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A Collaborative Route Optimization Model for Regional Multi-Airport System

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ABSTRACT In this paper, the author set up an index system on the airport collaboration of the multi-airport system (MAS), including the number of external routes, the total cost of the route network, the passenger volume of the MAS, the airport primacy ratio, the route repetition rate, the capacity utilization and the purpose matching rate of airport. Next, the airports within the same MAS are regarded as one airport in the general sense, and the ground transit between the internal airports and the external routes from the single airport are combined to satisfy the demand for passenger transport in the MAS. On this basis, a mathematical model was constructed for collaborative optimization of the route network of the MAS, and used to determine the transit airport and its passenger volume. The indices were transformed into constraints and optimization objectives. Taking the MAS in the Beijing-Tianjin-Hebei (BTH) region for example, the model settings and parameters were further refined. Through model simulation, the collaborative optimization model was further improved, allowing two internal airports to serve as transit airports. The empirical results show that the collaborative optimization successfully improved the overall efficiency of the MAS, clarified the division of labor among the internal airports and balanced the allocation of aviation resources.

INDEX TERMS Multi-airport system (MAS), collaborative optimization, Beijing-Tianjin-Hebei (BTH) region.

I. INTRODUCTION

With the development of regional economy and integrated transport, many airports in the same region have increasingly deep interactions, forming a multi-airport system (MAS). The MAS was conceptualized by de Neufville [1] through an analysis on airport groups in New York and London. In 2007, Joint Planning and Development Office [2] clearly defines the MAS as an airport group system of multiple airports in the metropolitan area, sharing basically the same landing and takeoff procedures. Ren *et al.* [3] explored how the interaction between airports affect the development of the four MASs in the US. Li *et al.* [4] put forward a plan to coordinate the MAS. Overall, the existing studies on the MAS mainly focus on the passenger selection, release strategy and airport site selection.

In recent years, there are three main aspects of multi-airport system optimization. The first is the optimization of the terminal capacity of the airport system. Murça and Hansman [5], Sidiropoulos *et al.* [6] predicted traffic flow patterns in the terminal area of multi-airport systems toward improved capacity planning decision support. The second optimization direction is MAS flights. Liu *et al.* [7] considered a scheduling problem for multi-airport departure flights. Gao *et al.* [8], Ramanujam and Balakrishnan [9] optimized flight time optimization to reduce MAS delays. The third aspect is the optimization of revenue distribution between airports [10] or airports and high-speed rail [11].

Air route network refers to the structural system of connecting air routes in a certain region in a certain way, which consists of airports, air routes and other elements to form the spatial distribution of air transport. Research results on airline network mainly include the following three aspects: evolution and selection of airline network. Jiang *et al.* [12] discussed the network changes of low-cost airlines. Oster and Strong [13] compared trends in the route networks of traditional and low-cost airlines. Ciliberto *et al.* [14] and Silva *et al.* [15] studied

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the choice of airline network structure type under the mode of amalgamation of enterprise or oligopoly. Using complex network theory, airline network is studied. For example, Lee and Park [16] analyzed that airline network of American airlines is scale-free. Du *et al.* [17] and Wei [18] used complex network theory to analyze the importance of nodes and routes in airline network. Airline networks interact with aircraft assignments; flight frequency interacts with flight time et al. Brueckner and Zhang [19] studied the relationship between hub network systems and flight frequency or fares.

The route network is an important indicator of the MAS. In this structural system, the routes and airports in a region are linked up by a specific pattern. The route network has been adopted to measure the impacts of other elements of the MAS. For instance, Burghout [20] probed into the airport expansion strategy in the MAS based on the route network. Jiang *et al.* [21] coordinated and optimized the traffic and capacity of the route network for multiple airports. Derudder *et al.* [22] investigated the impacts of different route networks on the airport functions in New York MAS and the other three MASs in the US.

To sum up, the MAS is not a simple cooperation between airports, and it needs to form an organic whole through planning and operation. Therefore, the management of MAS should have synergy indicators in addition to production indicators, but the research results in this area are blank. In addition, the relevant collaborative optimization studies mainly tackle the economic development of the MAS, failing to consider the overall planning of the route network for the MAS. To make up for the gap, this paper puts forward an index system on the airport collaboration within the MAS. Furthermore A mathematical model is constructed for collaborative optimization of the route network of the MAS from the angle of the route network. The research findings promote the synergic development of the airports in the MAS, giving full play to the advantages of each airport.

II. CONSTRUCTION OF THE INDEX SYSTEM

The high-quality collaboration within the MAS is out of the question, if the resources are concentrated in the core airport, or the routes between the airports are too repetitive. Unlike that of a single airport or airline, the route network of the MAS must cater to the different purposes of internal airports and the features of the routes to external airports (external routes), in addition to the accessibility and route density. The following seven features of the MAS were extracted to measure the degree of collaboration between the airports in the MAS.

A. THE NUMBER OF EXTERNAL ROUTES

This index is the total number of external routes, considering the MAS as a single airport in the general sense. Note that the external routes leading to the same external airport are counted as one route only. This number reflects the connectivity of the MAS to external airports.

B. THE TOTAL COST OF THE ROUTE NETWORK

This index is the sum of the cost to open a new route (new route cost), the transit cost, and the air transport cost. It describes the cost input of the route network of the MAS.

C. THE PASSENGER VOLUME OF THE MAS

This index is the sum of annual passenger volumes of all internal airports. It measures the transport efficiency of the MAS.

D. THE AIRPORT PRIMACY RATIO

This index is the passenger throughput ratio between the core airport to the MAS. It reflects the equilibrium degree of the MAS' business volume.

E. THE ROUTE REPETITION RATE

This index is the weighted ratio of the number of non-unique routes to the total number of routes. It manifests the route network efficiency of the MAS.

F. THE CAPACITY UTILIZATION

This index is the ratio of the annual passenger throughput of the MAS to the designed capacity of each airport. The capacity utilization of each airport should be calculated separately.

G. THE PURPOSE MATCHING RATE OF AIRPORT

This index is the ratio of the number of routes in line with the purpose of an airport to the total number of routes of the airport. The purpose matching rate of each airport should be calculated separately.

III. COLLABORATIVE DESIGN OF MAS ROUTE NETWORK

The operating efficiency of a mature MAS relies on the completeness of the integrated transport system. The integration of ground transport in the MAS has attracted much attention from the government and the academia. Since 2000, the US Federal Aviation Administration has updated the *National Plan of Integrated Airport Systems* (NPIAS) each year, with the aim to integrate multiple modes of transport [23]. Givoni [24] examined the ground transport of Heathrow Airport and summed up the connection mode between the airport and high-speed rail. These studies have shown that an important way to enhance airport collaboration in the MAS lies in configuring and adjusting the passenger source via ground transport.

In this paper, the airports within the MAS (the internal airports) are considered as a single airport in the general sense, while the airports outside the MAS (the external airports) are allocated to the same set. The single airport has only one route leading to each airport in the set of external airports. One of the three largest internal airports was selected as the transit airport, and the passengers in the other internal airports were relocated to the transit airport via ground transport, thereby reducing the total cost of the route network, enhancing the purpose matching rate of the transit airport, and lowering the route repetition rate. In addition, the MAS must also satisfy the capacity limits and the current passenger throughput of each internal airport.

A. HYPOTHESES AND SYMBOLS

Two hypotheses were put forward for the collaborative design of MAS route network.

Hypothesis 1: The routes between internal and external airports are direct routes.

Hypothesis 2: Passenger transport is the only consideration. The cargo and mail transports are easily adjustable, and thus not taken into account.

The symbols in our research are explained as follows:

E_1: the set of airports within the MAS (internal airports);

E_2: the set of airports outside the MAS (external airports);

$\{ij\}$: the airport pair of airport i and airport j;

(ij): the directed edge of the airport pair $\{ij\}$;

Z: the total cost of the route network;

C_{kj}^{a}: the air transport cost per unit of passenger volume along the route (kj);

C_{ik}^{g}: the ground transit cost per unit of passenger volume along the path (ik);

C_{kj}^{o}: the fixed cost of route (kj);

O_{kj}: the purpose matching rate of an internal airport;

M^{p}: the penalty coefficient for a route not in line with the purpose of the airport (purpose mismatch penalty);

W_{ij}: the passenger volume from airport i to airport j, i.e. the original-destination (O-D) flow demand;

D_k: the designed capacity of airport k;

T_{ij}^{k}: the passenger volume of the route (ij) that is transferred to the transit airport k;

V_{kj}: the capacity of route (kj);

Y_{kj}: the state indicator of route (k, j) (if $Y_{kj} = 1$, then the route (kj) is open; if $Y_{kj} = 0$, then the route (kj) is closed).

B. COLLABORATIVE OPTIMIZATION MODEL OF MAS ROUTE NETWORK

The collaborative optimization of MAS route network is a combinatorial optimization problem. Therefore, the hybrid integer programming model can be established as:

$$\min Z = \sum_{j \in \boldsymbol{E}_2} \sum_{k \in \boldsymbol{E}_1} \left[\left(\begin{array}{l} C_{kj}^{\mathrm{o}} + \sum\limits_{i \in \boldsymbol{E}_1} C_{ik}^{\mathrm{g}} T_{ij}^{k} + \\ C_{kj}^{\mathrm{a}} \sum\limits_{i \in \boldsymbol{E}_1} T_{ij}^{k} + (1 - O_{kj}) \mathrm{M}^{\mathrm{p}} \end{array} \right) Y_{kj} \right] \tag{1}$$

$$s.t. \quad \sum_{k \in \boldsymbol{E}_1} Y_{kj} = 1 \tag{2}$$

$$\sum_{i \in \boldsymbol{E}_1} \sum_{j \in \boldsymbol{E}_2} T_{ij}^{k} Y_{kj} \leq \mathrm{D}_k \tag{3}$$

$$\sum_{k \in \boldsymbol{E}_1} T_{ij}^{k} \geq \mathrm{W}_{ij} \tag{4}$$

$$\sum_{i \in \boldsymbol{E}_1} T_{ij}^{k} \leq V_{kj} Y_{kj} \tag{5}$$

$$T_{ij}^{k} \geq 0, \quad Y_{kj} = 0, 1 \tag{6}$$

$$i \in \boldsymbol{E}_1, \quad k \in \boldsymbol{E}_1, \ j \in \boldsymbol{E}_2 \tag{7}$$

Formula (1) is the objective function: minimizing the total cost of the route network of the MAS. This cost consists of four parts: the fixed cost of each route, the ground transit cost, the air transport cost, and the purpose mismatch penalty.

Formulas (2)(7) are the constraints on the optimization problem. Specifically, formula (2) limits the number of external routes in the MAS, that is, the external routes can only start from one internal airport at the most; formula (3) requires that the passenger volume after the transit should not surpass the design capacity of the airport; formula (4) means the passengers originally in route (i, j) are all transferred to the transit airport; formula (5) specifies that the passenger volume on any external route after the transit should not exceed the capacity of that route.

IV. EMPIRICAL ANALYSIS OF THE MAS IN BTH REGION

The MAS in the BTH region has three primary airports, namely, Beijing Capital International Airport (BCIA), Tianjin Binhai International Airport (TBIA) and Shijiazhuang Zhengding International Airport (SZIA), and several secondary airports, including Beijing Nanyuan Airport, Zhangjiakou Ningyuan Airport, Tangshan Sannühe Airport, Handan Matou Airport, Qinhuangdao Shanhaiguan Airport and Chengde Puning Airport.

The last five airports are reginal airports, and they are all in Hebei Province. Among them, SZIA is a domestic trunk airport, and the rest are feeder airports. Their navigation city, passenger and cargo volume are far lower than the SZIA in the same province. Taking 2018 as an example, the passenger throughput of SZIA accounted for 81% of the province's total, while the other airports accounted for no more than 5%. The relevant research and government planning of the Beijing-Tianjin-Hebei Airport Group basically only analyzes Shijiazhuang Airport.

In 2014 and 2017, the National Development and Reform Commission (NDRC) and Civil Aviation Administration (CAA) of China announced that the MAS in the BTH region should develop collaboratively into a world-level MAS, ensuring that the internal airports have clear division of labor and strong complementary advantages.

Recent years has seen rapid development of the MAS in the BTH region. The number of routes and flights have increased year by year. In 2018, the MAS has service to 316 cities, including 160 in Chinese mainland, 10 in Hong Kong, Macao and Taiwan, and 145 in other countries. Despite the marked

TABLE 1. Shuttle bus prices of the BCIA.

Destination	Distance	Price
Tianjin	140km	82 yuan
Qinhuangdao	300km	140 yuan
Tangshan	185km	80 yuan
Baoding	182km	95 yuan
Langfang	77km	40 yuan

TABLE 2. The optimization results.

Destinations outside the BTH region	Former transit airports	Original cost (100 million yuan)	Current transit airport	Cost of each route after optimization (100 million yuan)
Shanghai	Beijing\Tianjin\Shijiazhuang	127.8	Beijing	121.2
Chengdu	Beijing\Tianjin\Shijiazhuang	117.6	Beijing	110.7
Guangzhou	Beijing\Tianjin\Shijiazhuang	127.6	Beijing	118.5
Shenzhen	Beijing\Tianjin\Shijiazhuang	119.5	Beijing	111.7
Xian	Beijing\Tianjin\Shijiazhuang	50.2	Beijing	42.3
Hangzhou	Beijing\Tianjin\Shijiazhuang	55.8	Beijing	47.7
Chongqing	Beijing\Tianjin\Shijiazhuang	70.8	Beijing	64
Qunming	Beijing\Tianjin\Shijiazhuang	85.4	Beijing	77.1
Sanya	Beijing\Tianjin\Shijiazhuang	82.8	Tianjin	76.3
Harbin	Beijing\Tianjin\Shijiazhuang	45	Tianjin	39.3
Changsha	Beijing\Tianjin\Shijiazhuang	47.3	Tianjin	37
Dalian	Beijing\Tianjin\Shijiazhuang	29	Tianjin	23.6
Xiamen	Beijing\Tianjin\Shijiazhuang	59.3	Tianjin	49.8
Urumqi	Beijing\Tianjin\Shijiazhuang	72	Tianjin	66.4
Wuhan	Beijing\Tianjin	34.4	Tianjin	24.5
Haikou	Beijing\Tianjin\Shijiazhuang	62.7	Tianjin	47.8
Qingdao	Beijing\Tianjin\Shijiazhuang	25	Tianjin	13.4
Changchun	Beijing\Tianjin\Shijiazhuang	30.6	Tianjin	23.7
Lanzhou	Beijing\Tianjin\Shijiazhuang	35.6	Tianjin	25.7
Guiyang	Beijing\Tianjin\Shijiazhuang	46.1	Tianjin	38.1
Fuzhou	Beijing\Tianjin\Shijiazhuang	41.4	Tianjin	31.8
Hohhot	Beijing\Tianjin\Shijiazhuang	21.9	Shijiazhuang	12.5
Yinchuan	Beijing\Tianjin\Shijiazhuang	27	Shijiazhuang	15.7
Nanning	Beijing\Tianjin\Shijiazhuang	44.6	Shijiazhuang	34.7
Nanjing	Beijing\Shijiazhuang	25.5	Shijiazhuang	15.5
Nanchang	Beijing\Tianjin\Shijiazhuang	31.7	Shijiazhuang	19.4
Shenyang	Beijing\Shijiazhuang	21.4	Shijiazhuang	14.4
Ningbo	Beijing\Tianjin\Shijiazhuang	31.6	Shijiazhuang	19.3
Wenzhou	Beijing\Tianjin\Shijiazhuang	33.5	Shijiazhuang	22
Hefei	Beijing\Shijiazhuang	19.4	Shijiazhuang	9
Total cost		1622.5		1353.1

progress, there is still ample room to deepen the airport collaboration of the MAS in the BTH region, and optimize the overall planning of the route network.

The integration of the regional ground transport system has ushered in a golden opportunity for the development of the MAS in the BTH region. The Chinese CAA stated in its 13th Five-Year Plan that, Beijing should pursue coordinated airport development with nearby cities, clarify the division of labor and purpose of regional airports, and fully integrate air transport with other modes of transport.

The previous reports on the MAS in the BTH region only deals with individual features of the route network, without considering the synergy between cost, production efficiency and structure efficiency. For instance, Wang *et al.* [25] take airports in BTH region as the research object, through analyzing the operating status and the business volume of Beijing Airport, come to the conclusion that the capital of Beijing Airport is closing to saturation, its current operation status and performance results is poor, while the utilization of other airports in the region is inadequate. Song and Gao [26] constructed A model of airline network in a regional multi-airport, and solved it with Tabu-research algorithm. In this paper, the route network of the MAS in the BTH region is optimized with the model in Subsection III.B.

A. SAMPLE SELECTION AND PARAMETER SETTINGS

1) SAMPLE SELECTION

The three primary airports in the BTH region takes up more than 95% of the volume of passengers, cargoes and mails in the MAS. Hence, the set of internal airports in the following analysis only contains these three airports. As for the set of external airports, 30 routes were added to this set, each with an annual passenger volume of over 450,000. The 30 routes transport 59.6% of all passengers in the MAS of the BTH region.

TABLE 3. **The passenger volume of each route before and after the optimization.**

	Pre-optimization			Post-optimization		
Passenger volume (10,000)	Beijing	Tianjin	Shijiazhuang	Beijing	Tianjin	Shijiazhuang
Shanghai	777.44	127.73	66.98	956.97	15.18	-
Chengdu	496.83	72.82	46.68	599.81	16.51	-
Guangzhou	467.97	99.15	32.38	599.34	0.17	-
Shenzhen	407.05	71.96	30.80	507.90	1.91	-
Xian	252.46	71.44	28.76	350.56	2.11	-
Hangzhou	248.15	54.29	45.66	324.32	23.78	-
Chongqing	246.24	67.37	40.28	347.68	6.22	-
Qunming	229.20	45.13	40.35	291.86	22.82	-
Sanya	200.18	32.45	19.67	-	219.98	32.32
Harbin	194.07	52.68	28.63	-	263.80	11.58
Changsha	187.67	23.44	15.63	-	218.45	8.29
Dalian	181.51	26.25	19.68	-	205.49	21.95
Xiamen	162.80	59.48	28.68	-	222.98	27.99
Urumqi	158.48	23.70	16.89	-	184.23	14.84
Wuhan	141.17	31.30	0.00	-	168.03	4.44
Haikou	130.70	26.76	18.70	-	171.10	5.05
Qingdao	125.90	17.68	12.63	-	155.48	0.74
Changchun	119.31	23.49	16.88	-	155.33	4.35
Lanzhou	116.08	24.67	18.57	-	145.82	13.50
Guiyang	107.81	28.99	21.60	-	136.49	21.90
Fuzhou	107.51	29.76	21.96	-	157.79	1.44
Hohhot	97.21	27.69	20.96	-	-	145.86
Yinchuan	92.84	19.68	14.89	-	-	127.41
Nanning	90.59	25.97	16.75	-	-	133.32
Nanjing	89.89	0.00	19.35	-	-	109.24
Nanchang	88.61	19.37	15.68	-	-	123.66
Shenyang	85.85	0.00	9.36	-	-	95.21
Ningbo	72.61	24.89	18.63	-	-	116.13
Hefei	39.89	0.00	6.88	-	-	46.76
Wenzhou	74.49	26.39	19.63	-	-	120.51

2) MAIN PARAMETERS AND SIMULATION RESULTS

a: GROUND TRANSIT COST

The ground transit cost of passengers is positively correlated with the transport distance. The ground transit cost was determined as 0.5 yuan, according to the pricing table for the shuttle buses of the BCIA (Table 1).

b: AIR TRANSPORT COST

In 2004, the NDRC and the CAA of China jointly issued the *Price Reform Plan for Domestic Air Transport in Civil Aviation*, which specifies that the airlines can set the price between +25% and −45% of the benchmark price of air transport cost (0.75 yuan/km· person). Considering the mean discount rate, the air transport cost was set to 0.6 yuan/km· person.

c: PURPOSE MISMATCH PENALTY

The three primary airports in the BTH region have different purposes. The BCIA operates trunk lines, with more than 3 million passengers, flying to hub airports; the TBIA operates trunk lines or branch lines, with $1.5\sim3$ million passengers, flying to hub airports or trunk-line airports; the SZIA operates trunk lines or branch lines, with fewer than 1.5 million passengers.

If a route is in line with the purpose of an internal airport, then the purpose matching rate O_{kj} equals 1; otherwise, the O_{kj} equals 0. The purpose mismatch penalty M^p is generally a large positive number. Here, the air transport cost is selected as $\sum_{i\in \mathbf{E}_1} C_{ik}^{g} T_{ij}^{k}$.

Under the high penalty, the Matlab Optimization Toolbox was employed to optimize the route network of the MAS in the BTH region based on the model established in Subsection III.B, and the passenger volume of each route in 2017. The optimization results are listed in Table 2 below.

As shown in Table 2, the optimization results changed with the purpose mismatch penalty. When M^p is reduced to zero, the ground transit cost is much lower than the air transport cost. In this case, the passengers of the former transit airports

TABLE 4. The pre- and post-optimization values of airport collaboration indices.

	Original data			First optimization			Second optimization		
Number of external routes	86			30			51		
Total cost of the route network (100 million yuan)	1622.5			1353.1			1384.7		
Passenger volume of the MAS (10,000)	7658.6			7658.6			7658.6		
Airport primacy ratio (%)	76.6			53.1			51.9		
Route repetition rate (%)	186.7			0			70		
	Beijing	Tianjin	Shijiazhuang	Beijing	Tianjin	Shijiazhuang	Beijing	Tianjin	Shijiazhuang
Purpose matching rate (%)	26.7	48.1	31	100	100	100	100	61.9	40.9
Capacity utilization (%)	100	56	21	47.3	85.8	50.9	39.3	88	73.3

will move to the internal airport with the largest passenger volume on the original route. For instance, the annual passenger volumes from Beijing, Tianjin and Shijiazhuang to Qingdao were 1,259,000, 176,800 and 126,300, respectively. With the decline in the purpose mismatch penalty, the passengers of the TBIA and the SZIA both moved to the BCIA, whose route had the highest passenger volume.

B. FURTHER OPTIMIZATION

In the first optimization, there was only one airport operated by the regional foreign airlines, which greatly optimized the cost. But the mode of single transit airport may over throng the routes that were already very busy, causing problems to flight timing and traffic control. Once a delay occurs, lots of passengers will be stranded at the airport. In order to improve the feasibility of the scheme, the following optimization is carried out by sacrificing part of the cost target. When other regional multi-airport systems are to be similarly optimized, the maximum number of transit airports in the system is selected according to their specific circumstances. This model is more generalizable in theory.

To solve the problem, the optimization strategy was adjusted in the light of the historical data on air transport of the MAS in the BTH region. After the adjustment, two internal airports were allowed to open routes to a destination with an annual passenger volume greater than 1.5 million, and one internal airport was permitted to open route to a destination with a lower annual passenger volume. Hence, formula (2) was modified as formulas (8)(10):

$$\sum_{k\in \boldsymbol{E}_1} Y_{kj} = 1^*S_j + 2^*(1-S_j) \tag{8}$$

$$\sum_{i\in \boldsymbol{E}_1}\sum_{k\in \boldsymbol{E}_1} T_{ij}^{k} \geq 150 - S_j^*\mathrm{G} \tag{9}$$

$$S_j = 1, 0 \tag{10}$$

where G is a very large positive number; S_j is the variable for passenger volume level (if the annual passenger volume is above 1.5 million, $S_j = 0$; Otherwise; $S_j = 1$)

The new model was executed, and the results are listed in Table 3 below.

The pre- and post-optimization indices of airport collaboration in the MAS were analyzed. The results are recorded in Table 4 below.

As shown in Table 4, all airport collaboration indices were improved to different degrees through the two optimizations, except for the passenger volume of the MAS, which was set as a constant. This means the passenger volume is distributed more rationally among the routes, the purpose of each airport is clarified, and the division of labor is more accurate among the internal airports. The capacities of the TBIA and the SZIA were fully utilized to absorb the excess passengers on domestic routes in the BCIA. In this way, the BCIA's route network became more rational, and its primacy ratio fell to the level of mature MASs around the world. With the decline in domestic routes, the BCIA now has extra capacity for more international routes and better international transit services, making it a stronger international hub.

V. CONCLUSION

Thanks to the boom of civil aviation, many MASs have emerged based on administrative divisions and geographical locations. To improve the competitiveness and radiation of the MAS, many parties, e.g. governments, airports and airlines, are competing to enhance the airport collaboration and optimizing the route network of the MAS.

This paper sets up an index system for the airport collaboration in the MAS, including productivity indices like the number of external routes, the total cost of the route network and the passenger volume of the MAS, the collaboration efficiency indices like the airport primacy ratio and the route repetition rate, and the airport efficiency indices like the purpose matching rate and the capacity utilization.

The passengers of the MAS were transferred and diverted to transit airport(s) via ground transport in the region. The established indices were transformed into constraints and optimization objectives. On this basis, a mathematical model was constructed for collaborative optimization of the route network of the MAS.

Taking the MAS in the BTH region for example, the model settings and parameters were further refined. The empirical results show that, when only one internal airport served as the transit airport, the number of external routes, the total cost of the route network and the route repetition rate were fully optimized. However, this optimization strategy reduces the reliability of flight plan or over throngs the only route to the same destination.

Based on the passenger volume and airport scale in the MAS, the collaborative optimization model was further improved, allowing two internal airports to serve as transit airports. The improved model outputted more operable results, and optimized the seven indices to different degrees.

Moreover, the model has the same reference significance for other MAS route network layouts, especially the MAS with unified management rights. To put it another way, this model is also applicable to airlines, which can improve overall operational efficiency through adjustment of route network and resource allocation.

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