of the four world-class airport clusters from 2015 to 2019.

Table 3. Descriptive statistics of air accessibility of the four major airport clusters from 2015 to 2019

Year / Norm	2015	2016	2017	2018	2019
minimum value	5.78	5.52	5.23	5.61	5.91
maximum value	7054.72	7303.73	7785.73	14943.90(5975.87 *)	3894.23
extremely poor	7048.94	7298.221	7780.50	14938.29 (5970.27*)	3888.32
average value	1418.29	1282.95	1080.49	1376.16	787.55

Source: By authors.

(*Notes: Foshan Shadi Airport ceased operations on October 18, 2017, and resumed operations on October 12, 2018. The abnormal data in 2018 in all of the following tables refer to those on Foshan Shadi Airport.)

As shown in Table 3, the maximum value of the overall air accessibility of the four major airport clusters decreased from 7054.72 in 2015 to 3849.23 in 2019. The average value decreased from 1418.29 in 2015 to 787.55 in 2019. Meanwhile, it can be seen by the change of the air accessibility of the airports within the airport clusters in Table 1 that the air accessibility of the airport cluster is steadily improving in general. From 2015 to 2019, there was a significant difference between the minimum and maximum values of air accessibility each year, indicating disparities in air accessibility among cities within the airport clusters, presenting a different pattern. However, the overall difference of accessibility's average value has been decreasing year by year, suggesting a narrowing gap in air accessibility levels among airports within the airport clusters.

3.3 The Descriptive Statistics and Analysis of Air Accessibility in Cities Within the Four Major Airport Clusters

The development of air accessibility within airport clusters is unbalanced. There are significant differences in the development of air accessibility within the airport clusters. As can be seen from the data in Table 4, there are differences in the maximum, minimum, and average values of air accessibility among the four major airport clusters. The minimum value of air accessibility in the Yangtze River Delta Airport cluster is lower than that in the other three clusters, especially when compared to the Chengdu-Chongqing Airport cluster, within which the airports have great development potential. The average value of air accessibility in the Yangtze River Delta Airport clusters is generally better than that in the other three clusters, indicating an imbalance in development among the four airport clusters. The standard deviation values of air accessibility within each of the four airport clusters are at relatively high levels, suggesting internal differentiation and disparities in development among the airports within each cluster.

Table 4. Descriptive statistics of air accessibility of the four major airport clusters from 2015 to 2019

airport clusters	Year / Norm	2015	2016	2017	2018	2019
Beijing-Tianjin-Hebei	maximum values	4332.06	3303.29	7785.73	4228.58	3161.85
	minimum value	6.42	6.37	6.82	7.90	6.89
	average value	2135.78	1635.76	1970.08	1768.19	1489.10
	variance (statistics)	3910183.28	2321295.09	6710788.00	2727422.78	1899009.49
	(statistics) standard deviation	1977.42	1523.58	2590.52	1651.49	1378.05
Yangtze-River Delta	maximum values	7054.72	7303.73	7322.84	5975.87	3861.79
	minimum value	5.78	5.52	5.23	5.61	5.86
	average value	1248.07	1205.76	868.63	789.79	603.24
	variance (statistics)	2404146.49	3259939.61	2290223.69	1617775.27	737222.12
	(statistics) standard	1550.53	1805.53	1513.35	1271.92	858.62

	deviation					
Guangdong-Hong Kong-Macao	maximum values	3839.85	4227.10	3306.21	14943.90(5975.87*)	1875.41
	minimum value	10.79	10.17	9.89	9.74	9.33
	average value	1380.80	1274.83	909.83	3101.45	461.26
	variance (statistics)	3271141.69	3449715.15	2008407.76	43866542.30	643907.35
	(statistics) standard deviation	1808.63	1857.34	1417.18	6623.18	802.44
Chengdu-Chongqing	maximum values	2395.46	2772.86	2521.38	5625.67	1484.85
	minimum value	16.30	14.45	13.13	12.39	11.26
	average value	1205.76	1178.54	851.60	1538.64	711.58
	variance (statistics)	1013400.67	1103678.08	829110.47	3799141.33	443224.24
	(statistics) standard deviation	1006.68	1050.56	910.56	1949.14	665.75

Source: By authors.

The flight frequencies between airport clusters are gradually consolidated in general, but there are significant differences in flight frequency between them. Table 5 shows the flight frequencies between the four world-class airport clusters in each year from 2015 to 2019, with the Yangtze River Delta airport cluster and Guangdong, Hong Kong and Macao airport clusters being the most closely connected, followed by the Beijing-Tianjin-Hebei airport cluster and Yangtze River Delta airport cluster, and the Yangtze River Delta airport cluster and Chengdu-Chongqing airport cluster; and the Beijing-Tianjin-Hebei airport cluster and Guangdong, Hong Kong and Macao airport cluster and the Beijing-Tianjin-Hebei airport cluster and Chengdu-Chongqing airport cluster are less frequent, pending further encryption of their inter-airline network. Based on air accessibility, opening up the air transportation market among the four major airport clusters is of great significance in promoting the high-quality development of China's air route network and the economic and social exchanges among people.

Table 5. Annual frequency of flights between the four world-class airport clusters from 2015 to 2019

Year	airport clusters	Beijing, Tianjin and Hebei	Yangtze River Delta	Guangdong, Hong Kong and Macao	Chengdu Yudong or Chongqing municipality, formerly in Sichuan
2015	Beijing-Tianjin-Hebei	3417	123902	67713	59215
	Yangtze- River Delta	123902	16342	195527	104303
	Guangdong-Hong Kong-Macao	67713	195527	34	74742

	Chengdu-Chongqing	59215	104303	74742	263
2016	Beijing-Tianjin-Hebei	3457	133758	70487	64051
	Yangtze-River Delta	133758	18173	210184	112497
	Guangdong-Hong Kong-Macao	70487	210184	43	78695
	Chengdu- Chongqing	64051	112497	78695	398
2017	Beijing-Tianjin-Hebei	5562	136834	95968	69300
	Yangtze- River Delta	136834	21192	229764	119224
	Guangdong-Hong Kong-Macao	95968	229764	21	90208
	Chengdu-Chongqing	69300	119224	90208	418
2018	Beijing-Tianjin-Hebei	5455	142873	80374	69161
	Yangtze- River Delta	142873	21442	226148	133891
	Guangdong-Hong Kong-Macao	80374	226148	75	89477
	Chengdu-Chongqing	69161	133891	89477	426
2019	Beijing-Tianjin-Hebei	5038	142229	82696	70022
	Yangtze-River Delta	142229	20431	256182	145623
	Guangdong-Hong Kong-Macao	82696	256182	4	91424
	Chengdu- Chongqing	70022	145623	91424	382

Source: By authors.

3.4 Analysis of the Evaluation Results of Air Accessibility to International Hubs, Regional Hubs and Non-Hub Airports

The air accessibility of international hub airports is significantly better than that of regional hub airports, and the air accessibility of regional hub airports is notably better than that of non-hub airports. Table 6 demonstrates the mean values and coefficients of variation of international hub, regional hub, and non-hub airports within the four major airport clusters from 2015 to 2019. It can be seen from the statistical results that there is a difference in the air accessibility level between various hubs. And a one-way ANOVA analysis was performed on the means of the data in each group by using SPSS.26.0, and all of them passed the significance test, which shows that the air accessibility level of international hubs is significantly better than that of regional hubs and also significantly better than that of non-hub airports. In terms of the coefficient of variation, the international hubs and regional hubs are kept around 0.5, indicating that the gap between these two types of hubs in the same level of internal access is relatively small. The coefficient of variation of air accessibility of non-hub airports is around 1, which is a larger value, indicating that there is a large difference in the level of air accessibility between non-hub airports and there is a phenomenon of differentiation.

Table 6. Descriptive statistics of air accessibility to various types of hubs within the four major airport clusters

Norm	Typology	2015	2016	2017	2018	2019

average value	international hub	12.65	11.17	10.39	10.51	9.92
	regional hub	63.90	52.90	41.81	40.22	34.62
	non-hub	2058.10	1862.99	1552.61	1981.17	1130.17
coefficient of variation	international hub	0.50	0.42	0.37	0.33	0.34
	regional hub	0.55	0.53	0.52	0.54	0.45
	non-hub	0.74	0.89	1.19	1.48	0.91

Source: By authors.

4. Policy Suggestions

World-class airport clusters such as Beijing-Tianjin-Hebei, Yangtze River Delta, Guangdong-Hong Kong-Macao Greater Bay Area and Chengdu-Chongqing airport Group are important carriers to support the functions of economic development of urban clusters, and the level of aviation accessibility determines the connectivity quality of air route networks among airport clusters. In this study, the weighted frequency air accessibility model was used to calculate 42 cities where China's four world-class airport clusters are located. The results show that the air accessibility of each airport city presents a vertical steady improvement and horizontal polarization, and the air accessibility of international hub, regional hub and non-hub cities presents a clear downward trend.

Based on the above research conclusions, this study puts forward the following countermeasures and suggestions: First, to further encrypt the frequency of flights between international aviation hubs and build the main backbone of air transport in four world-class airport clusters. The six international aviation hub cities of Beijing, Shanghai, Guangzhou, Shenzhen, Chengdu and Chongqing, as the core of the world-class airport group, have significant comparative advantages in aviation accessibility by virtue of their strong economic foundation, large population size and high density of flight frequency, and have become important fulcrum and platform to promote the economic connection of the four world-class urban clusters. In the future, the supply of time resources and airspace resources between the six international aviation hubs should be increased, the frequency and density of flights should be encrypted, and the unique role of the main backbone of air transport in promoting the internal circulation of China’s economy should be given full play. The second is to effectively promote the division of labor and cooperation among international aviation hubs, regional aviation hubs and non-hub airports within the airport group, and give full play to the driving function of hub airports to non-hub airports. The four world-class airport clusters should establish an internal collaborative operation mechanism on the basis of the differentiated division of labor and positioning of each airport, promote the differentiated design of route networks of international aviation hubs, regional aviation hubs and non-hub airports, and strengthen the interconnection corridors among airports in the airport groups with the help of ground transportation, so as to help the passenger source transportation from international hubs to regional hubs and regional hubs to non-hubs. We will build a modern world-class airport cluster system with complete design, complete functions and coordinated development.

5. Conclusions

The construction of China's four world-class airport clusters still has a long way to go. The measurement of air accessibility shows that the urban development of airports within the airport clusters is unbalanced. The route network between the clusters needs to be further constructed. The degree of coordinated development of airports within the clusters needs to be further strengthened. In the future, more comprehensive indicators can be chosen to measure the level of coordinated development of airports within the airport cluster and the overall development quality of the airport cluster, improve the division of labor among different types of airports, increase the overall coordination and international competitiveness of the airport cluster, and build an internationally leading world-class airport cluster, which can strongly support the function of Beijing-Tianjin-Hebei and other urban clusters as a comprehensive three-dimensional transportation hub and an important power source.

Although this study uses frequency-based aviation accessibility evaluation to quantitatively evaluate the accessibility results of 42 airport cities in four major world-class airport clusters in China, future studies can further improve and revise the accessibility model on the one hand. On the other hand, the research sample can be further expanded, so as to comprehensively measure the aviation accessibility level of Chinese airports.

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