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Railway Timetable Optimization for Air-Rail Intermodal Service

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Railway Timetable Optimization for Air-Rail Intermodal Service

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Abstract—Both aviation and high-speed rail are developing rapidly, which promotes the popularity of intermodal services. However, most cooperation only comes from political support. Operational measures should be taken for further improvement. In such circumstance, a model is proposed in this study to improve the quality of services and strengthen the connectivity between two modes by optimizing the railway timetable. The model is set to maximize the connection numbers of two modes. To take journey is "air-rail" or "rail-air" into consideration, we divide passengers into four groups. The original model is linear and can be calculated by commercial solvers. The models were applied on a case China. The results showed that the model is effective, the connection numbers improved by 40.2%.

1. Introduction

Aviation and high-speed rail are developing rapidly. The relationship between the two is not just pure competition; Cooperation happens. The potential profit of integration and cooperation between airlines and railways is more significant than that of competition [1]. Many of the rail lines are connected to the airport, where they can be integrated. Some intermodal transport services have been successfully provided and promoted all over the world. In addition to political support, business adjustment is essential for smooth service, which can significantly shorten the waiting time. Therefore, people pay more and more attention to the development of multimodal transport service optimization model.

Many studies focused on interactions and practices of aviation and railway. For example, the AIRail service is offered by Deutsche Bahn and Lufthansa at Germany Frankfurt Airport, which provides a schedule with 50 mins of total travel time and a frequency of 16 links every day on the Frankfurt-Cologne route [2]. Roman et al. studied the influence of transfer mode on the travel of air-rail combined transport from passengers' perspective of air-rail combined transport. They put forward suggestions for railway and aviation to carry out air-rail combined transport cooperation [3]. Costa J D analyzed the feasibility and necessity of air-rail combined transport cooperation, proposed the essential factors for the success of air-rail combined transport: infrastructure construction, connection mode, transfer time, ticketing cooperation and information sharing, and analyzed the driving factors for the development of air-rail combined transport cooperation[4]. Peter Jorritsma analyzed the competitiveness of air and rail combined transportation and pointed out that the travel time, travel cost, travel distance and punctuality rate of air and rail combined transportation are the critical influencing factors of the market competitiveness air and rail combined transportation[5]. Z. Li et al. analyzed the whole process of air and rail combined transportation. They pointed out that the transfer time of air and rail combined transportation directly affects the competitiveness of air and rail combined transportation. When the transfer time exceeds a certain threshold, air and rail combined transportation will lose the attraction of passenger flow[6]. Zhang Lianbiao et al. analyzed the impact of the high-speed railway on civil aviation after the opening of the Wuguang section of the Beijing-Guangzhou high-speed railway. They discussed the competition and cooperation relationship between aviation and railway from the passenger load factor, rate of return and passenger volume of the Wuhan-Guangzhou route[7]. Yuqiang et al. used the Logit model to analyze the influence of various factors on passenger travel by taking the security, speed and economy of different travel modes as influencing factors[8].

This paper deals with railway timetable optimization aiming at air-rail service. A MILP model is proposed to solve the problem. Also, different from the existing literature, the method is devoted to more realistic situations, where two directions of passengers both exist, and they are included in the model. The rest part of the paper is organized as follows. Section 2 introduces the hypotheses, parameters and models. The models are applied with real-world cases in China in Section 3. A conclusion is followed in Section 4.

2. Model

Parameters needed for the model are introduced first. Table 1 illustrates the list of sets, including trains, stations and flights. Other symbol notations are listed in Table 2. Some of the parameters are from sets, while some are not. Variables in our model is shown in Table 3.

TABLE 1. LIST OF SETS

I	Set of trains
I_{st}	Set of trains that stop at the transfer station, where $I_{st} \subseteq I$
S	Set of stations
K	Set of flights
$\mathrm{K}^a, \mathrm{K}^d$	The set of ingoing and outgoing flights respectively, where $\mathrm{K}^a, \mathrm{K}^d \subseteq \mathrm{K}$

TABLE 2. LIST OF PARAMETERS

i, j	Train index, where $i, j \in I$
ori_i	Original station of train i
des_i	Terminus station of train i
$xs_{i,j}$	The first station that both train i and j visit
$xe_{i,j}$	The last station where both train i and j visit
$\overline{dw_i}$, $\underline{dw_i}$	Upper bound and lower bound of the departure time of train i at the original station
$\overline{aw_i}$, $\underline{aw_i}$	Upper bound and lower bound of the arrival time of train i at the terminus station
dtw_i, atw_i	Ranges of departure time window and arrival time window at the original station and the terminus station of train i, respectively
s	Station index, where $\mathrm{s} \in \mathrm{S}$
S_i	The set of trains that train i visits, $\mathrm{S}_i \subseteq \mathrm{S}$
st	The transfer station

HA_s	The minimum headway for two successive trains arriving at station s, where s ∈ S
HD_s	The minimum headway for two successive trains departing from station s, where s ∈ S
$r_{i,s}$	The pure running time of train i between the section from station s to station s + 1, where $s \in S_i/\{des_i\}$
$\beta_{i,s}$	The acceleration time for train i departing from station s, where $s \in S_i/\{des_i\}$
$\gamma_{i,s}$	The deceleration time for train i arriving at station s, where $s \in S_i/\{ori_i\}$
$y_{i,s}$	The supplement time of train i between the section from station s to station s + 1, where $s \in S_i/\{des_i\}$
$x_{i,s}$	=1, if train i stops at station s, =0, if train i does not stop at station s
$\overline{d_{i,s}}, \underline{d_{i,s}}$	The upper bound and lower bound of dwell time of train i at station s, where $s \in S_i/\{ori_i, des_i\}$
$a^o_{i,s}$	The arrival time of train i at station s in the original timetable, where $s \in S_i/\{ori_i\}$
$d^o_{i,s}$	The departure time of train i at station s in the original timetable, where $s \in S_i/\{des_i\}$
k	Flight index
$l_k u_k$	The lower bound and upper bound of the connection time of flight k at the transfer city, k ∈ K
A_k	Arrival time of ingoing flight k, where $k \in K^a$
D_k	Departure time of outgoing flight k, where $k \in K^d$
$C_{i,k}$	The percentage of "rail-air" passengers, who catch the flight, where $I \in I_{st}, k \in K^d$
$M_{i,k}$	The percentage of "rail-air" passengers, who miss the train, where $C_{i,k} + M_{i,k} = 1$ and $I \in I_{st}, k \in K^d$
T	Transfer cost between two hubs at the transfer place
$f(i), f(k)$	missing costs of "air-rail" and "rail-air" passengers respectively, where $I \in I_{st}, k \in K^d$

TABLE 3. LIST OF VARIABLES

$a_{i,s}$	Arrival time of train i at station s, where $s \in S_i/\{ori_i\}$
$d_{i,s}$	Departure time of train i at station s, where $s \in S_i/\{des_i\}$
$O^s_{i,j}$	=1, if train i departs from station s earlier than train j, =0, if train i departs from station s later than train j
$P_{i,k}$	=1, if train i is connected with flight k, where an air-rail service is provided, =0, otherwise

In order to make the model reflect the real problem more accurately, we need to state some assumptions.

(1) All schedules on the line will be adjusted, but the stop mode will remain unchanged. If only the trains stopping at the transfer station are adjusted, it is impossible to keep all the rules of safety interval, interval and station capacity. The stop mode is invariant because of the scope of the problem, which is the input to the model.

(2) If all trains stop at the transfer station, they will join the intermodal service, while only a limited number of flights will participate in the intermodal service. For the same reason, as we discussed in the introduction, the stakeholders and operators of railway and aviation are strikingly different. Some airlines may not be interested in intermodal services, which will be considered in the model.

(3) Consider two types of travel. The first stage is by train, the second stage is by plane, or the first stage is by plane, the second stage is by train. However, due to the poor punctuality of airlines, in order to ensure the reliability of integrated services, some parameters are introduced to describe the delay of the second kind of flights.

(4) The transfer time between flight and train is determined according to the transfer location. The distance between the two places and the comprehensive facilities are the main factors. Although luggage, age and travel purpose are relatively related to transfer time, passenger attributes and preferences are not taken into account. Let's assume that the transfer time of all kinds of passengers is the same.

Firstly, train operation constraints (1) and (2) are introduced. The travel time between the departure time of the starting node and the arrival time of the terminal node shall not be less than the train running time in each section. When the train stops at the beginning of the section and / or at the end of the section, the acceleration time and / or deceleration time shall be added respectively. In order to make the schedule more flexible, additional time is added.

$$a_{i,s} - d_{i,s} \geq \gamma_{i,s} + \beta_{i,s} x_{i,s} + \gamma_{i,s} x_{i,s}$$
$$, \ \forall i \in I, s \in S_i / \{des_i\} \quad (1)$$
$$a_{i,s} - d_{i,s} \geq \gamma_{i,s} + \beta_{i,s} x_{i,s} + \gamma_{i,s} x_{i,s} + y_{i,s}$$
$$, \ \forall i \in I, S_i / \{des_i\} \quad (2)$$

At each stop, constraints (3) and (4) ensure that the dwell time is within a reasonable range. Enough time should be provided for passengers to get on and off. At the same time, for the effective travel time of the whole journey, it will not be too long. The maximum and minimum stop time of each train at each station are set as constraints. If the train passes through the station, the dwell time is 0.

$$a_{i,s} - d_{i,s} \leq \overline{d_{i,s}} x_{i,s}, \ \forall i \in I, s \in S_i / \{ori_i, des_i\} \quad (3)$$
$$a_{i,s} - d_{i,s} \geq \underline{d_{i,s}} x_{i,s}, \ \forall i \in I, s \in S_i / \{ori_i, des_i\} \quad (4)$$

The time window is set at the starting station and the destination station by constraints (5) and (6). One reason is to reduce the impact of the adjustment on the entire network. If the route layout is acceptable, there is no need to change the vehicle plan and crew plan. Another reason is to narrow the gap between the new schedule and the original schedule. The original schedule is designed effectively in terms of performance and cost. Adjustments make difference on other intersecting lines as well. Therefore, the time window is restricted to define the departure time and arrival time of trains at the departure and terminal stations.

$$\underline{dw_i} \leq d_{i,ori_i} \leq \overline{dw_i}, \ \forall i \in I \quad (5)$$
$$\underline{aw_i} \leq a_{i,des_i} \leq \overline{aw_i}, \ \forall i \in I \quad (6)$$

In order to ensure the operation safety, the interval between two trains is limited. When two trains arrive at the same station, the departure time difference shall not be less than the minimum departure interval, and the arrival time difference of two trains at the same station shall not be less than the minimum arrival interval. According to the arrival sequence of the train, it can be expressed by conditional constraints (7) to (10).

$$if \ O_{i,j}^{s} = 1:$$
$$d_{j,s} - d_{i,s} \geq HD_s$$

$$, \forall i, j \in I, s = xs_{i,j} \dots xe_{i,j} - 1 \quad (7)$$

$$a_{j,s+1} - a_{i,s+1} \geq HA_{s+1}$$

$$, \forall i, j \in I, s = xs_{i,j} + 1 \dots xe_{i,j} \quad (8)$$

$$if\ O_{i,j}^{s} = 0:$$

$$d_{i,s} - d_{j,s} \geq HD_s$$

$$, \forall i, j \in I, s = xs_{i,j} \dots xe_{i,j} - 1 \quad (9)$$

$$a_{i,s+1} - a_{j,s+1} \geq HA_{s+1}$$

$$, \forall i, j \in I, s = s = xs_{i,j} + 1 \dots xe_{i,j} \quad (10)$$

These four constraints can be linearized into constraints (11), (12), (13) and (14) by introducing a large M, which is much larger than minimum headways HD and HA.

$$d_{j,s} - d_{i,s} + \mathrm{M}\left(1 - O_{i,j}^{s}\right) \geq HD_s$$

$$, \forall i, j \in I, s = xs_{i,j} \dots xe_{i,j} - 1 \quad (11)$$

$$a_{j,s+1} - a_{i,s+1} + \mathrm{M}\left(1 - O_{i,j}^{s}\right) \geq HA_{s+1}$$

$$, \forall i, j \in I, s = xs_{i,j} + 1 \dots xe_{i,j} \quad (12)$$

$$d_{i,s} - d_{j,s} + \mathrm{M}O_{i,j}^{s} \geq HD_s$$

$$, \forall i, j \in I, s = xs_{i,j} \dots xe_{i,j} - 1 \quad (13)$$

$$a_{i,s+1} - a_{j,s+1} + \mathrm{M}O_{i,j}^{s} \geq HA_{s+1}$$

$$, \forall i, j \in I, s = s = xs_{i,j} + 1 \dots xe_{i,j} \quad (14)$$

Logical constraints are introduced between trains. Constraint (15) ensure either train i or train j should arrive at station s first.

$$O_{i,j}^{s} + O_{j,i}^{s} = 1, \ \forall i, j \in I, s \in S \quad (15)$$

Connection numbers constraints are defined to integrate the trains and flights. As shown in constraints (16) and (17), if the arrival time or departure time of ingoing and outgoing flights is between the set upper bound and lower bound, a successful connection is built.

$$if\ l_k \leq a_{i,st} \leq u_k: Q_{i.k} = 1$$

$$\text{Otherwise: } Q_{i.k} = 0, \ \forall i \in I_{st}, k \in \mathrm{K}^d \quad (16)$$

$$if\ l_k \leq d_{i,st} \leq u_k: P_{i.k} = 1$$

$$\text{Otherwise: } P_{i.k} = 0, \ \forall i \in I_{st}, k \in \mathrm{K}^a \quad (17)$$

Constraint (16) and (17) can be linearised by a large M and converted into linear constraints (18) and (19). The M' is much larger than the time horizon of a day.

$$l_k - M'(1 - Q_{i.k}) \leq a_{i,st} \leq u_k + M'(1 - Q_{i.k})$$

$$, \forall i \in I_{st}, k \in \mathrm{K}^d \quad (18)$$

$$l_k - M'(1 - P_{i.k}) \leq d_{i,st} \leq u_k + M'(1 - P_{i.k})$$

$$, \forall i \in I_{st}, k \in \mathrm{K}^a \quad (19)$$

The upper bound u_k and lower bound l_k could not be figured out directly, which can be calculated by the time window range $[\underline{b}, \overline{b}]$ to ensure the minimum acceptable transfer time and maximum acceptable transfer time respectively. The range restrains l_k and u_k at a reasonable range as shown in constraints (20), (21), (22) and (23).

$$l_k = D_k - \overline{b},\ \forall k \in \mathrm{K}^d \quad (20)$$

$$u_k = D_k - \underline{b},\ \forall k \in \mathrm{K}^d \quad (21)$$

$$l_k = A_k + \overline{b},\ \forall k \in \mathrm{K}^a \quad (22)$$

$$u_k = A_k + \underline{b},\ \forall k \in \mathrm{K}^a \quad (23)$$

$[\underline{dw_i}, \overline{dw_i}]$ and $[\underline{aw_i}, \overline{aw_i}]$ are used to restrain the departure time and arrival time of a train at its starting station and terminus station separately. They should be set according to the original departure time and arrival time to keep the timetable approximately the same,. Slack time is set to make a range of time windows.

$$\underline{dw_i} = d_{i,s}^o - wt_i,\ \forall i \in I, s \in ori_s \quad (24)$$

$$\overline{dw_i} = d_{i,s}^o + wt_i,\ \forall i \in I, s \in ori_s \quad (25)$$

$$\underline{aw_i} = a_{i,s}^o - wt_i,\ \forall i \in I, s \in des_s \quad (26)$$

$$\overline{aw_i} = a_{i,s}^o + wt_i,\ \forall i \in I, s \in des_s \quad (27)$$

The objective is to maximise the number of intermodal services, which can be expressed $P_{i.k}$ and $Q_{i.k}$. If an air-rail connection is valid, $P_{i.k}$ is 1, otherwise $P_{i.k}$ is 0. If a rail-air connection is valid, $Q_{i.k}$ is 1, otherwise $Q_{i.k}$ is 0.

$$\mathrm{Max}\ \mathrm{Z}_1 = \sum_{i \in I_{st}} (\sum_{k \in \mathrm{K}^a} P_{i.k} + \sum_{k \in \mathrm{K}^d} Q_{i.k}) \quad (28)$$

3. Case Study

As one of the busiest high-speed railways in the world, the Beijing Shanghai high-speed railway connects Beijing and Shanghai in China, with a total length of 1318 km. Besides Beijing and Shanghai, there are 22 stops in the middle. There are mainly cr400 and crh380 EMUs on this line. Each EMU has its own variant. The operating speed is 380 km / h. The fastest train on this line between Beijing and Shanghai takes 4 hours and 28 minutes.

Tianjin Binhai International Airport is located in Dongli District of Tianjin, about 40 kilometers away from the center of Tianjin and Tianjin South high speed railway station. According to the commercial navigation software, it takes 36 minutes from the high-speed railway station to Tianjin airport by subway or bus. Passengers from a range of neighbor places can refund train and metro tickets from their cities to the airport. In addition, there are vouchers for luggage and rest room. In addition, there is an airport city terminal in Beijing south station, providing boarding and other services. Some airlines carry out comprehensive service cooperation with Tianjin Binhai airport, including but not limited to China Eastern Airlines, Xiamen Airlines, China Southern Airlines and Hainan Airlines.

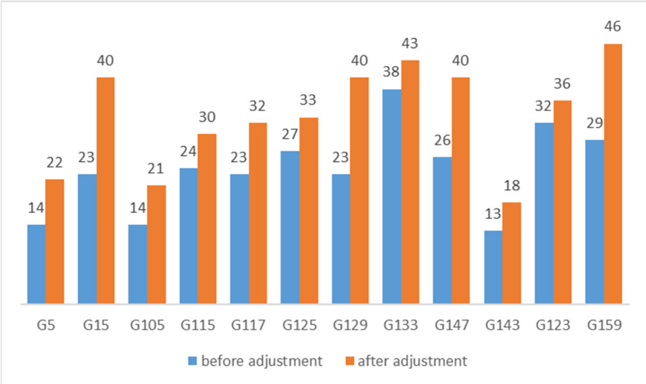

Fig. 1. Number of the sum of "Rail-air" and "Air-rail" connections for each train

This section applies the model to a real case. Parameters can be collected online or from the operator. For those that are not available, we will make reasonable assumptions.

After the application of M1 type, the number of "air railway" and "railway air" connections has been improved. When we use the 60 minute time window (which is the initial condition of this example), the number of "air rail" connections increases from 130 to 201, with a percentage increase of 54.6%. In addition, the number of "railway aviation" connections also increased sharply, from 156 to 200, an increase of 28.2%. The total number of all connections changed from 286 to 401, with an average upgrade rate of 40.2%.

As shown in Figure 1, separate results for the total number of "air rail" and "air rail" connections are given. It can be seen that the number of connections per train increases after adjustment. The number of trains like G15 and G147 is almost double. Some trains will grow slightly, such as G133 and G123.

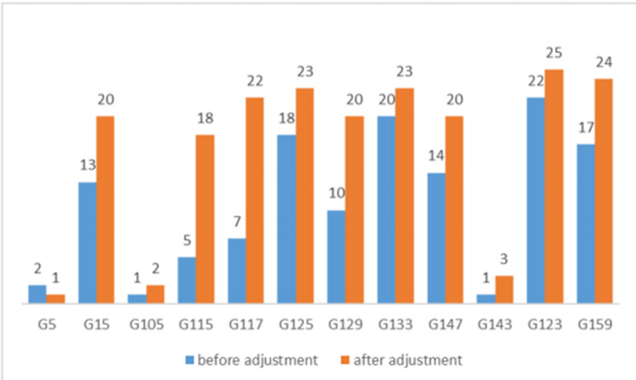

Fig. 2. Number of "Air-rail" connections for each train

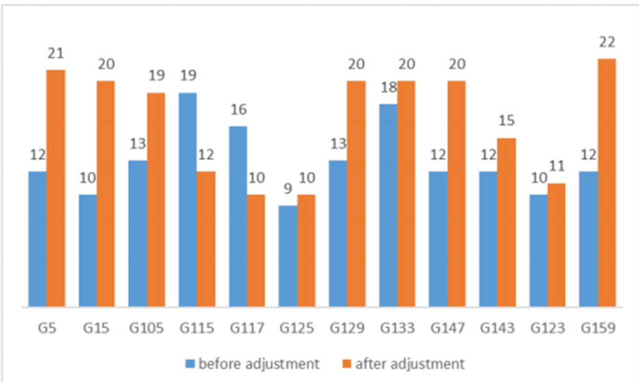

Fig. 3. Number of "Rail-air" connections for each train

Figs. 2 and 3 show the "air rail" connection and the "air rail" connection, respectively. The most impressive thing is that the number of "air rail" connections between G115 and G117 has tripled. However, the situation is that the number of "air rail" connections has decreased, which is the only two drops in the "air rail" chart. " The "rail to air" connection of G5 dropped by 1, which is a single drop in Figure 2, similar to the reason for the compromise of "air to rail" connection. The poor performance of some trains in the "rail air" connection is due to the special time slot, when there are not many outbound flights taking off, there are adjustments before and after.

4. CONCLUSION

Air-rail service is becoming an essential transport mode for passengers to transfer between trains and flights. In order to offer a better service, the optimization model of railway timetable is established. The purpose of the model is to integrate trains and flights by maximizing the number of rail and rail air connections. The model is linearized and solved by commercial solver CPLEX.

The model has been applied to a real world case of Chinese flight network and high speed railway network. The number of air-rail combined transport and rail air combined transport increased by 54.6% and 28.2% respectively. The results show that the model proposed in this paper worked well.

One disadvantage of this study is the limitation from data. There are few parameters set manually to describe passengers' preferences. If such data can be collected from the survey, they may be more realistic. With more detailed data, it can be evaluated from different perspectives to testify the model. Furthermore, only one transit city is considered in the model, which can be extended to more airports to realize the network.

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