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Air express network design based on express path choices – Chinese case study

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ABSTRACT

Due to the shortage of cargo aircraft, Chinese express companies have to provide transportation services with a hybrid method that consists of “rented bellies and self-owned cargo aircraft”. Because the bellies are rented from air passenger companies and because the cargo aircraft are owned by the express companies, it is important for the express companies to use their cargo aircraft as effectively as possible. This paper constructs a bi-level model to optimize the flight transportation network of an express company. The upper model designs the network and allocates the transportation capacity with the objective of minimizing the total transportation cost, and the lower model calculates the link flows in user equilibrium. Data from ShunFeng (SF) Express Company (China) are used to conduct the case study. Using the model outputs, the flows on links and at nodes are analyzed to illustrate the transportation and transshipment situations.

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1. Introduction

Over the last twenty years, the air cargo industry in China has seen a rapid expansion. In particular, with the rapid expansion of e-commerce markets, the amount of cargo transported by such express companies has increased continuously. For example, the cargo transported by ShunFeng (SF) Express Company by air in 2014 reached 0.83 million tons, increasing 84.4% compared with 2011. However, Chinese air express companies typically only own a few cargo aircraft, and their capacity is far behind the increasing demand. For example, the SF Express Company, one of the largest such companies in China, has established a flight network covering 80% of the main cities; however, the company only has 15 cargo aircraft. Due to this shortage of cargo aircraft, Chinese air express companies have to rent the bellies of passenger aircraft from passenger airline companies and provide transportation services under the hybrid model of “bellies + cargo aircraft”.

In China, direct passenger flights are currently operated between most main cities. Thus, the flight network of the bellies of

passenger aircraft transportation mode presents a “point-to-point” configuration, and cargo aircraft are operated between mega-cities to maximize the loading ratio. In this case, the cargo in cargo aircraft contains cargo traveling directly from one mega city to another mega city and cargo transshipping from the bellies of passenger aircraft. Thus, cargo aircraft and belly transportation utilize a “hub-and-spoke” configuration. As the result, the Chinese air express transportation network is a mixture of “point-to-point” networks and “hub-and-spoke” networks. In this mixed network, due to short of cargo aircrafts, the rented bellies play the main role.

This study designs the structure of the mixed air cargo transport network, in which the bellies of passenger aircraft and cargo aircrafts are jointly used. Then we optimize the operation plans for transporting cargos between O-D pairs based on the mixed network. With the calculated results, we further analyze the paths of cargos and discuss the transshipments at some airports.

The remainder of this paper is organized as follows. Next section reviews the relevant literature. In section 3, the problem of this paper is described. Section 4 constructs a bi-level programming model to tackle the problem. In section 5, a genetic algorithm is developed to solve the upper model and the lower model is solved with the algorithm of Frank-Wolfe. Section 6 tests the constructed model with a case study. In section 7, this paper ends with some conclusions of the research.

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2. Literature review

Some literature have studied the hub-and-spoke network. O'Kelly (1987) reported a new formulation of a general hub location model as a quadratic integer program and discussed a variety of alternative solution strategies. Gelareh and Nickel (2011) proposed a 4-index formulation for the uncapacitated multiple allocation hub location problem tailored for urban transport and liner shipping network design. Vasconcelos et al. (2011) proposed a new hub location model defined by the minimization of costs. Oktal and Ozger (2013) modeled constrained choices when establishing cargo hub and spoke networks. They developed a mixed integer linear programming model introducing additional constraints to the traditional model of un-capacitated multiple allocation hub location problem. An et al. (2015) proposed a set of reliable hub-and-spoke network design models, where the selection of backup hubs and alternative routes were taken into consideration to proactively handle hub disruptions. Damgacioglu et al. (2015) studied the un-capacitated single allocation planar hub location problem. In this problem, all flow between pairs of spokes went through hubs and the capacities of hubs were infinite, they could be located anywhere on the plane and were fully connected, and each spoke must be assigned to only one hub. Gelareh et al. (2015) proposed a mathematical model for a Multi-period uncapacitated multiple allocation hub location problem with budget constraint. However, these studies do not consider the problem of transport capacity, while in reality, the transport capacity is not always enough.

Elhedhli and Hu (2005) studied the hub-and-spoke network design problem with congestion, they proposed extends current models by taking congestion effects into account. However, in these studies, the congestion is only in hubs and not on the link.

Some literature take the capacity into consideration, for example, Lin et al. (2003) compared the economic effects of hub-and-spoke networks with center-to-center directs on the carrier's operations. They constructed an integer program model of hub-and-spoke network with center directs in the paths and evaluated the results against the Federal Express AsiaOne express network. Lin and Chen (2008) proposed a generalized hub-and-spoke network in a capacitated and directed network configuration that integrated the operations of three common hub-and-spoke networks: pure, stopover and center directs. Lin et al. (2012) studied the problem of hub-and-spoke network design considering economy of scale and constraints on the paths. They constructed a relative model and solved it by genetic algorithm using the path for encoding. Correia et al. (2011) considered an extension of the capacitated single-allocation hub location problem in which the capacity of the hubs was part of the decision making process and balancing requirements were imposed on the network. Sender and Clausen (2013) presented a capacitated multiple allocation hub location problem. They developed heuristic solution approaches based on local improvements.

Some literature studied the solving methods of hub and spoke network. Saberi and Mahmassani (2013) presented continuous approximation techniques for the airline hub location and optimal market problems, and illustrated the usefulness of continuous approximation modeling in airline operations and network design with example applications. Zheng et al. (2015) proposed a liner hub-and-spoke shipping network design problem by introducing the concept of a main port, as well as some container shipping constraints such as multi-type container shipment and transit time constraints. He et al. (2015) developed an improved MIP heuristic combining branch-and-bound, Lagrangian relaxation, and linear programming relaxation.

de Camargo et al. (2009) addressed the multiple allocation hub-and-spoke network design under hub congestion problem. They

proposed a non-linear mixed integer programming formulation, modeling the congestion as a convex cost function. Karimi and Bashiri (2011) studied the hub covering problem with different coverage type over complete hub networks. Furthermore, hub set and maximal covering were expressed with single and multiple allocation strategies. Alumur et al. (2012a,b) addressed several aspects concerning hub location problems under uncertainty. Alumur et al. (2012a,b) approached the hub location problem from a network design perspective. In addition to the location and allocation decisions, they also studied the decision on how the hub networks with different possible transportation modes must be designed. Rahimi et al. (2016) present a new bi-objective model for a multi-modal hub location problem under uncertainty considering congestion in the hubs. Mahmutogullari and Kara (2016) proposed a competitive hub location problem where the market was assumed to be a duopoly.

These studies mainly focused on the network structure with the objective to determine the hub location (Yao et al., 2014a,b). When the network structure is determined, the cargos from origin to the destination mostly have only one path, thus it is not necessarily to study the path choice behaviors and transportation schemes. Meanwhile, in most of the literature, there is only one type of carriers, while the reality in China is that both passenger aircraft bellies and cargo aircrafts are used in the network. Especially, when the cargo aircrafts is self-owned and the bellies are rented, the operators need to simultaneously determine the cargo aircrafts' operation and the quantity of rented bellies, which makes the network design much more complicated.

Some studies discussed the price and revenue management of air cargo transportation. Alderighi et al. (2005) identified conditions under which asymmetric equilibria may exist when carriers compete in designing their network configurations in a game-theoretical framework. They assumed that carries offer all their capacity to the market so that the price a carrier receives only depends on market demand. However, in China, the belly capacity are not always rented out by passenger flight companies. Fu et al. (2011) examined the forms and effects of vertical relationships between airports and airlines with a focus on the North American and European aviation markets. Zhang et al. (2013) explored factors influencing the pricing behavior of full-service carriers in hub-to-hub markets. Saraswati and Hanaoka (2014) analyzed airport–airline cooperation where an airport offers to share a proportion of its commercial revenue with airlines in exchange for a fixed payment. Feng et al. (2015) proposed a tying mechanism for capacity allocation by integrating hot-selling routes and underutilized routes. They designed the tying mechanism for air cargo capacity allocation and derived the closed-form optimal solution. Chi and Baek (2012) examined the demand for airfreight in the US as a function of real income and the price of airfreight between 1996 and 2010.

3. Problem description

Chinese air express companies adopt the method of jointly using the self-owned cargo aircrafts and the rented bellies to transport express cargos, among which the rented bellies play the main role. The operation cost of the express companies mainly includes the bellies' rents and the costs covering holding and using the cargo aircrafts. As the total supply for air cargo transportation is not enough as a whole, Chinese passenger flight companies are not willing to rent all their owned bellies out for the whole year while the express companies want to rent a batch bellies in long term. For the demand varies seasonally, the passenger flight companies wish to hold some capacity to obtain more profits in the peak season. As a result, the long term unit rent of the bellies of passenger aircrafts

will go up as the increment of the being rented amount when the supply capacity is less than the demand as a whole in air cargo transportation market. In this context, the air express companies have to use the self-owned cargo aircrafts as more effectively as possible to reduce the rental cost. While since the cargo aircrafts are self-bought ones the operation cost only changes with running distance. Therefore, the decision making of the express companies with the objective to maximize the benefit equals to determine the way of using the cargo aircrafts and the amount of renting bellies on each link. The process can be described as follows:

In the network of passenger flights, air express companies need to choose some airports as hubs to arrange cargo aircrafts between them. After that, the capacities of links between airports should be decided, i.e. making schemes of deploying cargo aircrafts between hubs and setting amounts of the rented bellies of passenger aircrafts. At last, the transportation schemes of express cargos between ODs are determined.

4. Mathematical model

The decision making of the express companies with the objective of maximizing benefits can be described using the idea of a bi-level programming model, where the upper model chooses hubs and creates links and the lower model simulates the path choice behavior based on a user equilibrium principle to find paths for the cargo between OD pairs. Finally, the schemes designed by the upper model will be evaluated.

According to the above analyses, the upper model here represents the problem of designing an air cargo transportation network and deploying link capacities to minimize transportation costs. The model's output is the network structure, which contains the topological relationship and the impedance functions of links. Because cargo between cities is assumed to choose paths based on path impedances, decision makers may assign the cargo between OD pairs to paths with the user equilibrium assignment model in the lower level. The assignment model can output link flows and the corresponding unit costs, which will be used as the value of the objective function of the upper model.

4.1. Variable explanation

- $N = (1, 2, 3, \dots, n)$: Set of airports;
- m : Maximum number of cargo aircraft;
- d_{ij} : Distance between airport i and airport j ;
- W_{ij} : Transportation demand from city i to city j ;
- q_{ij} : Flow in the bellies on Link (i, j) ;
- Q_{ij} : Flow on the cargo aircraft on Link (i, j) ;
- C_{ij} : Unit rental cost of a belly between airport i and airport j , varying with the rental amount, i.e., $C_{ij}(q_{ij}) = f(q_{ij})$;
- C : The transportation cost of a unit distance of a cargo aircraft, not changing with the flow due to it is self-bought one, namely $C(Q_{ij}) = C$;
- t_{ij} : Impedance of Link (i, j) ;
- L_{ij} : Transportation capacity of the bellies from airport i to airport j ;
- U_{ij} : Transportation capacity of cargo aircraft from airport i to airport j ;
- f_k^{rs} : Cargo flow on k_{th} path from city i to city j ;

$$z_i = \begin{cases} 1, & \text{If airport } i \text{ is a hub airport;} \\ 0, & \text{Otherwise} \end{cases}$$

$$\delta_{ij,k}^{rs} = \begin{cases} 1, & \text{If Link}(i,j) \text{ is on the } k_{th} \text{ path from city } r \text{ to city } s \\ 0, & \text{Otherwise} \end{cases}$$

4.2. Model construction

The upper model:

$$\text{Min} : \sum_{i \in N} \sum_{j \in N} z_i z_j d_{ij} (C(Q_{ij}) + q_{ij} C_{ij}(q_{ij})) + \sum_{i \in N} \sum_{j \in N} (1 - z_i z_j) C_{ij}(q_{ij}) d_{ij} q_{ij} \tag{1}$$

$$\text{S.T.} : \sum_{i \in N} z_i \times \left(\sum_{i \in N} z_i - 1 \right) / 2 \leq m \tag{2}$$

$$z_i \in \{0, 1\} \forall i, j \in N \tag{3}$$

The objective of the upper model (Eq. (1)) is to minimize the total transportation cost, where the first part represents the transportation cost between hub airports, including the costs of cargo aircraft and the cost of renting bellies, and the second part is the cost of renting bellies between hub airports and other airports and the cost of renting bellies between other airports. Eq. (2) is a constraint on the number of hub airports, where the left part denotes the number of unidirectional links between hub airports, which should not be greater than the maximum number of the cargo aircraft.

The lower model:

$$\text{Min} : \sum_{i \in N} \sum_{j \in N} \int_0^{q_{ij}} C_{ij}(w) dw + \sum_{i \in N} \sum_{j \in N} \int_0^{Q_{ij}} C dw \tag{4}$$

$$\text{S.T.} : \sum_k f_k^{rs} = W_{rs} \forall r, s \in N \tag{5}$$

$$f_k^{rs} \geq 0 \forall r, s, k \in N \tag{6}$$

$$q_{ij} \leq L_{ij} \forall i, j \in N \tag{7}$$

$$Q_{ij} \leq U_{ij} \forall i, j \in N \tag{8}$$

$$q_{ij} + Q_{ij} = \sum_r \sum_s \sum_k f_k^{rs} \delta_{ij,k}^{rs} \tag{9}$$

The lower model is a user equilibrium assignment model. Because the transportation costs of cargo aircraft are independent of the cargo being carried, this can be set to 0. Eq. (5) indicates that the sum of the flows on all paths between an OD pair equals the OD flow. Eq. (7) and Eq. (8) guarantee that the total amounts of carried cargo are less than the capacities. Eq. (9) means that the link flow is the accumulation of path flows.

5. Solution algorithm

Currently, the aircraft used for passenger transportation in China is mainly Airbus-320. Its belly loading capacity is 9435 kg in total. While the average load of passenger's luggage of each flight is 2471 kg, thus the belly capacity of one flight for express parcels is 6964 kg (Luo, 2011). Furthermore, from a survey we get to know

that a round-trip of 2×1316 km long flight of one cargo aircraft costs is 18,000 Yuan and the belly rental price of a 443 km flight of a passenger aircraft is 0.7 Yuan/kg. As air transportation costs are mainly fuel and labor costs, among which the fuel cost holds the main role. Because the fuel cost is proportional to distance, we assume the transportation costs are proportional to distance for the convenience of calculation. So the transportation costs of a unit distance of a cargo aircraft can be calculated as $C = 18000 / (2 \times 1316) = 6.84$ Yuan/km and the rental price of a unit distance of passenger aircraft bellies will be $0.7/443 = 0.00158$ Yuan/km/kg.

At present, most air passenger companies want to keep some belly capacities in hand in order to obtain greater profits in busy seasons, thus, if the order amount of a belly rent from an express company surpasses air passenger companies' expectation, they may raise rental price. In this case, the unit rental price on a link can be denoted as $C_{ij}(q_{ij}) = 0.00158(q_{ij}/V_{ij})^\alpha$, where V_{ij} is the expected lending belly capacity and q_{ij} is the actual rending belly capacity.

From the data of a sample airline company, we get to know that the highest price of the belly rent from January to October in 2011 is 13.5 Yuan/kg, and the lowest one is 11.6 Yuan/kg (Zou, 2012). It is rational to consider that the rental price for the biggest profit is $13.5/11.6 = 1.16$ times of that of the lowest profit. Moreover, from January to October in 2011, the largest monthly demand is 694.8 tons, which is 2.42 times of the off-season demand of 287.5 tons. Putting the ratios of $13.5/11.6 = 1.16$ and $694.8/287.5 = 2.42$ into $C_{ij}(q_{ij}) = 0.00158(q_{ij}/V_{ij})^\alpha$, we get $\alpha \approx 0.17$. For setting V_{ij} there is no clear criterion. In this study we assume that flight companies will raise the rent if the ordered belly capacities exceed 60% of the owned ones.

5.1. Algorithm of the upper model

Many literature suggested that heuristic algorithm was often a first choice to solve this kind of complicated problems (Yao et al., 2014a,b, 2015). Among heuristic algorithms, genetic algorithm (GA) is a heuristic which has been successfully applied to solve many problems (Chakroborty, 2003; Yan et al., 2006). Thus, a GA is developed to solve the upper model. The fitness function of the GA is the inverse of the total cost that is associated with a chromosome. Next, Encoding, Crossover and Mutation will be introduced in detail.

5.1.1. Encoding

We represent a feasible network with a binary chromosome. This chromosome is composed of a few genes, and the number of such genes is equal to the number of airports. If the value of a gene is 1, the corresponding airport is selected as a hub. For example, in Fig. 1, the values of the genes of 1, 2, 8 and 12 are 1, which means that the airports of 1, 2, 8 and 12 are the hubs.

5.1.2. Crossover

We select some pairs of chromosomes for crossover at random and adopt the single-point crossover method in our algorithm. For example, suppose that a selected pair of parent chromosomes are 1-0-1-1-0-0 and 1-1-0-0-1-1; if the crossover situation is between the fourth and fifth genes, then their offspring chromosomes are 1-0-1-1-1-1 and 1-1-0-0-0-0, respectively.

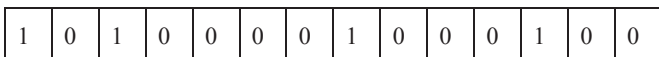


Fig. 1. Genetic code.

5.1.3. Mutation

We select a probability between 0 and 1 for each chromosome; if its probability is no larger than the probability for mutation, the chromosome mutates. The single-point mutation method is adopted, namely, selecting a gene randomly and making the gene 0–1 exchange. For example, if a chromosome is 1-0-0-1-1-0 and the selected gene is the fifth one, this chromosome will be changed into 1-0-0-1-0-0.

5.2. Algorithm of the lower model

We use the Frank-Wolfe algorithm to solve the lower model. Because the cargo aircraft are used on links between hub airports, cargo from one hub to another hub will be transported by cargo aircraft first. Therefore, the impedance of links between hub airports is zero if the link flow does not exceed the capacity of the cargo aircraft, and the exceeding parts will be transported in the bellies of passenger aircraft. The solution algorithm is as follows:

- Step 1 Initialization: Set $C_{ij}^0 = C_{ij}(0), \forall \text{Link}(i,j)$, do all-or-nothing assignment to obtain a set of feasible flows $\{x_{ij}^1\}$, and set $n = 1$;
- Step 2 Link-impedance update: set $C_{ij}^n = C_{ij}(x_{ij}^n), \forall \text{link}(i,j)$.
- Step 3 Direction finding: repeat all-or-nothing assignment with $C_{ij}^n = C_{ij}(x_{ij}^n), \forall \text{arc}(i,j)$ to additional link flows $\{y_{ij}^n\}$;
- Step 4 Move-size determination: solve $\sum_{ij}(y_{ij}^n - x_{ij}^n) \times C_{ij}[x_{ij}^n + \lambda(y_{ij}^n - x_{ij}^n)] = 0$ to obtain λ ;
- Step 5 Flow update: $x_{ij}^{n+1} = x_{ij}^n + \lambda(y_{ij}^n - x_{ij}^n)$.
- Step 6 Convergence judgment. If $\sum_{ij}(x_{ij}^{n+1} - x_{ij}^n)^2 / \sum_{ij} x_{ij}^n < \epsilon$ (ϵ : a given threshold), stop calculation and output x_{ij}^{n+1} . Otherwise, set $n = n+1$, and go to Step 2.

6. Case study

6.1. Utilized data

We chose 14 cities in the transportation network of the SF Express Company for the case study: Beijing (BJ), Shanghai (SH), Chongqing (CQ), Shenyang (SY), Wuhan (WH), Chengdu (CD), Xi'an (Xi), Zhengzhou (ZZ), Nanjing (NJ), Hangzhou (HZ), Fuzhou (FZ), Changsha (CS), Shenzhen (SZ) and Urumqi (Ur). The utilized data are from Zhang (2011). Table 1 shows the daily number of passenger flights among the 14 airports. We perform the calculation under the condition that 6 cargo aircraft are available and that the capacity of an aircraft is 20 t.

Table 1 Number of daily direct flights between 14 airports.

	BJ	SH	CQ	SY	WH	CD	Xi	ZZ	NJ	HZ	FZ	CS	SZ	Ur
BJ	0	53	18	9	14	35	19	2	9	19	12	11	31	17
SH	53	0	27	20	18	29	28	16	1	0	17	14	47	12
CQ	21	26	0	1	6	0	11	8	11	13	3	8	17	7
SY	10	20	1	0	4	1	4	6	4	6	0	0	5	0
WH	15	18	6	3	0	7	6	0	0	5	4	0	8	3
CD	36	30	0	1	7	0	13	8	9	12	5	7	19	10
Xi	24	26	11	4	6	13	0	0	7	16	3	5	14	13
ZZ	2	16	9	6	0	8	0	0	2	8	4	0	11	10
NJ	11	1	11	4	0	9	7	2	0	0	6	7	16	1
HZ	23	0	12	6	5	12	16	9	0	0	2	5	21	1
FZ	13	17	2	0	4	5	3	4	6	2	0	5	3	0
CS	14	14	8	0	0	7	5	0	7	5	5	0	2	2
SZ	31	47	18	5	8	19	15	11	16	21	3	2	0	1
Ur	17	12	7	0	3	10	14	11	1	1	0	2	1	0

Source: <http://flights.ctrip.com/>.

6.2. Network representation

The abstractions of a physical network are different for different analyses. Fig. 2(a) shows a roughly abstracted network that contains three airports and the corresponding flight lines. In this way, we can analyze the link flows but not the node flows. The transshipment activities at airports could not be understood if we were to assign the OD flows on this type of network.

Because we want to both design a flight network and develop schemes for transporting express parcels between OD pairs, we have to represent the physical network in a way whereby node flows must be analyzed. Fig. 2(b) shows the method of our representation wherein an airport will be separated into a node to represent the home city and another two nodes to represent the terminals used to berth the flights from the other two airports. In Fig. 2(b), the thick lines represent the flights of cargo aircraft, and the fine lines represent the flights of passenger aircraft. These lines are physical flight links. Links between the node of a city and the corresponding terminals and links between the nodes of the terminals of the same airport are dummy links used to represent transshipments.

6.3. Result analysis

6.3.1. Output of the upper model

Fig. 3 shows the output of the upper model when terminating the solution calculation. The figure shows that the Beijing, Shanghai, Nanjing, and Shenzhen airports are selected as hub airports.

Because 4 airports are hubs, all 6 cargo aircraft will be used. The corresponding link and node flows are as follows:

6.3.2. Link flows

Fig. 4 shows the cargo flows on the links between hub airports. The number in front of the parentheses is the total flows from an origin airport to the destination airport, and the number in the parentheses represents the transshipped flows at the destination airport. The cargo flows on the links from Shanghai to Nanjing and from Nanjing to Shanghai are both 20.9 t, namely, less than the flows on the other links. The flows on links from Beijing, Shanghai and Nanjing to Shenzhen are, respectively 27.3 t, 28.4 t, and 28.9 t, among which the total amount of transshipped cargo at Shenzhen airport is only 0.07 t. This is because the transportation demand of Shenzhen itself is too large for the Shenzhen airport to transfer the cargo from Beijing, Shanghai and Nanjing to other airports.

6.3.3. Node flows

The flows from other airports to the four hub airports are shown

in Fig. 5, Fig. 7, and Fig. 8, where the flows on the links ending at the hub airports represent the cargo to these hubs and the flows on the links starting from the hub airports represent that transshipped cargo at hub airports being shipped to other airports.

From Fig. 5, it can be seen that over 60 t of cargo is sent to Beijing airport, among which the cargo transshipped from Beijing to other airports represents 18.4 t. The transshipped cargo is mainly from Shenyang (11.5 t) and Zhengzhou (4.8 t) because the Beijing airport is located in the north of China. It is convenient to transship cargo for the two nearby cities. The cargo from the Hangzhou, Wuhan, Chengdu and Chongqing airports to the Beijing airport represents all the cargo ending at Beijing, and none of this cargo is transshipped at the Beijing airport. This is because the four cities are located in the central and south of China; thus, it is not convenient for Beijing to transfer their cargo to other cities.

Fig. 6(a) and Fig. 6(b) show the flows from the Shenyang and Zhengzhou airports to some other airports via the Beijing airport, respectively. It can be seen that, among the cargo from the Shenyang airport to the Beijing airport, 11.4 t of cargo is transshipped to other cities. Most of this cargo is transshipped to hub airports (Shenzhen, Shanghai, Nanjing airports), and a small amount is transshipped to the Urumqi airport. The cargo from the Beijing airport to the Urumqi airport is the cargo destined for Urumqi city. It can also be seen that, among the cargo from the Zhengzhou airport to the Beijing airport, 4.8 t of cargo is transshipped to other hub airports, and the other cargo is destined for Beijing city.

From Fig. 7, it can be seen that large amounts of cargo (21.9 t) are transported from non-hub airports to the Shenzhen airport; all this cargo is destined for Shenzhen city. In other words, no cargo is transshipped at the Shenzhen airport from non-hub airports. Therefore, it can be considered that the Shenzhen airport is a typical “hinterland”-type hub.

It is unreasonable for two adjacent airports, namely, the Shanghai and Nanjing airports, to both be hub airports. However, from Fig. 8, we can see that the Shanghai airport transships 3.3 t of cargo for the Wuhan airport and 9.2 t of cargo for the Fuzhou airport and that the Nanjing airport transships 0.7 t of cargo for the Xi'an airport, 2.5 t of cargo for the Changsha airport, 1.0 t of cargo from the Chengdu airport and 0.6 t of cargo from the Chongqing airport.

The Shanghai and Nanjing airports transship large amounts of cargo for airports in central and southern cities. Due to the insufficient belly capacities, cargo between two cities located long distances away from each other and with minimal belly capacities may need to be transported to the hub airports in central areas and then transshipped to their destinations. As the result, in central areas, there is a large transshipment demand, and the two adjacent airports there, i.e., the Shanghai and Nanjing airports, must be hub

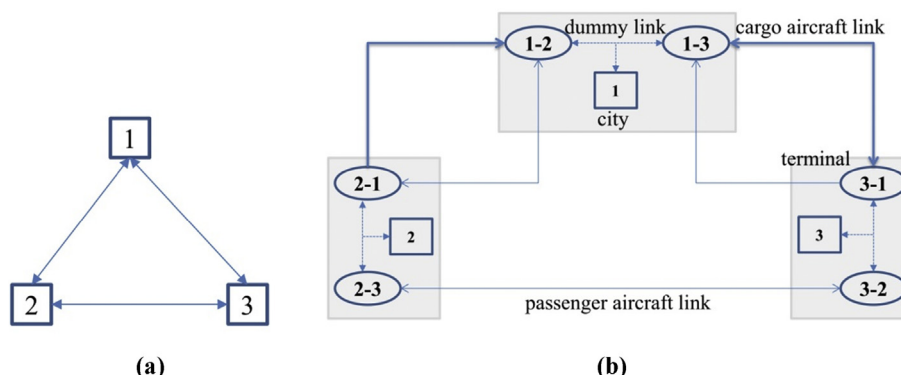


Fig. 2. Two methods used to represent a Flight Network.

1	1	0	0	0	0	0	0	1	0	0	0	1	0
BJ	SH	CQ	SY	WH	CD	Xi	ZZ	NJ	HZ	FZ	CS	SZ	Ur

Fig. 3. Solution of the upper model.

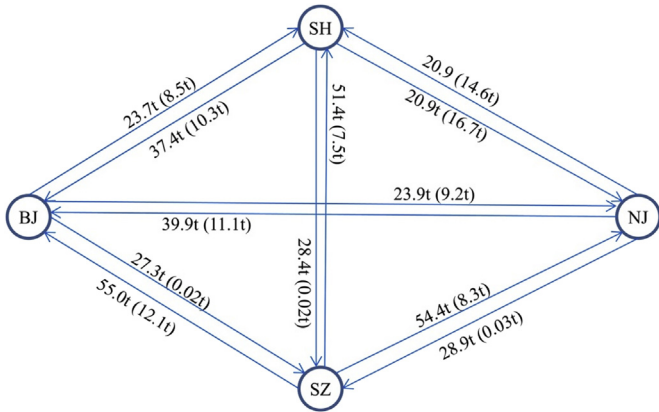


Fig. 4. Cargo flows between hub airports.

hub airports but also other airports. For example, Fig. 9 shows the node flows at the Hangzhou airport. It can be seen that the total inflow is 87.7 t, and most of these flows are cargo with Hangzhou as the destination. In addition, the outflow is 1.6 t, which means that 1.6 t of cargo is transshipped at the Hangzhou airport. Among the transshipped cargo, 0.6 t of cargo is from Wuhan, 0.8 t of cargo is from Zhengzhou, and 0.2 t of cargo is from Changsha.

6.4. Rationality discussion and relevant suggestion

In our results, the airports of Beijing, Shanghai, Nanjing, and Shenzhen are selected as hub airports. In reality, Beijing airport and Shanghai airport are hubs in China, which is same as the calculation results. The transportation demand of the corresponding cities of the four hub airports under SF Express Company ranks in former of the 14 cities, so it is reasonable for these 4 airports to be hub ones for the large transport volume. From the aspects of location, the 4 airports are relatively located in the north, central and south of China. Beijing airport as a north hub can transship express cargos for Shenyang and Zhengzhou. It seems unreasonable for the airports of Nanjing and Shanghai to be hubs together because they are in same area. While the express network is a mixture of “point-to-point” network and “hub-and-spoke” network, direct passenger flights exist on almost all links, as a result, the airports in central

airports to facilitate transshipments. Moreover, the shortage of transshipment abilities in Shenzhen for the southern cities is also a reason for both the Shanghai and Nanjing airports to be hubs.

In a network consisting of point-to-point belly lines and hub-to-hub cargo aircraft lines, the cargo can be transshipped at not only

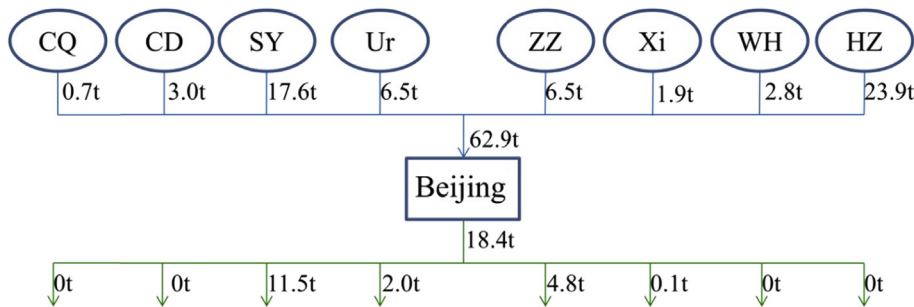


Fig. 5. Node flows at the Beijing airport.

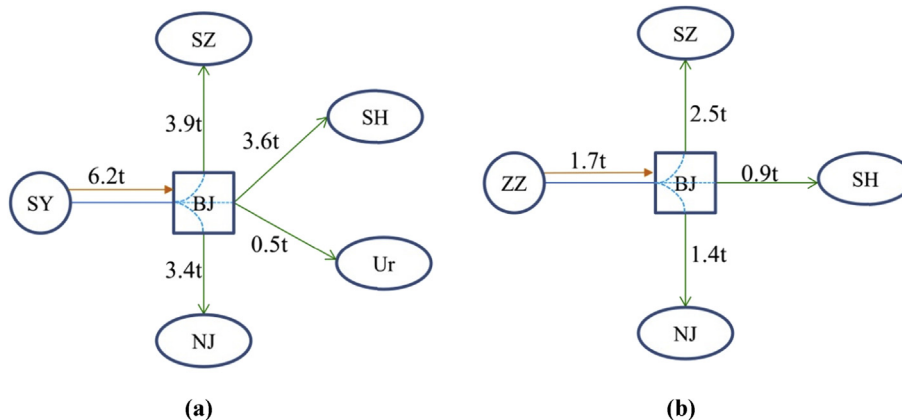


Fig. 6. Flows from Shenyang and Zhengzhou to other airports via the Beijing airport.

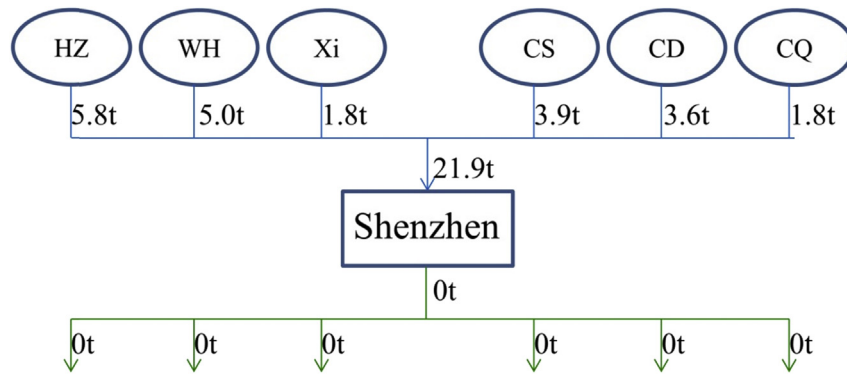


Fig. 7. Node flows at the Shenzhen airport.

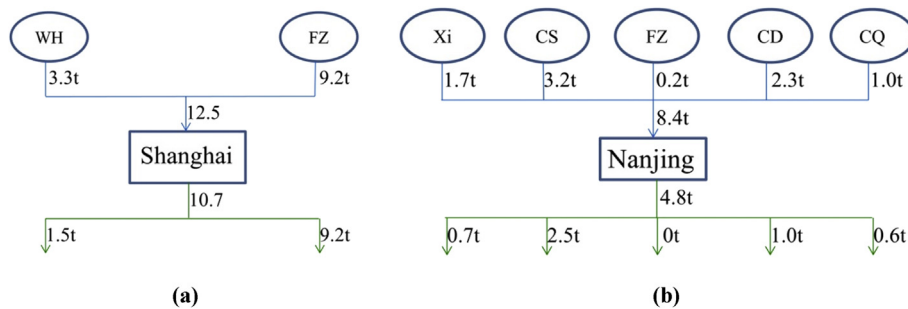


Fig. 8. Node flows at the Shanghai and Nanjing airports.

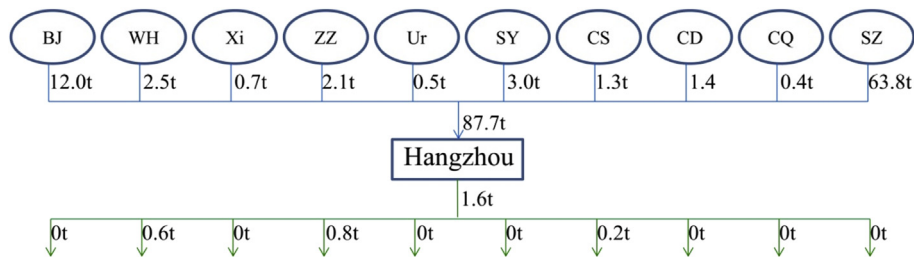


Fig. 9. Node flows at the Hangzhou airport.

areas are faced with large transshipping demand. So selecting the two airports as combination hubs can be convenient for the large amount of express cargos to be transshipped.

In the actual transport network of SF Express Company, some cargo aircrafts are not used effectively, for example, there is a cargo aircraft arranged on the link from Dalian airport to Hangzhou airport and the capacities are often underutilized. To make full use of the cargo aircrafts, they should be arranged on hub links primarily. In addition, to make the hub airports more effective, not only the links between hub airports, but also the links between hub airports and non-hub airports should be arranged with enough transportation capacity, includes setting more cargo aircrafts and renting more belly capacities. If the self-owned cargo aircrafts are enough, it is reasonable to set more large transportation demand airports as hubs in order to use the cargo aircrafts effectively.

7. Conclusions

This paper constructs a bi-level model for optimizing the flight networks of express companies. We use data on the SF express company to conduct this case study to test the model. In the case

study, we represent a physical flight network so that link flows and node flows can be analyzed. Through the analysis of the calculation results we can draw the following conclusions: 1) With our network abstraction method, we can analyze the paths of cargos more exactly. 2) Cargos may be transshipped at some airports to reduce the transportation costs. 3) The bi-level model in this paper may be generalized to other fields, such as road transportation. In reality, the numbers of passenger flights are quite different in different time periods of the same day. In the future, we will study the express transportation cases in each time period of one day.

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