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DESIGN OF TIMETABLE FOR AIRPORT COACH BASED ON 'TIME–SPACE' NETWORK AND PASSENGER'S TRIP CHAIN

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Abstract. This paper designs the timetable for the airport coach which is a new access service provided by the airport with the purpose of attracting more passengers. Firstly, the 'time–space' network is constructed for analyzing the formation of the passengers' trip chain; Secondly, the timetable design model is built with the aim to minimize the unit operation cost per transported passenger of the airport coach and a genetic algorithm with matrix coding is used for solving the model. In the model, the coach departure time and the flight schedule are connected with each other; the quality of the coach service and the passenger's demand are both considered. Finally, the coach of Dalian airport in China is taken as an example to test the proposed method. Through solving the model and sensitivity analysis, we obtain a coach timetable for Dalian airport. The results show that the proposed model can provide a practical method to design the timetable for the airport coaches with 'hub-and-spoke' network.

Keywords: timetable design; 'hub-and-spoke' network; 'time–space' network; trip chain; matrix coding.

Introduction

In 2009, the total turnover of China civil aviation reached 42.71 billion ton-kilometres, the passenger volume reached 4.9 billion persons, the cargo and mail volume reached 9.45 million tons, which was respectively 1.5, 4 and 3.7 times of those in 2002. China has 166 civil airports in 2012 and its density has increased from 14 airports per million square kilometres to 48 airports per million square kilometres in last 10 years (From a Statistical Look… 2012). Under this level of density, the hinterlands of several airports overlap with each other and the competition between the airports becomes fierce (Chi-Lok, Zhang 2009; Yang *et al.* 2009; Zhang *et al.* 2010). Thus, the airports propose some methods to attract passengers, such as opening more air routes, signing contracts with more airlines and developing the surface access systems (Liu *et al.* 2011; Zeng *et al.* 2010). Among the methods, improvement of the surface access system is adopted most recently, because it can quickly raise the competitiveness of an airport (Jou *et al.* 2011).

The airport coach is an extension of the shuttle bus. It can provide transportation service between the airport and the surrounding cities (Ashley, Kateley 1996). The 'hub-and-spoke' network is always adopted for airport coach system since it can satisfy the passengers' demand and save the operating cost (Bryan, O'Kelly 1999). However, it impels the passengers in the spoke nodes to transfer. Therefore, the coach managers must pay attention to the connection of the dispatching times between the branch coaches and the trunk ones (Wei, Hansen 2006). Meantime, they must arrange the dispatching time of the trunk coaches according to the flight schedule. On the other hand, the high dispatching frequency means more coach vehicles are needed which is a key component in the operation cost (Yu *et al.* 2010). Therefore, the purpose of this paper is to design a reasonable coach timetable, which can both satisfy passengers' demand and control the operation cost.

There are a lot of studies focus on the research of bus frequency and departure interval.

Sun *et al.* (2007) analyze the bus-dispatching schedule of the public transit lines and provide a model of controlling the dispatching interval considering both generalized trip cost of passengers and bus operation cost. They figure out that the interval have a great influence on bus operation cost.

Qin and Wang (2009) add the loading factor and the operation profits into the constraints of the interval decision making. They found that the appropriate interval can largely save the operation cost by raising the loading factor.

Chen *et al.* (2004) analyze the dispatching interval of the urban bus. They build a multi-objective model

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considering both the passengers' satisfaction and the benefit of the bus. The results show that consideration of passengers' demand can make the timetable more useful in practice.

The literatures above focus on optimizing the bus-dispatching interval. The models consider the passengers' demand as well as the operation cost. Their methods are suitable for analyzing the bus schedule when the passenger's arrival follows an even distribution. However, if the passenger's arrival does not follow the even distribution, the uniform dispatching interval cannot satisfy the passengers' demand. Thus, many researchers have designed the timetable according to the situation that arrivals are uneven.

Yan *et al.* (2006b) analyze the routing and timetable optimization for a point-to-point network. They take the passenger's demand on every time point into account and use two heuristic algorithms to solve the model. The results show that the timetable, which is designed based on the actual passenger's arrival pattern can be more useful in practice.

De Palma and Lindsey (2001) analyze the timetable optimization on a single transit line when riders differ with respect to the time at which they prefer to travel. The results show that the timetable can fit passenger's demand very well as the model considers the demand of every passenger.

Except for the passenger's demand, the network structure is also important in the timetable design. For the simple network structure, such as the 'point-to-point' network, the most important thing in timetable design is to satisfy the passenger's demand on every point. For the complex network structure, such as the 'hub-and-spoke' network, the connection between the trunk lines and the branch lines is also very important. As the 'hub-and-spoke' network is commonly used in the operation of the airport coach, we should focus on the timetable design model of the 'hub-and-spoke' network.

There are few literatures focusing on bus timetable design in the context of 'hub-and-spoke' network. However, some researchers designed the airline timetable in the context of 'hub-and-spoke' air route network. The proposed methods may be useful for us and are referred as follows.

Rietveld and Brons (2001) analyze the quality of the co-ordination of timetables in airlines' 'hub-and-spoke' network. They find that a good timetable will reduce the airline operation costs. Dobson and Lederer (1993) study the flight schedules of the airlines operating in a 'hub-and-spoke' system. The optimization model is built with goal of maximizing the profit and satisfying the passengers' demand. The results show that the timetable design in the 'hub-and-spoke' network should consider the operation cost, the routes and passengers' demand.

Yan *et al.* (2006a) develop an integrated scheduling model, which combines the airport selection, fleet routing and timetable setting of air cargos. In the analysis, the cargo flow is analyzed based on the 'time–space' network. The results show that the 'time–space' network is helpful for timetable setting of 'hub-and-spoke' network.

In contrast with the methods of designing the bus timetable and the flight schedule, the relationship between the coach departure time and the flight schedule should be considered during designing the airport coach.

This paper introduces the 'time–space' network to analyze and build the timetable design model with the aim to minimize the unit operation cost per transported passenger. Because the airport coach timetable should be connected to the flight schedule, here the 'time–space' network will be more complicated.

Based on the methods of designing the flight schedule and designing bus timetable, this paper introduces the timetable designing method of the 'hub-and-spoke' network into research and specifically pays more attention to the passengers' demand of the airport coach, thus to design the most appropriate timetable for the airport coach which is a special travel mode with a lot of characteristics.

This paper is arranged as follows, the 'hub-and-spoke' and the 'time–space' network are described in Section 1; The formation of passengers' access trip chain is analyzed in Section 2; The timetable design model is built in Section 3. Data and results are discussed in Section 4, while Section 5 does the sensitivity analysis and obtains a suitable timetable. Last section offers the conclusion.

1. 'Hub-and-Spoke' Coach Network

Fig. 1 shows a 'hub-and-spoke' coach network. The aircraft at the bottom represents the airport, the large coaches represent the hub nodes and the small ones represent the spoke nodes. The spoke nodes are linked to the hub nodes by branch routes, while the hub nodes are linked directly to the airport via the trunk routes, but the hub nodes are not linked with each other. In the network, passengers in the hub nodes can go to the airport directly, while passengers in the spoke nodes should go to a hub firstly and then go to the airport along with those in the hub node by trunk coaches.

Taking the passengers from the spoke nodes as an example, their trip chain from the spoke nodes to the airport includes four components. First, is the trip from

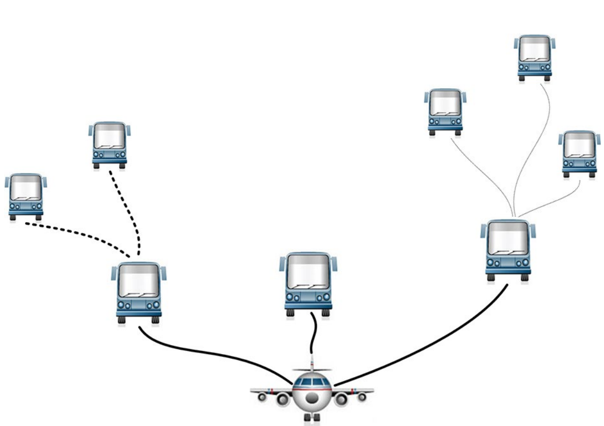

Fig. 1. The structure of the 'hub-and-spoke' coach network

the spoke node to the hub node, second is the waiting for the trunk coach in the hub node, and third is the moving from the hub node to the airport and forth is the waiting in the lounge. For designing the timetable for the airport coach, we should consider the connection of the routes, the route length and the passengers' flight departure times. It is a two-dimensional problem where the time and space should be considered together. In order to combine the time with the space, a 'time–space' network (Kliewer *et al.* 2006, 2008) is constructed to illustrate the trip chain on a one-dimensional platform.

The 'time–space' network is shown in Fig. 2. It presents the time and the space on the same plane. Its forepart describes the construction of the network. The numbers represent the nodes (1–10 are the city nodes and 11 is the airport node); each row of the number stands for a coach route, the first number of each row is the origin of the route and the second is the destination; and the square behind the number represents the characteristic of each route (the solid stands for the trunk route and the hollow one means the branch one). The origins of the branch routes are spoke nodes and those of the trunk routes are the hub ones. The two kinds of routes connect with each other to compose the coach network. For example, node 1 is connected to the airport firstly through the branch route (1–3) and then the trunk route (3–11).

The remaining part behind the network structure is the 'time–space' grid, the time axis at the bottom includes 24 time points from 1:00 to 24:00 in one day, the routes and time are connected by the grids. The solid dot means that there is a dispatched coach. For example, the first row means the route (1–3) is a branch one, and a coach will depart to node 3 at 4:00, 6:00, 11:00, and 20:00 respectively.

2. The Formation of Passenger's Trip Chain

Based on 'time–space' network, we can analyze the formation of passenger's trip chain. The trip chain contains three parts: departure time point, time on the way and arrival time point. Because the flight time, the coach network and the travel time of the coach are fixed, a passenger can decide his coach departure time. If we know the departure time of all passengers, we can get to know the passengers' demand on the dispatching time of the coaches. Then, we can design the timetable based on the demand data.

In the paper, we just consider the demand of the passengers who prefer the airport coach. Other passengers may use other modes to go to the airport, such as the private car or the taxi. To simplify the analysis, the passengers are divided into several groups according to their flight times, the interval is 1 hour. Passengers are assumed to board the plane at the beginning of each time period. We take the passengers in the spoke nodes as an example to analyze the formation of the trip chain, and the whole process is shown in Fig. 3. The dotted arc represents the travel from node to node, while the dotted line represents the transit or the waiting in the

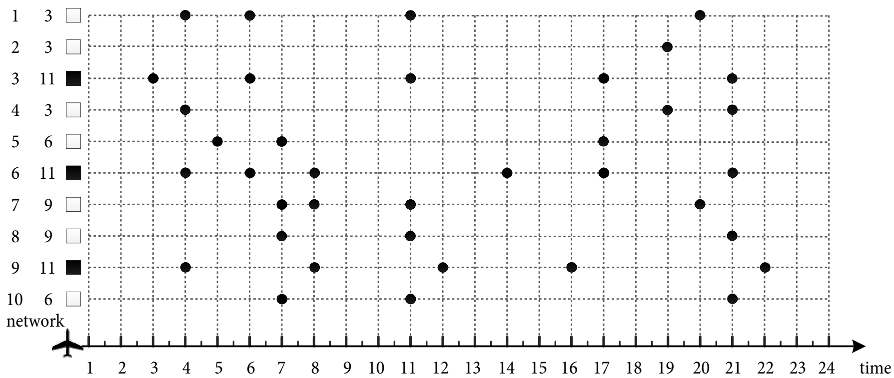

Fig. 2. The structure of the 'time–space' network

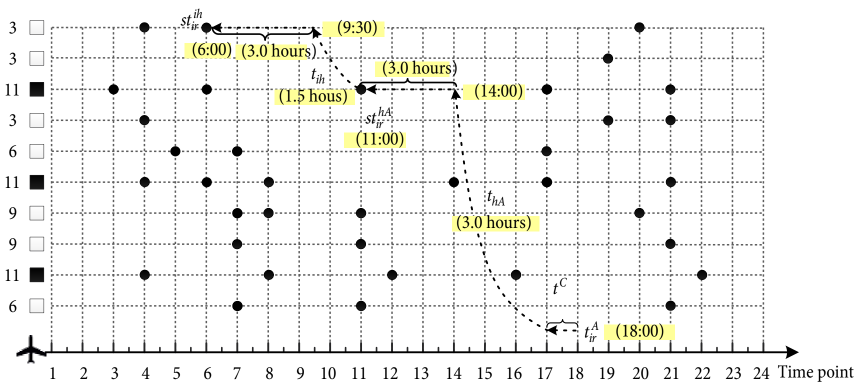

Fig. 3. The decision process of the departure time in the trip chain

lounge. Their combination presents the passenger's decision process of the departure time at the spoke node, which includes determination of the departure time at hub nodes, and the departure time at spoke nodes.

For example, if the flight departure time of the passengers in group r at spoke node i is t_{ir}^{A}, then the latest time to reach the airport A should be $t_{ir}^{A} - t^{C}$, because the passenger needs to reach the airport t^{C} before the flight. Due to the transfer at node h and the coach travel time from node 3 to the airport is 3 hours, the latest departure time at node h should be $t_{ir}^{A} - t^{C} - t_{hA}$. In order to board on time as well as wait for the shortest time in the lounge, the passengers should take the last coach to the airport which is earlier than $t_{ir}^{A} - t^{C} - t_{hA}$. Therefore, the passenger's departure time at the hub node should be st_{ir}^{hA}, similarly the departure time at the spoke node should be st_{ir}^{ih}.

3. Timetable Design Model

Here, we introduce the assumptions of the model:
- only the departure passengers are taken into account in the model;
- all the passengers are rational;
- the network of the airport coach and the coach travel time is given.

Based on the above assumptions, the model is built to design the airport coach timetable with the goal of minimizing the unit operation cost per transported passenger of the airport coach. The inputs and the outputs are shown in Fig. 4. We can see that the 'passenger volume', the 'flight departure time of every passenger', the 'network construction' and the 'coach travel time on every link' are firstly transformed to the distribution of the passengers' arrival at the coach station, and then the distribution is put into the timetable design model, finally the designed timetable and the loading factor of the dispatched coach are got by solving the model.

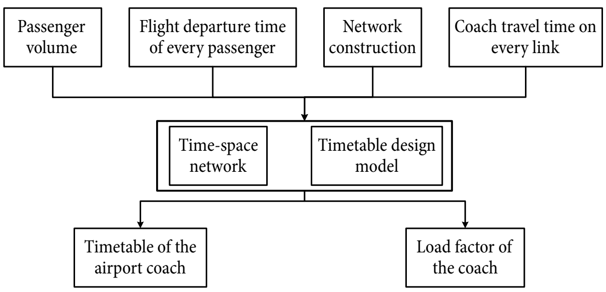

Fig. 4. The inputs and outputs of the model

The symbols used in the paper are listed as follows:

A – the airport (variable, integer);
$\overline{C}$ – the unit operation cost per transported passenger of the airport coach [Yuan] (variable, continuous);
c_{ih} – the operating cost of the branch coach for a unit distance [Yuan] (constant, continuous);
c_{hA} – the operation cost of the trunk coach for a unit distance [Yuan] (constant, continuous);
d_{ih} – the length of the branch route [kilometre] (variable, continuous);
d_{hA} – the length of the trunk route [kilometre] (variable, continuous);
h – the hub node in the network of the airport coach (variable, integer);
i – the spoke node in the network of airport coach (variable, integer);
k_t^{ih} – the coach vehicles needed on the branch route (i–h) at time t (variable, continuous);
k_t^{hA} – the coach vehicles needed on the trunk route (h–A) at time t (variable, continuous);
K, K', K'' – the storage variable (variable, continuous);
N_B – the capacity of the branch coach (constant, integer);
N_T – the capacity of the trunk coach (constant, integer);
n_t^{ih} – the passenger volume on branch route (i–h) at time t (variable, continuous);
n_t^{hA} – the passenger volume on trunk route (h–A) at time t (variable, continuous);
q_{ir} – the passenger volume in rth group at node i (variable, continuous);
q_{hr} – the passenger volume in rth group at node h (variable, continuous);
st_{ir}^{ih} – the passenger's departure time at the spoke node [passenger from the spoke node] (variable, continuous);
st_{ir}^{hA} – the passenger's departure time at the hub node [passenger from the spoke node] (variable, continuous);
st_{hr}^{hA} – the passenger's departure time at the hub node [passenger from the hub node] (variable, continuous);
T – the upper limit of the waiting time in the lounge [hour] (constant, integer);
T' – the upper limit of the transfer time at the hub node [hour] (constant, integer);
t – the time point during one day (variable, continuous);
t_{ir}^{A} – the passenger's flight departure time [passenger from the spoke node] (variable, continuous);
t_{hr}^{A} – the passenger's flight departure time [passenger from the hub node] (variable, continuous);
t_{hA} – the coach travel time from the hub node to the airport [hour] (variable, continuous);
t_{ih} – the coach travel time from the spoke node to the hub node [hour] (variable, continuous);
t^{C} – the check in time of the passenger in the airport [hour] (constant, continuous);
x_t^{ih}, x_t^{hA}, y_{ir}^{iht}, y_{ir}^{hAt}, y_{hr}^{hAt} – 0, 1 variables (variable, integer).

3.1. Objective Function

The objective function is as follows:

$$\text{Min: } \bar{C} = \left(\sum_i \sum_h \sum_t k_t^{ih} c_{ih} d_{ih} x_t^{ih} + \right.$$
$$\left. \sum_h \sum_t k_t^{hA} c_{hA} d_{hA} x_t^{hA} \right) \Bigg/ \left(\sum_i \sum_t n_t^{ih} + \sum_h \sum_t n_t^{hA} \right). \quad (1)$$

The first part of the numerator is the daily cost of the branch coach, the second part is that of the trunk coach, and the denominator is the daily coach passenger volume. In the equation, x_t^{ih} and x_t^{hD} are 0, 1 variables, which are as follows:

$$x_t^{ih} = \begin{cases} 1\text{, a coach dispatching on route } i\text{–}h \text{ at time } t; \\ 0\text{, no coach dispatching on route } i\text{–}h \text{ at time } t; \end{cases} \quad (2)$$

$$x_t^{hA} = \begin{cases} 1\text{, a coach dispatching on route } h\text{–}A \text{ at time } t; \\ 0\text{, no coach dispatching on route } h\text{–}A \text{ at time } t. \end{cases} \quad (3)$$

The needed coach vehicles $\left(k_t^{ih}, k_t^{hA}\right)$ can be calculated by Eqs (4) and (5) respectively. In Eq. (4), n_t^{ih} is determined by Eq. (6). y_{ir}^{iht} in Eq. (6) is used to judge whether the dispatching coach on the branch route (*i*–*h*) at *t* is chosen by the passengers in *r*th group. The value y_{ir}^{iht} is determined by Eq. (7). Passengers' departure time at node *i* st_{ir}^{ih} is determined by Eqs (8) and (9). Eq. (8) calculates the departure time at hub node *h*, it shows that passengers will choose the coach, which makes them, have the least waiting time in the lounge. Eq. (9) determines the departure time at the spoke node and structure is similar to Eq. (8).

$$k_t^{ih} = \frac{n_t^{ih}}{N_B}; \quad (4)$$

$$k_t^{hA} = \frac{n_t^{hA}}{N_T}; \quad (5)$$

$$n_t^{ih} = \sum_r q_{ir} \cdot y_{ir}^{iht}; \quad (6)$$

$$y_{ir}^{iht} = \begin{cases} 1, & st_{ir}^{ih} = t; \\ 0, & st_{ir}^{ih} \neq t; \end{cases} \quad (7)$$

$$st_{ir}^{hA} = K,\ K \geq t \cdot x_t^{hA} > 0; \quad (8)$$

$$st_{ir}^{ih} = K',\ K' \geq t \cdot x_t^{ih} > 0. \quad (9)$$

Similarly, Eq. (10) is used to calculate n_t^{hA}. Its first part stands for the transfer passenger volume at hub node *h*, and the second part means the volume of the passenger whose origin is hub node (*h*). In addition, y_{ir}^{hAt}, y_{hr}^{hAt}, st_{hr}^{hA} are shown in Eqs (11–13) respectively.

$$n_t^{hA} = \sum_i \sum_r q_{ir} \cdot y_{ir}^{hAt} + \sum_r q_{hr} \cdot y_{hr}^{hAt}; \quad (10)$$

$$y_{ir}^{hAt} = \begin{cases} 1, & st_{ir}^{hA} = t; \\ 0, & st_{ir}^{hA} \neq t; \end{cases} \quad (11)$$

$$y_{hr}^{hAt} = \begin{cases} 1, & st_{hr}^{hA} = t; \\ 0, & st_{hr}^{hA} \neq t; \end{cases} \quad (12)$$

$$st_{hr}^{hA} = K'',\ K'' \geq t \cdot x_t^{hA} > 0. \quad (13)$$

3.2. Constraints

Eqs (14–20) are the constraints, among them Eqs (14–16) are the constraints on passengers' waiting time and transfer time. For example, Eq. (14) means that the waiting time of passenger in group *r* in the lounge should be greater than 0 and smaller than the upper limit *T*. It means that the system at least owns one coach making the passenger on board punctually and making the waiting time in a certain range. It can avoid sending the passengers to the airport too early. Accordingly, Eqs (15) and (16) can be explained. Eq. (17) shows that on branch route (*i*–*h*), the passenger volume on the dispatching coach at time *t* cannot be 0. Eq. (18) is similar to Eq. (17) but for the branch coach. Eqs (19) and (20) require that there must be at least one dispatching coach on each route.

$$0 < \left(t_{hr}^{A} - t^{C} - t_{hA} - t\right) \cdot x_t^{hA} \leq T; \quad (14)$$

$$0 < \left(t_{ir}^{A} - t^{C} - t_{hA} - t\right) \cdot x_t^{hA} \leq T; \quad (15)$$

$$0 < \left(st_{ir}^{hA} - t_{ih} - t\right) \cdot x_t^{ih} \leq T'; \quad (16)$$

$$T' \geq 0.5,\ T \geq 0.5;$$

$$\left(n_t^{ih} - 0.5\right) \cdot \left(x_t^{ih} - 0.5\right) > 0; \quad (17)$$

$$\left(n_t^{hA} - 0.5\right) \cdot \left(x_t^{hA} - 0.5\right) > 0; \quad (18)$$

$$\sum_t k_t^{ih} \geq 1; \quad (19)$$

$$\sum_t k_t^{hA} \geq 1. \quad (20)$$

3.3. Algorithm Design

Because the dispatching time interval of the airport coach is not fixed, the solution space of the model is huge. We use the genetic algorithm with matrix coding (Guan 2008; Bo *et al.* 2002; Yang *et al.* 2005) to solve the model, and the matrix coding is designed based on the 'time–space' network.

The structure of the coding is shown in Fig. 5. The rows and the columns of the coding correspond to the routes and the time points separately. Every gene in the code corresponds to the intersection of the latitude and

$$\text{10 rows}\left\{ \underbrace{\begin{array}{ccccccccc} 0 & 1 & 0 & 0 & \cdots\cdots & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & \cdots\cdots & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & \cdots\cdots & 1 & 0 & 0 & 0 \\ \vdots & & & & \cdots\cdots & & & & \vdots \\ 1 & 0 & 0 & 1 & \cdots\cdots & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 0 & \cdots\cdots & 1 & 1 & 0 & 0 \end{array}}_{\text{24 columns}} \right.$$

Fig. 5. The structure of the matrix coding

longitude lines in the 'time–space' network. The value 1 of the gene means a coach dispatched.

As we choose the roulette selection procedure, the fitness value (Eq. (17)) should be the negative of the objective. In addition, in order to collect the passengers' flight time, we implemented the survey on the passengers in Dalian airport:

$$FitV = -\overline{C}. \tag{21}$$

4. Case Study

By taking Dalian airport as the example, we design the coach timetable as follows.

4.1. The Needed Data

According to the hinterland and air travel demand, the 'hub-and-spoke' coach network shown in Fig. 6 has been adopted by Dalian airport. We can see that there are 5 hub nodes (Yingkou, Bayuquan, Pulandian, Dandong and Zhuanghe) and 5 spoke nodes (Panjin, Dashiqiao, Gaizhou, Wafangdian and Donggang). The number under the node is the daily air travel volume in the city. The solid line represents the trunk route and the dotted line means the branch route. The number on the line is its distance. The passenger capacity of the trunk coach is 50 seats and the unit running cost is 1.84 Yuan/km. The passenger capacity of the branch coach is 30 seats and the unit running cost is 1.3 Yuan/km.

In order to get the flight departure time distribution of the passengers from different cities, we deliver the questionnaires at the security checkpoint in Dalian airport to make the survey. We delivered 5000 questionnaires and then analyzed the flight departure time of the surveyed passengers. As the data size is large, we choose three cities (Yingkou, Dandong and Panjin) in the airport coach network and give the flight departure time distribution of the passengers from these three cities in Fig. 7. It can be seen that the passengers' flight departure

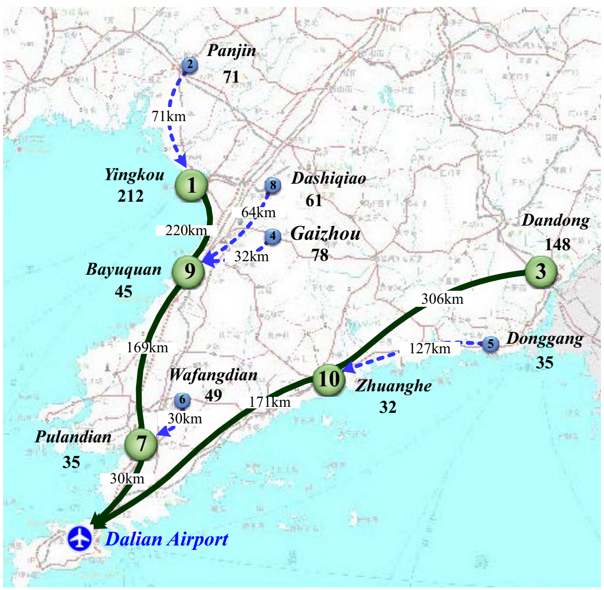

Fig. 6. The coach network structure of Dalian airport

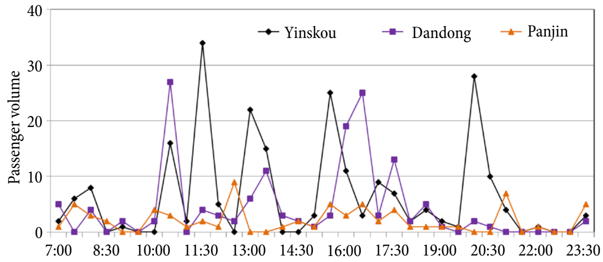

Fig. 7. The passengers' flight departure time distribution in a single day

time is concentrated in the three periods (10:00–14:00, 16:00–17:00, 20:00–21:00) in a single day. As the cities are far away from Dalian airport, the passengers seldom choose the flights departing during the period from 7:00 to 9:00 in the morning.

4.2. Results

In the case study, there are 11 nodes and 9 arcs in the network; 240 binary 0–1 variables. Because the model is non-linear and constrained by 8 inequality constraints, the solving space is huge. Therefore, the heuristic described in section 4 was used. The heuristic was coded in *MatLab.Net* 2010 and executed on a PC equipped with 3.0 GB of RAM and a Pentium processor running at 4.53 GHz. And the heuristics is coded on the basis of the Genetic Algorithm Toolbox designed by the University of Sheffield (UK). As the Toolbox can not be used to solve the model directly, we add some contents and make it suitable for solving the model.

The crossover rate P_c and the mutation rate P_m should be fixed when we are solving the model. In order to find the most appropriate value of P_c and P_m, we calculate different fitness value corresponding to different combinations of P_c and P_m when $T = 3$, $T' = 2$. The results are shown in Table 1. In the table, the range of P_c is from 0.3 to 0.8, the range of P_m is from 0.05 to 0.2. Because the fitness value reaches the highest value (–37.86), when $P_c = 0.1$ and $P_m = 0.7$, we set $P_c = 0.1$ and $P_m = 0.7$ when solving the model.

In the calculation, We set $T = 3$, $T' = 2$, $P_c = 0.1$ and $P_m = 0.7$; the initial optimization point is generated randomly by the algorithm $F = -9870.45$, the CPU time for the calculation is 9.45 minutes. The outputs are shown in Table 2. The unit operation cost per transported passenger of the airport coach is 37.86 Yuan/passenger.

Because we should guarantee that the passengers' waiting time does not exceed the upper limits, the dispatching time points in the timetable are dense. Moreover, as the coach timetable is designed on the basis of the flight schedule, the coach dispatching time concentrates in two periods: 6:00–9:00 and 11:00–14:00 and they are corresponding to the rush period of the airport.

The loading factor of the coach is shown in Table 3. In the table, the loading factor of the airport coach departing on different time points is not the same. The airport coaches with the loading factors which are larger than 60% account for 22.4%. The high loaded coaches are dispatched in the periods of 6:00–9:00 and 11:00–

Table 1. Fitness value corresponding to different combination of P_c and P_m

F \ P_c / P_m	0.3	0.4	0.5	0.6	0.7	0.8
0.05	–43.61	–46.77	–41.63	–42.79	–43.85	–54.99
0.10	–54.45	–42.87	–38.64	–39.56	–37.86	–49.12
0.15	–56.44	–57.23	–51.74	–48.51	–54.11	–57.34
0.20	–78.45	–79.69	–62.74	–64.23	–69.12	–65.21

Table 2. Coach timetable of Dalian airport (T = 3, T' = 2)

Route	Dispatching time point (coach vehicle volume)								
1–11	5:00	6:00 (2)	8:00	11:00	13:00	16:00	18:00	20:00	–
2–1	5:00	8:00	11:00	13:00	15:00	17:00	–	–	–
3–11	7:00	10:00	14:00	18:00	–	–	–	–	–
4–9	5:00	7:00	9:00	11:00	15:00	16:00	18:00	20:00	
5–10	6:00	9:00	7:00	11:00	14:00	–	–	–	–
6–7	5:00	7:00	9:00	11:00	14:00	17:00	17:00	–	–
7–11	5:00	7:00	9:00	10:00	12:00	13:00	16:00	19:00	–
8–9	5:00	8:00	10:00	12:00	14:00	16:00	19:00	–	–
9–11	5:00	7:00	9:00	11:00	13:00	16:00	18:00	20:00	21:00
10–11	6:00	7:00	10:00	13:00	15:00	18:00	–	–	–

Table 3. Loading factor of Dalian airport coach (T = 3, T' = 2)

Route	Loading factor of the coach								
1–11	28%	28%	77%	80%	78%	26%	98%	20%	–
2–1	57%	19%	57%	11%	20%	17%	–	–	–
3–11	80%	52%	69%	22%	–	–	–	–	–
4–9	5%	37%	31%	11%	17%	45%	8%	6%	–
5–10	20%	23%	28%	17%	20%	–	–	–	–
6–7	31%	6%	20%	20%	20%	20%	20%	–	–
7–11	56%	54%	78%	72%	70%	94%	48%	–	–
8–9	3%	85%	60%	17%	17%	20%	6%	–	–
9–11	16%	12%	60%	72%	26%	42%	60%	10%	8%
10–11	8%	20%	18%	22%	42%	10%	–	–	–

14:00. Because we set T = 3 and T' = 2 in the calculation, the combination of the T and T' guarantees the service quality but shortening the departure interval of the airport coach. In the circumstance, the average of the loading factor is not very high.

5. Sensitivity Analysis

Through setting different combinations of T and T', we can get the unit operating cost per transported passenger $\overline{C}$ of the coach in corresponding to different timetables. The variation of the cost is shown in Fig. 8.

The X-axis means the upper limit of the waiting time T in the lounge, Y-axis is the upper limit of the transfer time T' in the hub nodes, and Z-axis is the daily unit operating cost per transported passenger $\overline{C}$. It can be seen that $\overline{C}$ increases 4.5 Yuan averagely as T' de-

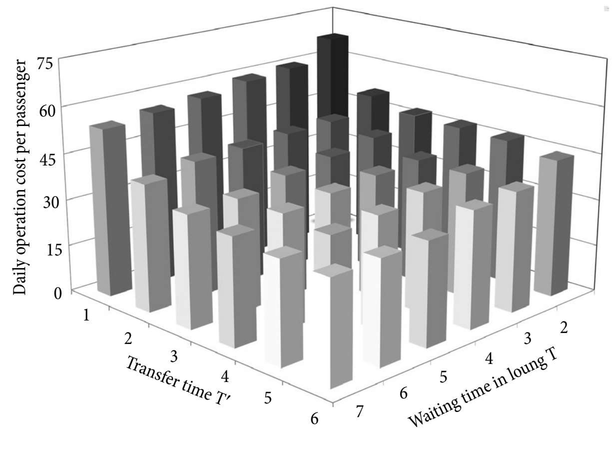

Fig. 8. The influence of the T and T' to the unit operation cost per transported passenger

creases 1 hour when T is fixed. The increase of $\overline{C}$ is the largest (23.0%), when T' decreases from 2 hours to 1 hour. However, the increasing speed of $\overline{C}$ becomes gentle as T' decreases. Conversely, when we fix T', $\overline{C}$ will increase 2.5 Yuan averagely as T decreases 1 hour. Specifically, the increase of $\overline{C}$ is the largest when T decreases from 2 hours to 1 hour which is 7.1% and the increasing speed of $\overline{C}$ also becomes gentle as T decreases.

We can see that the increase of $\overline{C}$ caused by 1-hour decrease of T' is larger than that of T. It is because the decrease of the loading factor caused by T' decrease is higher than that of T. Thus, we get to know that it is more useful to adjust the dispatching frequency of the branch coach for controlling the operation cost.

Generally, the operation cost will decrease as T and T' increment, however the decreasing speed is reducing gradually. Specifically, $\overline{C}$ decreases 32.5%, when $T - T'$ combination changes from $T = 2$, $T' = 1$ to $T = 3$, $T' = 2$ and only decreases 2.3 %, when the $T - T'$ combination changes from $T = 3$, $T' = 2$ to $T = 4$, $T' = 3$. It can be seen that $\overline{C}$ will not decease obviously when $T > 3$ and $T' > 2$. Therefore, the most suitable timetable can be got when $T = 3$, $T' = 2$.

Conclusions

This paper provides a method to design the timetable of the airport coach with the 'hub-and-spoke' network. In this paper, the 'time–space' network is established to provide a platform for the timetable design. By using the 'time–space' network, the actual trip in the two-dimensional space can be transformed to the trip chain on the one-dimensional plane. Through the trip chain, the passenger's departure time at the branch node and the hub node can be calculated based on their flight departure time. In this way, the passengers' arrival distribution at the airport coach station can be fixed. For the survey of the passengers' flight departure time in the airport is more convenient, the method can reduce the working intensity as well as increase the sample size.

In the existing literatures, the timetable is always designed without the constraint of the arrival time. However, as the airport coach is one of the access modes of the airport, the coach departure time should be related to the flight departure time. In the situation, In order to make the designed timetable suitable for the airport coach, we built the timetable design model by considering relationship between the coach departure time and the flight departure time.

Because the 'hub-and-spoke' network is adopted by the airport coach, we focus on the connection between the branch and the trunk lines in the model. Meanwhile, we consider the operation cost and the service quality when we build the model. Specifically, we set the upper limits of the transfer time and the waiting time in the lounge, the limits will keep the service quality of the airport coach and connect the passengers' demand to the coach departure time.

Through the sensitivity analysis, we find that decreasing the departure interval of the branch coach is more useful for controlling the cost than decreasing that of the trunk coach. Because the timetable design model is built considering the flight departure time, the result can both satisfy the passengers' demand and save the operation cost.

There are other factors influencing the timetable design, such as the other access modes of the airport, the passengers' the trip purpose and so on. The factors will be considered in the future.

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