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Indirect Connection Analysis Based on Wave-system Structures of Airlines Architecture in Hub Airport

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ABSTRACT

Slot resources are limited and not properly allocated, and the wave-system structures of airlines can organize slot time effectively. The article identifies and evaluates the wave-system structure of Beijing Daxing International Airport and Beijing Capital International Airport. It is found that: the wave-system of Beijing Capital International Airport is more obvious than that of Beijing Daxing International Airport, and the density and amplitude of waves are higher in summer and autumn than in winter and spring; the system waveforms of both Daxing Airport and Capital Airport are in the shape of morning and evening peaks; the indirect connection quality of flights from different departure airports via Capital Airport is higher than that of Daxing Airport; the indirect connections to destination airports via the two airports in Beijing are uneven in spatial distribution. The spatial distribution of indirect connections to destination airports via the two airports is uneven, but the wave-system plays a significant role in connecting small and medium-sized regional airports.

Keywords: Slot resources; Wave-system structures of airlines; Hub airport; Indirect connection; Indirect connection quality.

INTRODUCTION

Wave-system Structures of Airlines (WSA) refers to the effective organization and allocation of slot resources by airlines for airport flights, thus achieving a centralized arrangement of inbound and outbound flights (Cai 2020). The inbound and outbound peaks of flights are called "inbound waves" and "outbound waves" respectively. The wave-system refers to a number of consecutive wave-systems formed by all flights in the airport within one day (Huang and Wang 2018). Wave-system structures refers to multiple continuous wave-systems formed by all flights in an airport within one day. Slot is a scheduled time of arrival or departure for an aircraft to land or take off on a specific date, and is the permission for an aircraft to use or coordinate the airport's aviation services during a specified time (Tang *et al.* 2021).

Building a reasonable wave-system is an effective way to alleviate the contradiction between supply and demand of slot resources (Gao *et al.* 2012). Slot resources is an important market resource for the development of the civil aviation industry (Civil Aviation Administration 2018). However, with the year-on-year growth of the number of civil aviation passengers and

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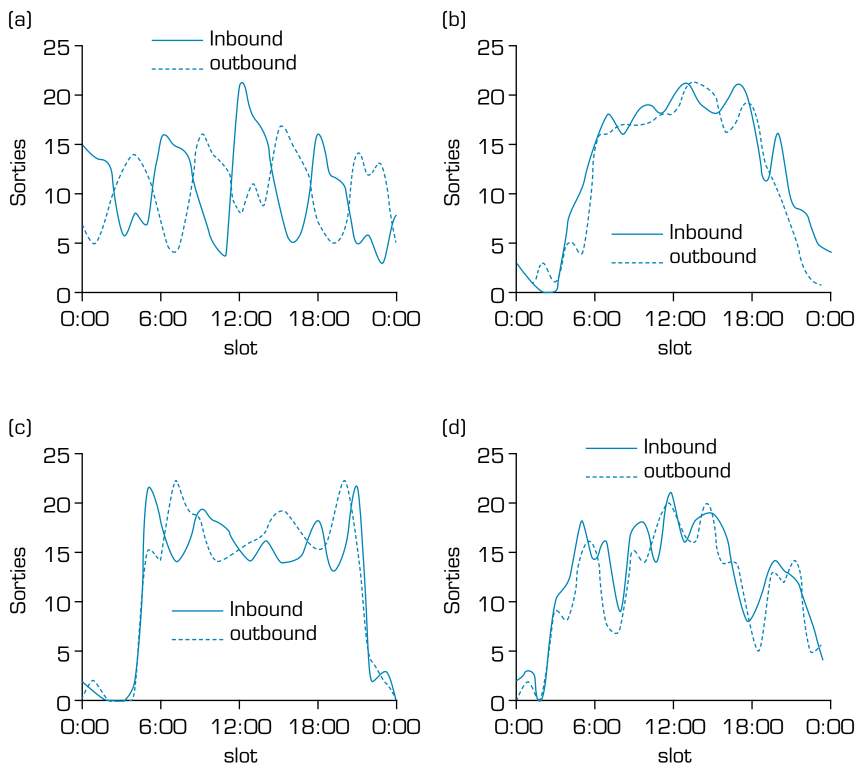
the regional concentration of flight traffic, the supply of limited slot resources at Chinese airports, especially hub airports, has become increasingly tight. By the end of 2020, China's civil aviation transportation scale has ranked second in the world for 16 consecutive years, at the same time, China's civil aviation airspace usage only accounts for 30% of the total airspace, while the United States, which is comparable to China's land area, has 75% of the total open airspace (Lin 2019). The capacity of airspace directly determines the capacity of slot resources. The eastern region of China has a dense airway network, with 22.7% of the country's licensed airports, yet it concentrates 80% of the civil aviation traffic, and the supply of slot resources is obviously insufficient. Some regional hub airports in the western region, such as Xi'an, Urumqi, Chengdu and other airports with high traffic volumes, have relatively tight slot resources, and the growth rates of flight movements of the three airports from 2011 to 2020 are 87.89%, 82.24% and 64.95% respectively. In addition, the allocation of slot resources in China is mainly in the form of inheritance-based grandfather rights, in which the number of slot resources allocated by grandfather rights rules accounts for more than 90% of the total, and even reaches 95% in busy airports, which also exacerbates the unfair allocation of slot resources and demand imbalance. Wave-system can effectively integrate slot resources and divide it into multiple waves; when one group of wave-system is finished, another group of wave-system will be activated (Jin and Wang 2005). It effectively promotes the circular cooperation of inbound and outbound flights at hub airports. It can also improve the efficiency of connecting passengers in different directions through the setting of different waves (Huang and Wang 2018), and it can optimize the airport's landing and takeoff planning settings and play a positive role in relieving slot resources tension.

Wave-system construction helps optimize the route network structure. Hub-and-Spoke System is a comprehensive network of feeder routes with a collection of mainline routes established in a large city as the hub and feeder airline networks with small and medium-sized cities, which can meet both the demand for passengers and cargo between hub networks and the collection and distribution of passengers and cargo between feeder networks (Yang and Wang 2018). The network can meet both the passenger and cargo demand between the central network and the regional network. By constructing a wave-system, the feeder network forms an inbound wave at the hub airport and a relatively concentrated outbound wave after transit through the hub airport, which strengthens the transit capacity of the hub airport and effectively relieves the transit pressure brought by the mainline flight traffic to the hub airport, and is more conducive to the hub airport to improve the efficiency of flight utilization, optimize the route network construction and save the cost of airline companies (Zhou 2008). The specific studies are as follows: Zhang (2016) studied the slot time operation characteristics of major airlines in the world based on the central radiation route network at the hub airport; a nd the time prediction analysis of hub and spoke airport, the gravity model is used to predict the city's flight and time density. On the basis of the airline's central radiation route network and the transportation demand prediction of cities, a full-transit time optimization model with sufficient resources and a selective time optimization model with insufficient resources are constructed. Finally, a case study of the global network model of Air China is taken to verify and analyze the feasibility of this study (Zhang 2016). Based on wave-system mode, Boonekamp and Burghouwt (2017) built a connectivity model for air cargo business, mainly evaluating the impact of transit capacity on the concentration of cargo service supply space at hub airports. This model is applied to analyze the connectivity of European hub airports. The results show that Amsterdam Airport, Frankfurt Airport, Paris Charles de Gaulle Airport and London Heathrow Airport have relatively high concentration of cargo service supply space. The cargo service of these four airports can cover South America, Northeast Asia and other regions, with the characteristics of global air cargo hub (Boonekamp and Burghouwt 2017).

Currently, studies on wave-systems have been conducted focusing on four main issues, mainly concentrated in four aspects:

- The basic parameters of a wave-system. The factors affecting the wave-system in the hub airport are runway airside and landside capacity (Li and Xu 2009), airport transit capacity, number of flights, passenger handling capacity (Liu 2015), etc. There are four key indicators for evaluating wave-systems in airports (Sun and Su 2013). There is wave density (number of waves), wave amplitude (number of flights in an inbound or outbound wave), directionality of inbound and outbound flights, minimum connecting time (MinCT) and maximum connecting time (MaxCT) (Sun and Su 2013). Among them, the greater the amplitude of the wave, the greater the probability of connecting the flight with the transit hit rate (Li 2016b), MinCT is the time interval between the last incoming flight and the earliest outgoing flight, the shorter the interval, the stronger the transit capacity of the airport, and the smaller the number of wave-systems (Liu 2015).

- Wave-system form characteristics. Wave-systems can be divided into four types (Li *et al.* 2016): (a) Sawtooth wave-systems. Flight peaks alternate closely with landing and takeoff peaks (Fig. 1a), forming three or more peak (trough) pairs of landing and takeoff flights every day, mainly found in hub airports, with high flexibility and efficiency of transit flights. (b) Trapezoidal wave-system. After the initial daily peak, the number of takeoff and landing flights maintains a narrow oscillation during the daytime operation phase until the number of landing and takeoff flights rapidly decreases at night to form a trough (Fig. 1b). This type of wave-system has a relatively balanced number of takeoffs and landings during the daytime operation period, and the airport is highly efficient and tends to operate at full capacity. (c) Morning and evening peak wave-systems. The peak and extreme values of daily takeoff and landing flights occur in the morning and evening peaks respectively, and there are certain fluctuations in the hourly number of takeoff and landing flights during daytime operation (Fig. 1c), with alternating peaks and valleys. (d) Superposition-shaped wave-system. The waveforms of takeoff and landing flights are similar (Fig. 1d), and the peaks of takeoff and landing waves overlap in some periods, and the total number of takeoffs and landings during the day has obvious fluctuations.



Source: Adapted from Li (2016).

Figure 1. Wave-system Structures: (a) Sawtooth; (b) Trapezoidal; (d) Superimposed; Peak Wave-system Structures; (c) Morning and Evening.

- Wave-system directionality. There are complex and obvious aggregation-separation directional characteristics among different hub airport feeder routes that constitute the wave-system. Most of the transit flights show a hub-to-hub spatial pattern, so the hub airport wave-systems play a role in connecting flights in different directions (Pan *et al.* 2017). For example, when westbound flights enter a transit hub airport, they tend to fly eastbound or southbound (Huang and Ye 2020). The passengers who originate from the eastbound/northbound direction tend to take westbound/southbound flights at the transit hub airport. As there are four modes of connecting flights at hub airports: domestic to domestic, domestic to international, international to domestic and international to international (Huang and Wang 2017). The significant spatial differences between international and domestic feeder routes are mainly related to the route network construction of the first airline at the hub airport and the geographical location of the airport (Xu 2017).

- Economic value of the wave-system. For airlines, to ensure that passengers complete the transit process (Katsigiannis and Zografos 2021). In airlines, wave-system mode means longer aircraft waiting time on the ground and higher ground stage cost, which in turn increases the economic burden on consumers and affects aircraft occupancy. As a result, some low-cost airlines are reducing their aircraft parking time in order to save costs and increase aircraft utilization (Xu 2017). In airports, concentrated arrivals are more important. Concentrated waves of arrivals increase the resource load of airports, resulting in congestion and inadequate services at peak times, which affects normal airport operations; while at off-peak times, airports have idle service resources (Ye 2019). Therefore, hub airports should fully consider their own reception capacity and economic value to make reasonable planning of wave-system time.

In summary, the theoretical research on wave-systems by scholars has been more systematic, but the practical research on wave-system discriminations still needs to be improved. In contrast to developed countries in Europe and the United States, China's civil airports, including hub airports, still suffer from insufficient transit ratio (Pan *et al.* 2017). This has seriously restricted the development of China's hub airports and the operational efficiency of airlines. In this study, Beijing Capital International Airport and Beijing Daxing International Airport were selected as the research objects, and the wave-systems of the two airports were firstly identified and characterized; then, the indirect connection quality of the wave-systems of the two airports and its influence on the indirect connectivity were determined. The construction of wave-system of hub airports is beneficial to enhance the spatial connectivity and temporal coordination of airports (Jiang *et al.* 2020). It is also useful for improving airport robustness (i.e., the ability of airports to cope with delays caused by irregular flights), enhancing airport transit operations, and promoting the sustainable development of civil aviation industry (Zhang W 2016).

DATA SOURCES AND RESEARCH METHODS

Research Subjects

Beijing Daxing International Airport (PKX), the largest world-class aviation hub in China, is officially opened in September 2019, providing aviation services mainly for Beijing, Tianjin and Hebei regions. It cooperates with more than 60 domestic and foreign airlines, operating 179 routes and covering 141 destinations worldwide. In 2020, the airport handled 130,000 flights, ranking 18th in China, and 16.09 million passengers, ranking 17th in China. Beijing Capital International Airport (PEK), built in 1958, is the first civil airport in China, providing aviation services mainly to North China. It cooperates with more than 90 domestic and foreign airlines, operating 252 routes and covering 294 destinations around the world. In 2020, there were 300,000 departures and landings, ranking fifth in China. The passenger throughput was 34.51 million, ranking fifth in China and first in China since 1978 (fifth in 2020 due to the impact of COVID-19). The two airports constitute a new pattern of operation and development in Beijing, and play an important role in promoting the construction of the core area of the capital and the integrated development of Beijing, Tianjin and Hebei. In view of the superb hub market position and traffic volume of the two airports in China, which makes the construction of the wave-system typical, they are chosen as the research subjects.

Data source and processing

This study evaluates the wave-system structure characteristics that mainly requires the flight schedule dataset, as well as the dataset of all transit routes via Beijing Daxing International Airport and Capital Airport. In order to preserve the completeness of the flight schedule data, The author collected the scheduled time data of all inbound and outbound flights from Beijing Daxing International Airport and Capital Airport from October 19 to October 25, 2021 in the summer-autumn season, and from November 1 to November 7 in the winter-spring season, including the cancelled flights. All data are obtained from Frequent Flyer platform (http://www.variflight.com), which mainly uses the network tracking method to extract slot resources and departure/arrival data. The data are collected at 20 minutes intervals to reflect the time characteristics of the inbound and outbound wave-system structure. Only domestic flights are considered in the determination of wave-system directionality, mainly because of the impact of the new crown epidemic on the international business of civil aviation transportation and the fact that international flights account for only 5.5% of the total flights and are concentrated in the early morning hours, which do not have a prominent impact on the daytime wave-system structure.

Research Methodology

Wave-system identification method

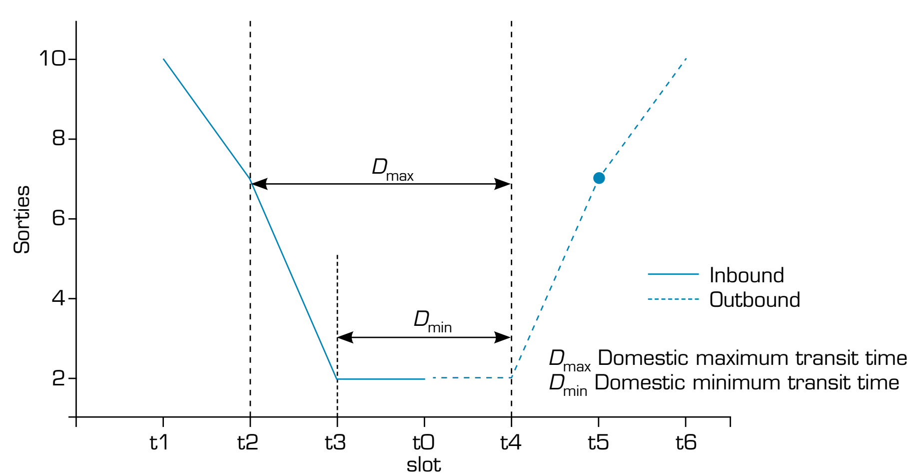
In the process of wave-system identification, scholars generally approach the identification from the perspective of flight takeoff and landing procedures (Harten 1998) or by simulating the schedule through time window iterations. The former emphasizes more on the time optimization of flight inbound and outbound, while the latter pays attention to the transit function of inbound and outbound flights, so the latter is adopted in this paper. The basic idea is:

First set the window time center t0 in the simulated idealized single wave-system window centered at time t0 (Fig. 2), the earliest arriving domestic flight is at time t2 (Jiang *et al.* 2020), with the latest connecting flight departing at time t4 (Pan *et al.* 2017). The earliest available connecting flight departs from t4 at the moment t3 , the latest arriving flight in China. The specific transit flow can be formed, i.e., domestic arrival flight (t2 ~t3) → connecting flight → domestic departure flight (t4 ~t5), then the time window of t2 ~t5 is recognized as a wave-system. The MinCT of different airlines for the completion of a wave-system is defined between 40-60 minutes; the MaxCT is affected by the psychological tolerance of passengers and is generally 120 minutes. Therefore, the MinCT of 40 minutes and the MaxCT of 120 minutes specified by Air China at the Capital Airport are used as the calculation criteria (Mirković and Tošić 2016). The wave-system intervals of Beijing Daxing International Airport and Capital Airport are identified by Eqs. 1 and 2.

$$S = [C - 0.5D_{max}, \quad C - 0.5D_{min}] \tag{1}$$

$$E = [C + 0.5D_{min}, \quad C + 0.5D_{max}] \tag{2}$$

where S represents the domestic inbound wave-system interval, E represents the domestic outbound wave-system interval, and C is the wave-system center. The inbound wave period is set as the first 60-20 min of the wave-system center, and the outbound wave period is set as the second 20-60 min of the wave-system center, and the wave-system interval is divided equally, with MinCT and MaxCT each accounting for half of the interval (Burghouwt and Wit 2005). Dmax is the maximum transit time and Dmin is the minimum transit time.



Source: Elaborated by the authors using data from Huang and Wang (2018).

Figure 2. Time windows of the domestic Wave-system structures of airlines.

Indirect connection index

Indirect connection means that the flight departs from the airport of departure and arrives at the airport of destination after one transit through the airport (Maertens 2018). The indirect connectivity of a wave-system is determined by the number of flights, the minimum number of connections and the connection quality (i.e., the spatio-temporal coordination of a set of connections). The connection quality is mainly affected by the transit time index in combination with the route index. Since many transshipments are unstructured routes formed by airlines based on economic efficiency, the connection quality of a wave-system needs to be judged with the help of the indirect connection index, which is given by (Ribeiro *et al.* 2018) (Eqs. 3–9):

$$WI = \frac{2.4*TI+RI}{3.4} \tag{3}$$

$$TI = 1 - \frac{1}{T_{j-M_j}} T_{jh} \tag{4}$$

$$R = \frac{IDT}{DTT} \tag{5}$$

$$RI = 1- \quad (2.5R - 2.5) \tag{6}$$

In the formula, WI represents the indirect connection index, reflecting the connection quality of the wave-system, its value range is [0, 1] , the larger the index, the better the connection quality, specifically can be divided into [0, 0.3] , [0.3, 0.5], [0.5, 0.7], [0.7, 1] 4 value range corresponds to the connection quality of the lower, medium, higher, very high; 4 levels (Cai 2020). The TI is the transit time index, which is used to determine the transit quality of transit flights in time, and is influenced by three factors: MaxCT, MinCT and the actual transit time of a specific flight, and the higher the index converges to 1, the higher the quality is; RI is the route index, which is used to determine the connection quality of transit flights in space, and is influenced by the ratio of slot resources (distance) between transit flights and direct flights. The higher the index converges to 1, the higher the quality of the transit; 2.4 indicates the ratio of passengers' significance of transfer time to slot resources (Veldhuis 1997); Tj and Mj are the MaxCT and MinCT of wave-system j of the airport involved in indirect connection, Tjh are the specific transit time of different flights in the airport, the larger Tjh is, the smaller WI is. R represents the detour time coefficient, which is used to judge the time efficiency of transit flight and analyze the influence of transit route on passenger transit, the value range is [1, 1.4] (Ribeiro *et al.* 2018). The lower value of R indicates that the slot resources efficiency is higher and the route value is more attractive, so the probability of passengers choosing transit will increase (Sun 2016). If the slot resources of a connecting flight are greater than 1.4 times that of a non-stop flight, the value of 0 is used to make the connecting flight ignored due to inefficiency; the larger the R, the smaller the RI (Lernbeiss 2016). The IDT is the actual total slot resources of indirectly connected flights, and the DTT is the estimated slot resources of direct connections based on the great circle distance of the Earth between the same origin and destination points (the study process excludes the case where the slot resources of flights in the transit scenario far exceeds the slot resources of direct flights).

ANALYSIS OF RESULTS

Wave-system identification

According to the wave-system identification method in 1.3.1, the data is defined and encoded using the num library in python. The results of the study show that wave-systems exist in both Capital Airport and Beijing Daxing International Airport, and the wave-systems are more pronounced in Capital Airport than in Beijing Daxing International Airport (Table 1).

Table 1. Beijing Daxing International Airport and Beijing Capital International Airport wave-system structures parameters.

Season	Airport	Density	Sorties	Total average daily flights
Summer and Autumn	Beijing Daxing International Airport	5	121	1477
	Beijing Capital International Airport	6	142	1775
Winter and Spring	Beijing Daxing International Airport	4	102	1297
	Beijing Capital International Airport	4	118	1656

Source: Elaborated by the authors.

Beijing Daxing International Airport has more wave-systems in summer and autumn than in winter and spring, and the number of flights is comparable. There are 5 wave-systems in summer and autumn (Table 2), in which the morning peak occurs at 6:20, with 121 flights, and the evening peak occurs at 18:40, with 113 flights. Except for the morning and evening peak waves, the volume of flights in the other three waves do not differ much and are all in the range of [90, 100] flights. The two waves at 12:20 and 12 :40 are closely connected, only 20 min apart, which means that the waves can form a better hub-and-spoke transit pattern and are more conducive to the airport's flight transit. During the winter and spring seasons, there are 4 wave-systems, and the number of flights in the wave-system interval accounts for 29.76% of the whole day's flights; the wave-system pattern starts at 8:00 and ends at 20:20, and there is a small peak during the 15:00-17:00 period, with 102 flights taking off and landing in total. The number of flights in other wave-systems do not vary much and are all in the range of [90, 100] flights. Overall, the wave-systems lasted longer in the summer and fall seasons, with an average of 120 min, and the average number of flights carried within the wave-systems is 104; the average number of flights carried within the wave-systems in the winter and spring seasons is 96, indicating higher passenger traffic in the summer and fall seasons.

Table 2. Wave-system structures of airlines time distribution of Beijing Daxing International Airport.

Summer/Autumn seasons				
Inbound band	**Inbound sorties**	**Outbound band**	**Outbound sorties**	**Total**
06:20–07:00	59	07:40–08:20	63	121
09:20–10:00	38	10:40–11:20	58	96
12:20–13:00	47	13:40–14:20	43	90
14:40–15:20	48	16:00–16:40	51	99
18:40–19:20	61	20:00–20:40	52	113
Percent of full day	35.33%	Percent of full day	35.02%	/
Winter/Spring Season				
Inbound band	Inbound sorties	Outbound band	Outbound sorties	Total
08:00–08:40	42	09:20–10:00	50	92
11:40–12:20	58	13:00–13:40	39	97
15:00–15:40	54	16:20–17:00	48	102
19:40–20:20	54	21:00–21:40	41	95
Percent of full day	33.17%	Percent of full day	26.56%	/

Source: Elaborated by the authors.

The number of flights taking off and landing after 12:00 a.m. is higher in the summer and autumn seasons, and the number of flights taking off and landing in the summer and autumn waves is also higher than that in the winter and spring seasons in Beijing Capital International Airport (Table 3). There are six wave-systems in the summer and autumn seasons, with the morning peak occurring at 7:00 a.m., when 115 flights take off and land, which is also the highest peak of incoming flights throughout the day. The midday peak occurs at 12:00, with a total of 142 flights, which is the highest number of flights in the whole day. The peak occurred again at 15:20, with a total of 120 flights. It is important to see that the C apital Airport has a larger number of flights taking off and landing after 12:00, which is in sharp contrast to the trend of outbound flights of Daxing Airport in summer and autumn.

The number of flights in and out of the airport at 21:00 is much higher, reaching 38 flights, second only to 7:00, mainly because Capital Airport is the base airport for Air China, China Eastern International Airlines, China Southern International Airlines, Hainan International Airlines and Capital Airlines. The airport is the base of 5 airlines, which are at the peak of inbound overnight; while a large number of outbound flights at the same time at this time are mostly to Shanghai, Guangzhou and other hub airports, which are also the base of many airlines. The density of the other three wave-systems are not very much, all within the [100, 115] frame range. There were 4 wave-systems in total during the winter and spring seasons, among which there was an evening peak during the time period of 18:40-20:40, with 118 inbound and outbound flights; the least number of flights took off and landed during the time period of 16:00-18:00, with 96 flights.

Table 3. Wave-system structures of airlines time distribution of Beijing Capital International Airport.

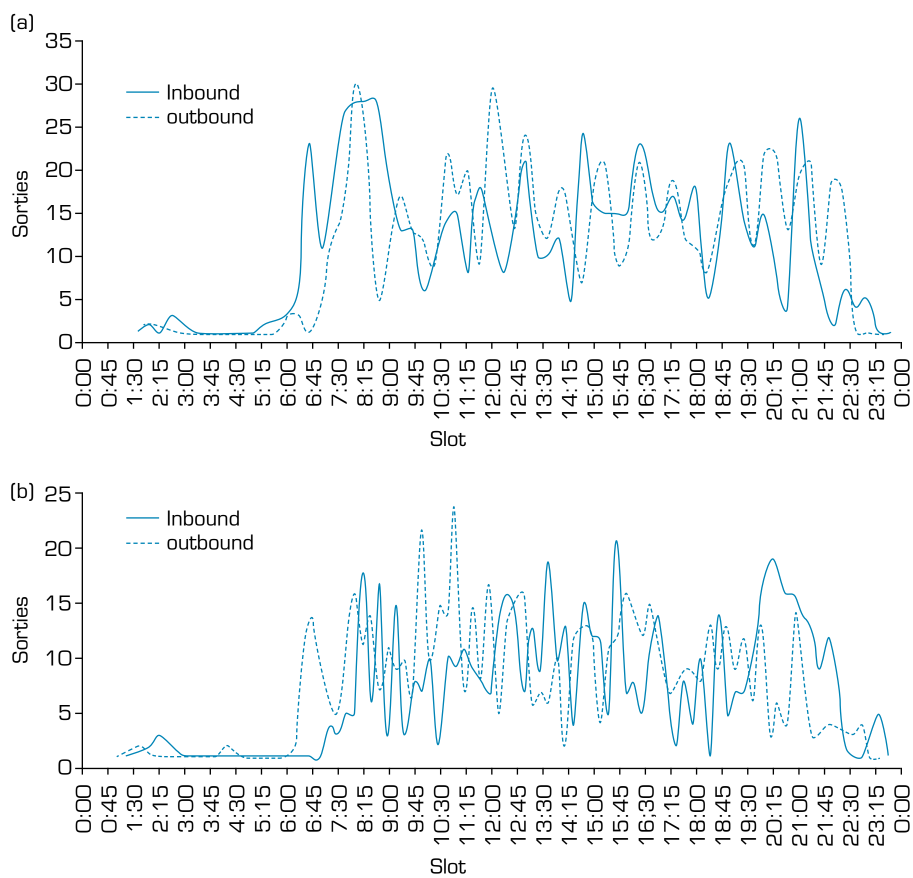
Summer/Autumn seasons				
Inbound band	**Inbound sorties**	**Outbound band**	**Outbound sorties**	**Total**
07:00–07:40	77	08:20–09:00	38	115
09:40–10:20	63	11:00–11:40	40	103
12:00–12:40	73	13:20–14:00	69	142
15:20–16:00	67	16:40–17:20	53	120
18:40–19:20	65	20:00–20:40	46	111
21:00–21:40	75	22:20–23:00	37	102
Percent of full day	43.48%	Percent of full day	35.06%	/
Winter/Spring seasons				
Inbound band	**Inbound sorties**	**Outbound band**	**Outbound sorties**	**Total**
08:40–09:20	54	10:00–10:40	55	109
11:20–12:00	56	12:40–13:20	59	114
16:00–16:40	35	17:20–18:00	61	96
18:40–19:20	56	20:00–20:40	62	118
Percent of full day	23.99%	Percent of full day	28.71%	/

Source: Elaborated by the authors.

The number of inbound and outbound flights within the wave-system at Beijing Beijing Daxing International Airport and Capital Airport accounted for less than 50%, and the time interval of the wave-system was larger. The ratio of the number of inbound and outbound flights within the wave-system interval to the average number of daily flights at Beijing Daxing International Airport is 35.33% and 35.02% in summer and autumn, respectively, 33.17% and 26.56% in winter and spring; the ratios at Capital Airport are 43.48% and 35.06% in summer and autumn, respectively, 23.99% and 28.71% in winter and spring. Although the number of flights within the wave-system reflects a certain concentration, in comparison, the number of peak departures as a percentage of the average daily number of flights at Paris-Charles de Gaulle and London's Heathrow International Airport are 65.4% and 51.8%, respectively, and the percentage of peak landings are 60.0% and 50.6%. The time interval between the wave-systems of the two Beijing airports is large, mainly because the wave-system interval is mostly during the traditional operating peak period, and by calculating the time difference between the starting times of the two immediately adjacent wave-systems (Li *et al.* 2016). The average time interval of wave-systems in summer-autumn and winter-spring seasons of Beijing Daxing International Airport is 180 min and 230 min respectively, and the average time interval of wave-systems in summer-autumn and winter -spring seasons of Capital Airport is 180 min and 200 min respectively, which shows that the time distribution and connection of wave-systems in different seasons of the two airports are not obvious. Therefore, the flight volume and time interval in the wave-systems of the two airports need to be improved, and there is still much space for improvement in the construction and use of wave-systems.

Wave-system form characteristics

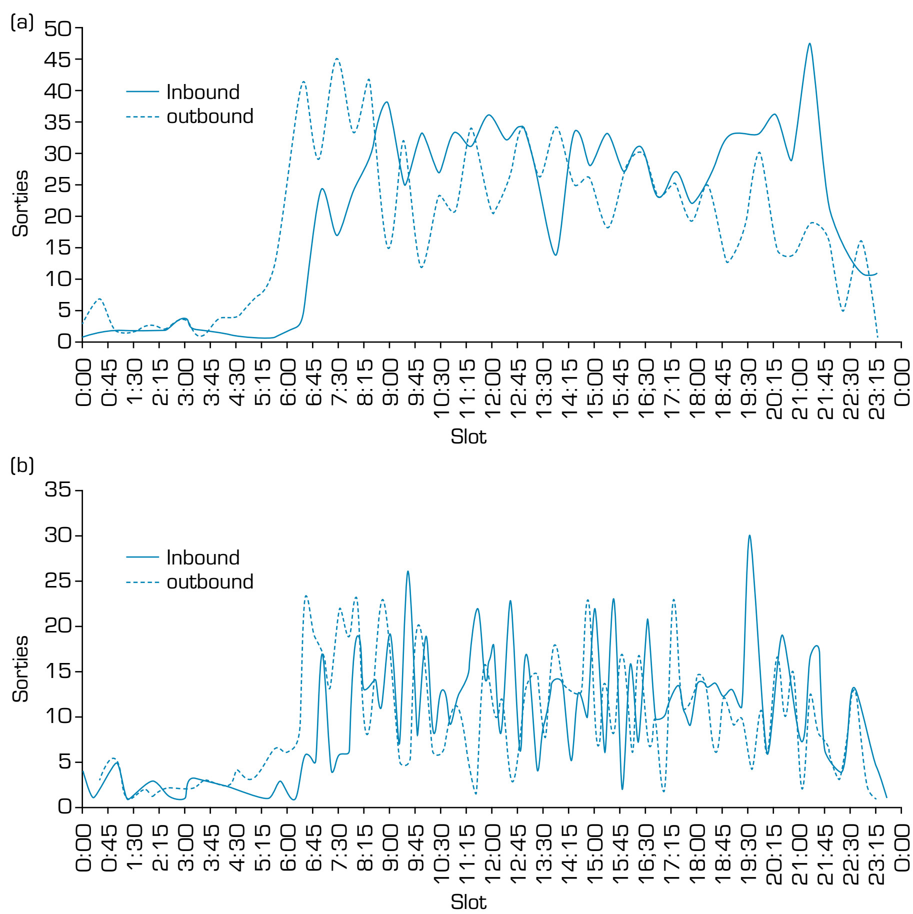
The wave-systems at Beijing Daxing International Airport belong to the morning and evening peak shape, and the inbound and outbound waves are superimposed during some periods. In the summer and autumn seasons, the inbound waves precede the outbound waves (Fig. 3a), and the inbound and outbound waves overlap during the morning peak hours, e.g. 7:30 a.m. The outbound slot resources are mainly derived from the grandfather rights of airlines, and the time allocation itself is a product of the checks and balances among ATC, airports and airlines, which is difficult to change once formed. The inbound slot resources are determined by the departure airport time, and the destination airport cannot be adjusted. The overlapping of inbound and outbound wave-systems greatly increases the instantaneous traffic pressure between the terminal area and the airport runway, resulting in a long detour for flights that do not have a suitable time to land before entering the port. The airport has limited margin for scheduling inbound and outbound flights, which in turn exacerbates the overlapping of inbound and outbound slot resources at the airport. Moreover, since there is a short delay between the inbound and outbound peaks, wave-system stack not only prolongs the transit time of passengers, but also causes spatial and temporal mismatch of airport service capacity, resulting in transient or short-term congestion. The outbound waves precede the inbound waves in winter and spring seasons (Fig. 3b), the wave amplitude of the outbound waves is higher than the inbound waves before 12:00, and the inbound waves are longer than the outbound waves; a 90-minute long inbound peak occurs from 20:15 to 21:45, showing the characteristics of early departure and late return, while in the daily wave-system changes, the frequency of wave ups and downs is intensive, and the wave occurrence length is more brief, showing comb-like pattern. It is mainly because Beijing Daxing International Airport has been in operation for less than 2 years and holds the scarce incremental time resources in the market, so the slot resources arrangement does not show a close continuity, this makes the number of flights fluctuate more over time.



Source: Elaborated by the authors.

Figure 3. (a) Airport slot distribution of Beijing Daxing International Airport in summer and autumn; (b) Airport slot distribution of Beijing Capital International Airport in winter and spring.

The wave-system at the Capital airport also shows a morning and evening peak, with the outbound wave preceding the inbound wave. During the summer and autumn seasons, the wave-system has obvious characteristics of early departure and late return (Fig. 4a), with a relatively stable change in wave amplitude and a "W" shape in the number of inbound and outbound flights throughout the day. The peaks of the outbound and inbound waves occur from 06:00 to 08:15 and from 19:30 to 21:45 daily, with three distinct outbound peaks between 6:00 and 8:15 and an all-day inbound peak at about 21:30. For example, Eastern Airlines flights from Shanghai often enter the Capital airport at around 22:00 and depart at 07:00 on the second day. In the winter and spring seasons, similar to Beijing Daxing International Airport (Fig. 4b), the wave-system shows a comb-like ebb and flow, with a peak inbound at 19:30 in the evening. This is mainly due to the large volume of flights at Beijing Daxing International Capital Airport, which makes the changes in the inbound and outbound dynamics particularly obvious; it also shows that Beijing Daxing International Capital Airport is the base airport for five major domestic airlines, and the large number of overnight flights increases the competition among airlines for time resources, which also makes the characteristics of morning peak departure and evening peak arrival unusually obvious. The number of inbound and outbound flights also peaks at 12:45 a.m. in summer and autumn and 9:45 a.m. in winter and spring.



Source: Elaborated by the authors.

Figure 4. (a) Airport slot distribution of Beijing Daxing, International Airport in summer and autumn; (b) Airport slot distribution of Beijing, Capital International Airport in winter and spring.

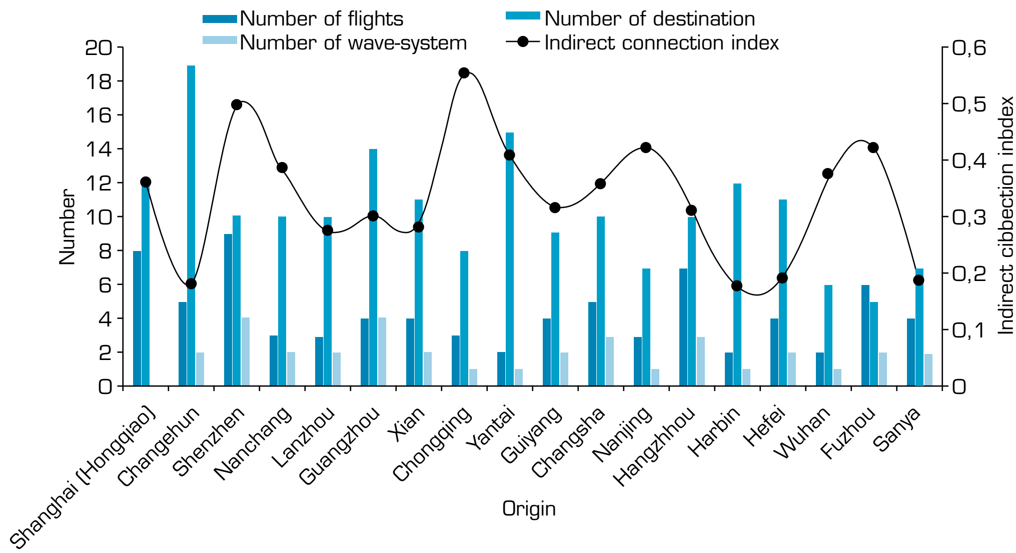
Through comparison, it is found that the density and magnitude of wave-systems in summer and autumn seasons are higher than those in winter and spring seasons at both airports, with peaks and valleys in terms of wave-system ups and downs. The summer and autumn seasons, especially the months from July to October, are the prime time for air transportation, while the winter and spring seasons have more stringent flight conditions and less passenger traffic, resulting in fewer flights, so the wave-system density and amplitude in the summer and autumn seasons are higher than those in the winter and spring seasons. The wave-system of Beijing Daxing International Airport is larger, mainly because the flight volume of Beijing Daxing International Airport is smaller, the minimum daily flight volume per hour is 5 and 2 in summer, autumn and winter-spring seasons, respectively, while the minimum daily flight volume per hour of Capital Airport is 12 and 5 in the same period, respectively. The total daily slot time of the two airports is 17 hours in winter and spring, and 20 hours in summer and autumn. The time interval between incoming and outgoing flights is therefore small, and the wave-systems are more undulating and denser, with a more obvious comb-like distribution.

Wave-system indirect connectivity analysis

Analysis of indirect connection of wave-systems at Beijing Daxing International Airport

The indirect connections within the wave-system are analyzed, and it is found that the indirect connection indices of flights from different departure airports transiting through Beijing Daxing International Airport are mostly distributed in the interval of [0.3, 0.5] (Fig. 5), with an average value of 0.33, indicating that the indirect connections of Beijing Daxing International Airport are more reliable, but its indirect connection combination allocation process still needs to be improved. Specifically, the indirect connection index is in the [0, 0.3] interval for six airports, namely Changchun Longjia International Airport, Harbin Taiping International Airport, Sanya Phoenix International Airport, Hefei Xinqiao International Airport, Lanzhou Zhongchuan International Airport, and Xi'an Xianyang International Airport, indicating that the flight combination benefits of the above departure airports with Beijing Daxing International Airport for transit are low because the transit time is longer for the first two airports, and the detour time coefficient is longer for the latter four airports. Beijing is a city with high latitude and close to Bohai Sea, so with Beijing airport as a transit, the connections that can be achieved by the departure airports in the western region are limited to Liaoning, Shandong and northern Jiangsu based on the detour coefficient limitation, and the connections that can be achieved by the departure airports in the southern region are limited to Northeast and North China, but Northeast can achieve extensive connections with most of the airports in East China, South China and Central China with the help of Beijing, so the number of destinations in the first two airports is greater than that in the last four. The largest number of airports with indirect connection indices in the [0.3, 0.5] include Guangzhou Baiyun International Airport, Hangzhou Xiaoshan International Airport, Guiyang Longdongbao International Airport, Shanghai Hongqiao International Airport, Changsha Huanghua International Airport, Wuhan Tianhe International Airport, Nanchang Changbei International Airport, Yantai Penglai International Airport, Fuzhou Changle International Airport, Nanjing Lukou International Airport, and Shenzhen Bao'an International Airport, reflecting that Beijing Daxing International Airport has the basic transit service capability as a hub airport. Only Chongqing Jiangbei International Airport has an indirect connection index in the range of [0.5, 0.7] and the routes connected to Beijing Daxing International Airport are mainly operated by China Southern Airlines based at the airport. Therefore, the indirect connection index of this route is higher than other routes in terms of transfer time scheduling and transfer destination allocation.

There is a mismatch between the quality of in-wave indirect connections and indirect connection opportunities for Beijing Daxing International Airport. Indirect connection opportunity refers to the number of flights from the originating airport connected by the transit airport, which is mainly related to the number of connecting destinations and the number of flights to the destinations after transit. For example, Changchun Longjia International Airport has the lowest indirect connection index with Beijing Daxing International Airport (0.181), mainly because the average transit time at this airport is greater than 80 min, which makes the transit time index only -0.275, and the latency time of passengers also reduces the quality of indirect connections. However, during the study period, Changchun Longjia International Airport has 6 flights connecting to Beijing Daxing International Airport and to 19 other destinations after transit through Beijing Daxing International Airport, which is the maximum among all study subjects, reflecting that the flight route with the most transit opportunities has insufficient indirect connection quality. The transit time index of Harbin Taiping International Airport is -0.25, which also directly affects the quality of its indirect connections. Shenzhen, Chongqing and Fuzhou have 10, 3 and 6 flights connecting to Beijing Daxing International Airport respectively, and their indirect connection indices are all in the range of [0.45, 0.7], but the number of destinations connected via Beijing Daxing International Airport after transit is less than 10, mainly because many transit routes are considered to be ineffective connections due to their large detour time coefficients after combination.



Source: Elaborated by the authors.

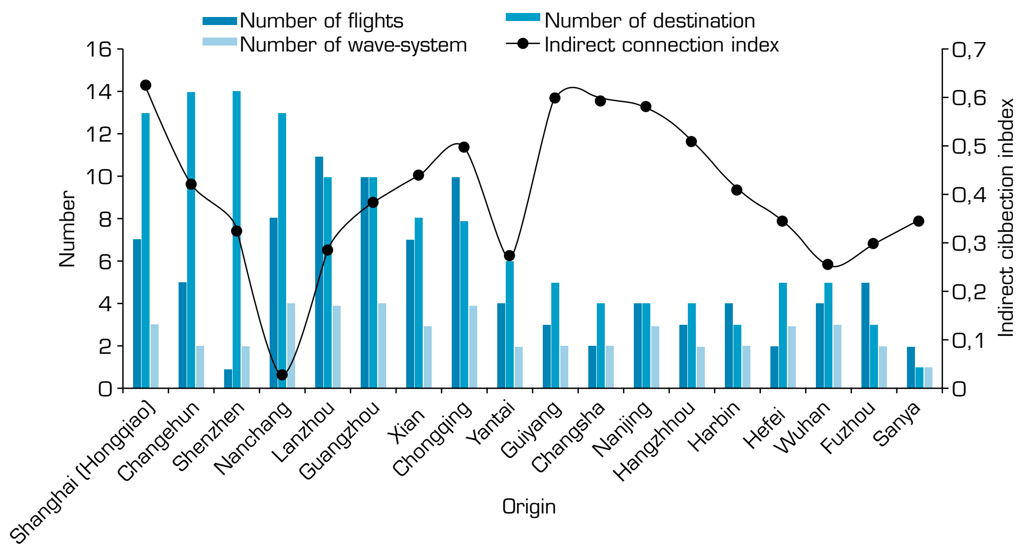
Figure 5. The indirect connection index of major inbound flights from Beijing Daxing International Airport.

Beijing Capital International Airport Wave-system Indirect Connection Analysis

The indirect connections within the wave-system were also analyzed, and it was found that the quality of indirect connections for flights transiting through the capital airport was higher than that of the Daxing airport, where the indirect connection index was in the range of [0, 0.3] for four airports (Fig. 6), namely Shenzhen Bao'an International Airport, Haikou Meilan International Airport, Nanjing Lukou International Airport, and Shanghai Pudong International Airport, mainly because of the geographical location of Beijing airport, which led to a higher indirect connection time factor for the four airports. For example, the transfer time of Shenzhen Bao ʻan International Airport is as long as 65-95 min, while the average level of the research object is 70 min. The indirect connection index is in the range of [0.3, 0.5] for eight airports, namely Chengdu Shuangliu International Airport, Hohhot Baita International Airport, Guiyang Longdongbao International Airport, Xiamen Gaoqi International Airport, Shanghai Hongqiao International Airport, Hangzhou Xiaoshan International Airport, Qingdao Jiaodong International Airport, and Fuzhou Changle International Airport. There are six airports with indirect connection index in the range of [0.5, 0.7], namely Chongqing Jiangbei International Airport, Zhuhai Jinwan International Airport, Wuhan Tianhe International Airport, Guangzhou Baiyun International Airport, Nanning Wux u International Airport, and Yantai Penglai International Airport, indicating that the above departure points are highly effective in combining flights with the capital airport for transit. Compared with Beijing Daxing International Airport , the number of airports in this zone is much higher than that of Beijing Daxing International Airport , mainly due to the long history of the airport, the mature construction of the hub-and-spoke network, and the rich passenger and cargo market demand that guarantees the operation of more intensive routes between the airport and other destinations, so that the capital airport as a hub airport can provide passengers with abundant and fast transit opportunities.

The indirect connection quality to the Capital Airport matches well with the connection opportunities. The different departure airports with indirect connections to the Capital Airport are mostly regional hub airports with more developed route networks and a larger number of connected destinations; after transit through the Capital A irport, the connection opportunities are greatly increased. Among the remaining 18 departure airports after screening, there are 10 airports with connections to the Capital Airport between [3, 7], namely Nanning Wux u International Airport, Zhuhai Jinwan International Airport, Nanjing Lukou International Airport, Wuhan Tianhe International Airport, Hangzhou Xiaoshan International Airport, Haikou Meilan International Airport, Qingdao Jiaodong International Airport, Chengdu Shuangliu International Airport, Yantai Penglai International Airport, Fuzhou Changle International Airport. There are six airports in the range of [7, 12], namely Yantai Penglai International Airport, Fuzhou Changle International Airport, Shenzhen Bao'an International Airport, Shanghai Hongqiao International Airport, Chongqing

Jiangbei International Airport, and Shanghai Pudong International Airport. Among the number of destination airports connected through the transit of Capital Airport, the number of destinations of 6 departure airports is in the range of [10, 15] and the remaining 11 airports, except Xiamen Gaoqi International Airport, have more than 3 destinations indirectly connected, indicating that there is a good match between the quality of indirect connections and connection opportunities at Capital Airport. Among them, the indirect connection index of Yantai Penglai International Airport has a good match with connection opportunities, reaching 0.627, with 7 flights connecting with Capital Airport and 13 destinations after transit. Only a few airports have a mismatch between the quality of connections and the number of connection opportunities, such as Shenzhen Bao'an International Airport, which has 8 flight connections with Capital Airport and 13 destinations after transit, but the indirect connection index is 0.0275, mainly due to the long transit time at Bao'an Airport, with a transit time index of 0.03; its path index is 0.05, indicating that its destination bypass coefficient is large, averaging around 1.38, which is mainly related to the relative geographical location between Shenzhen and Beijing.



Source: Elaborated by the authors.

Figure 6. The indirect connection index of major inbound flights from Beijing Capital International Airport.

Spatial differences in indirect connections of wave-systems

The wave-system structure is constructed to take into account the optimal results of airport spatio-temporal connections. The results show that there is an imbalance in the spatial distribution of destination airports indirectly connected by two airports in Beijing.

Among the airports connected to Beijing Daxing International Airport, the number of destinations after indirect connections from departure airports in central China, such as Wuhan and Nanchang, is around 10. Among the airports connected with the Capital Airport, except for the airports in Shandong Peninsula and Shanghai and Shenzhen regions, the number of destinations that can be connected to other regional departure airports is less than 10, and the number of destinations connected to departure airports in Wuhan and Hangzhou is only four . Airports in Shandong Peninsula can transit to the west or south after transit through Beijing, with many transit opportunities; airports in East China have destinations in Northwest and Northeast China after transit through Beijing.

The regional differences in indirect connectivity are not obvious. According to scholars' research on the connectivity of China's air transportation network, the cities with high direct connection quality are basically located in the lower right area of the "Hu Huanyong" line (Yang *et al.*, 2022), which has a developed economy and a large population, and a dense point-to-point route network, forming Beijing-Shanghai, Beijing-Guangzhou, and Shanghai-Shenzhen route corridors. The indirect connection quality does not reflect this regional distribution, for example, the indirect connection index between Beijing Capital Airport, Shanghai Pudong International Airport and Shenzhen Bao'an International Airport is only 0.0275 and 0.285. This indicates that the eastern region with dense aviation demand is more suitable for the development of a direct flight network, which makes the airlines not enough to build an indirect connection network considering flight transit.

The wave-system plays a significant role in connecting small and medium-sized regional airports. Regional airports refer to civil airports with an annual passenger throughput of less than 2 million passengers for landing and taking off short-haul aircraft (Civil Aviation Administration 2006). Beijing's two airports often serve as important transit points for large airports in East and South China to connect with regional airports in the Midwest and Northeast China. For example, the destination airports connected to Beijing Daxing International Airport via wave-system transit include Dongying Shengli Airport, Qingyang Xifeng Airport, Ordos Ejin Horo International Airport, Wuhai Airport and other regional airports (accounting for 13% of all destinations). The destination airports connected to the Capital Airport via wave-system transit include Changye Wangcun Airport, Daqing Sal Airport, Yanji Chaoyangchuan Airport, etc (15% of all destinations). Most of the regional airports have only opened 6 to 8 domestic routes, and the connection via Beijing Airport not only enhances the external connectivity of the regional airports, but also enhances the time accessibility of regional airlines by effectively linking them with other regional hub airports via wave-systems. It solves the problem that regional airports (such as Wuhan, Zhengzhou and other airports in central China) are constrained by geographic distance and have difficulty in exercising the indirect connection capacity, improves the number of destinations connected by airports and the quality of indirect connections.

DISCUSSION

- In the sense that the wave-system realizes the transit value, the emergence of the outbound wave before the inbound wave does not play a prominent role in the transit of the day's flights and affects the systemic nature of the wave-system. The first step to realize the wave-system is to feed sufficient passenger traffic to the transit airport before the inbound wave occurs to generate abundant passenger transit demand and complete the demand through the outbound wave. The airports' base overnight flights constitute the earliest batch of outbound waves at the airport, and the outbound wave precedes the inbound wave, which makes it difficult for the transit benefit of the airport to be played at that time. In this regard, airlines can extend the time of the outbound wave composed of overnight flights when arranging flight schedules, i.e., to "cut the peak and fill the valley" for the early outbound wave, which can, on the one hand, take more inbound flights and increase the transit demand of passengers; On the other hand, it can avoid the imbalance of runway utilization due to the concentration of flights, so as to relieve the pressure of peak departure flights.
- Effective wave-system configuration is important to improve airport service capacity and airline flight indirect connection quality. By shortening the transit time window, adjusting the aircraft inbound and outbound queues, and establishing a wave-system optimization model based on ground waiting strategy to improve the connecting hit rate of transit time window. Thus, the articulation and stability of the wave-system can be improved. For example, rational use of terminal resources, shorten the transfer distance of passengers and baggage, and strengthen the transit function of the airport; increase the number of gatherable flights per unit time, shorten the flight operation time, and enhance the competitiveness of airport hub services.
- Airports have insufficient margin to adjust slot resources. In the absence or imperfection of the secondary trading market for slot resources, the adjustment of slot resources by airlines is mostly based on the optimization of individual destinations, and it is difficult to integrate the slot resources of the whole route network, which makes the ideal allocation of slot resources difficult to realize. In addition, traditional large airlines are created early and mostly held by state-owned capital, with richer moment resources, and grandfather rights inheritance makes their moment resource allocation advantages increase, further forming the dissipation structure of flight moments and affecting the ideal inbound and outbound flight allocation status of airports. In this regard, we should actively explore the secondary market trading mechanism of flight moments, so that airports and airlines can have greater coordination and control over flight moments, and at the same time establish a cooperative decision-making mechanism among air traffic control, airports and airlines to reduce the contradiction of adjusting flight moments among the three, so as to promote the efficient flow of stock moment resources and ensure the effective operation of airports.

RESEARCH LIMITATIONS AND PROSPECTS

In the research process of this paper, although I consulted a wealth of literature and sorted out the wave-system mode and indirect connection theory of the hub airport, due to the limited time and the limited level of the author, the research of this paper still has the following shortcomings.

- The study of the two hub airports was conducted at a time when the prevention and control of the novel coronavirus epidemic was normalized in China and international air routes were frequently disrupted, the study is inevitably somewhat one-sided. So, the study focused on the connectivity of the domestic air route network.
- Based on the existing research results at home and abroad, this paper measures the indirect connection of Beijing two hub airports based on the wave-system mode. Limited by the diversity of relevant models, the flexibility of navigation indicators and the author's subjective judgment, the depth and comprehensiveness of connectivity measurement may be affected. Therefore, this measurement method needs to be further verified in practice and further supplemented and adjusted with the development of the actual situation.

Based on the calculation results of two Beijing hub airports, this paper puts forward some optimization priorities and countermeasures for the route network construction of hub airports, but does not do further quantitative research. Therefore, further research on connectivity optimization is needed in the future to form a more systematic and accurate measurement method. In the future study and research process, the author will carry out further exploration on the above shortcomings and continue to improve this paper, in order to provide theoretical basis and method support for the construction of hub airport route network.

CONCLUSION

The study mainly relied on the slot resources data of Beijing Capital International Airport and Beijing Daxing International Airport in summer- autumn and winter-spring seasons, determined the wave-systems of the two airports, and evaluated the quality of transit flights within the wave-systems using the indirect connection index. The study found that:

- The wave-systems of Capital Airport are more obvious than those of Beijing Daxing International Airport. The density and magnitude of the wave-systems of the 2 airports are higher in summer and autumn than in winter and spring, and the flight volume is also larger, but the wave-systems of Beijing Daxing International Airport are higher in summer and autumn than in winter and spring. Although the number of flights in the waves of the two airports shows a certain concentration, the number of inbound and outbound flights in the waves is lower than 50% compared with foreign airports, and the time interval of the waves is larger, indicating that there still great space for improvement in the construction and use of wave-systems.
- The wave-system forms of Beijing Daxing International Airport and Capital Airport both belong to the morning and evening peak shape, showing obvious early departure and late return characteristics, mainly because the two airports are the base airports of large airlines with many overnight flights. Inbound and outbound waveforms are superimposed at some times, and the superimposition is more obvious in the morning and evening peaks. The inbound waveforms at Beijing Daxing International Airport precede the outbound waveforms in the summer and autumn seasons, and the outbound waveforms precede the inbound waveforms in the winter and spring seasons; the outbound waveforms at Capital Airport precede the inbound waveforms in both seasons, and a comparison of the waveforms at the two airports shows that the wave-system forms in the winter and spring seasons are larger than those in the summer and autumn seasons, and the amplitude of the wave-system form at Beijing Daxing International Airport is larger.
- The average value of indirect connection index for flights from different departure airports with transit through Beijing Daxing International Airport is 0.33, indicating that indirect connections at Beijing Daxing International Airport are more reliable, but its indirect connection combination allocation process still needs to be improved, and the quality of indirect connections within the wave-system at Beijing Daxing International Airport does not match the indirect connection opportunities. The indirect connection quality of flights transit through Beijing Daxing International Airport is higher than that of Beijing

Daxing International Airport, and the average value of indirect connection index is 0.41. The indirect connection quality of Beijing Daxing International Airport matches better with the connection opportunities.

- The construction of wave-system structure system should take into account the best results of spatio-temporal connection of airports, and there is an uneven spatial-regional distribution of destination airports via 2 airports in Beijing indirectly, and the regional differences are not obvious. The wave-system plays a significant role in connecting small and medium-sized regional airports.

CONFLICT OF INTEREST

Nothing to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Han Ruiling and Zhou Xiang; **Data curation:** Zhou Xiang; **Formal analysis:** Zhang Xiaoyan; **Acquisition of funding:** Han Ruiling; **Research:** Zhou Xiang; **Methodology:** Han Ruiling and Du Xiaohui; **Project administration:** Han Ruiling and Du Xiaohui; **Resources:** Han Ruiling; **Software:** Zhou Xiang; **Supervision:** Han Ruiling and Du Xiaohui; **Validation:** Zhang Xiaoyan; **Writing - Preparation of original draft:** Zhou Xiang and Han Ruiling; **Writing - Proofreading and editing:** Zhang Xiaoyan and Du Xiaohui.

DATA AVAILABILITY STATEMENT

The data will be available upon request.

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