## **Research Article**

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# Flight schedule adjustment for hub airports using multi-objective optimization

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**Abstract:** Based on the concept of "passengers self-help hubbing," we build a flight schedule optimization model where maximizing the number of feasible flight connections, indicating transfer opportunities, as one objective and minimizing total slot displacements as the other objective. At the same time, the "Demand Smoothing Model" is introduced into the flight schedule optimization model to reduce the queuing delays for arrival and departure flights. We take into account all aircraft itineraries, the difficulty level of schedule coordination, and the maximum displacement of any single flight acceptable to airlines when optimizing flight schedule. Given an original schedule, the model produces a feasible modified schedule that obeys the slot limits specified for an airport without canceling any flights, increases transfer opportunities, and improves on-time performance for hub airports while reducing interference with airline scheduling preferences. The model was verified with the operating data of the Urumqi international airport, and the results show that minor adjustments to flight schedules can increase the transfer opportunities of the airport and significantly reduce flight queuing delays.

**Keywords:** hub airport, flight schedule optimization, feasible flight connections, flight queuing delay, flight slot displacements

## **1** Introduction

A hub-and-spoke aviation system is an advanced form of air transportation organization commonly used by large airlines and airports in the world today. It has many advantages such as optimizing route network structure, rationally allocating resources, reducing airlines' operating costs, and promoting hub airport prosperity. Now the European and American regions have more advanced and developed hub-and-spoke air transport network systems, but such systems in the Asia-Pacific region are still under development. In order to attract airlines and passengers, neighboring countries around China are actively strengthening the development of hub airports. Singapore Changyi Airport, Jakarta Sukarno-Hada Airport, Seoul Incheon International Airport, Tokyo Narita International Airport, Bangkok International Airport have been hub airports with a high percentage of international transfer passengers. Realizing the need of accelerating the development of hub-and-spoke aviation system to be competitive in global aviation network, "National Civil Aviation Airport Plan" (2017 edition) in China proposed to build a modern airport system with extensive coverage, reasonable distribution, complete functions, and intensive environmental protection by 2025, forming 3 world-class multi-airport systems, 10 international hubs, and 29 regional hubs.

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Figure 1: Comparison of transfer rates of major hub airports between China and the United States.

Passenger transfer rate is an important index of classifying a hub airport. At present, the transfer level of main hub airports in China is obviously insufficient. The comparison of the transfer rate of major hub airports between China and the United States is shown in Figure 1. After deregulation, some US legacy airlines started a hub-and-spoke network and use hub airports as their bases. For example, Atlanta International Airport (ATL) is one of the hubs of Delta airlines and the market share of operations of Delta at ATL is about 80%. Charlotte Douglas International Airport (CLT) was one of the hubs of US Airways. After the merger of US Airways and American Airlines (AA), CLT continues to be one of the ten domestic hubs of AA, as the gateways to the Caribbean and Europe for the US Southeast market. AA's market share accounts for about 88% of CLT's operation. The market concentration of hub airports in China is not high, and the proportion of flights of airlines in some main hub airports is shown in Figure 2. From the data in Figure 2, we can see no airlines dominate the operations at these airports. Similar phenomena are observed at other national and regional hub airports in China. Compared to the situation in the US, it is difficult for hub airports in China to rely on a single airline to increase the passenger transfer rate. While turning to the European aviation network, Malighetti observed that two-third of the fastest connecting flights do not belong to the same airline or the same airline alliance in the European aviation market [1]. He gave such phenomenon a terminology of "passengers self-help hubbing," i.e. passengers choosing connecting itinerary based on the route network and flight time of different airlines [1]. Our study draws on this concept and proposes to optimize flight schedules at hub airports so as to provide passengers with more feasible transfer opportunities. With "passengers self-help hubbing," the optimized flight schedule can help increase passenger transfer rate and improve the competitiveness of the airport.



Figure 2: Proportion of airline flights in some main hub airports in China.

With the development of hub airports around the world, many scholars have studied the hub airport's transfer capabilities to analyze the competitiveness of airports and airlines. These research studies are mainly divided into two categories. One focuses on the spatial characteristics of the aviation hub network

and analyzes the air route network topology of airlines or airports by complex network theory [2–5], and the other focuses on the temporal characteristics of the aviation hub network. Flight schedule analysis models are established to evaluate the connection capabilities of airlines or airports. The proportion of feasible flight connections was proposed to evaluate the connection capability of the airport [6-8]. The weighted indirect connections (WNX) that considered comprehensively the impact of transfer time and the quality of the indirect flight compared to the direct flight in a weighted manner was proposed to assess the airport or airline's connection capabilities [9]. The NETSAN model that considered comprehensively the number and quality of direct and non-direct flights in a weighted manner is used to evaluate the connectivity of the hub airport [10]. The eight different hub airport connectivity assessment models are compared and analyzed, and each model is applied to the European air transport network [11]. The NETSCAN Connectivity Index is also used to evaluate the airport connectivity of Don Mueang International Airport in Thailand [12]. Some Chinese researchers also studied hub airport transfer capability based on temporal characteristics of the aviation hub network. Considering passenger transfer waiting costs and flight waves, a flight frequency optimization model is established with the objective function of maximizing airline benefits [13]. The structural evolution of the flight wave system of Chinese hub airports and the spatiotemporal characteristics of the feeding routes of hub airports with obvious flight wave systems were analyzed [14]. Taking Beijing Capital International Airport as the research object, a quantitative method was proposed to describe the spatial and temporal network configuration and differentiation structure of the flight schedule [15]. A transfer level evaluation model from the perspective of the layout of the airport route network and flight slot distribution was constructed [16].

On the other hand, based on the well-known observation that, for a given number of flight schedules in a day, the more evenly they are distributed along the day, the lower expected delays will be. Some researchers studied how to mitigate congestion through schedule coordination. A mathematical model was developed by comprehensively applying the deterministic queuing model and economic model. They considered the tradeoff between flight delay costs and flight schedule displacement costs caused by flight slot constraints to determine the appropriate scheduling limits for airports [17]. A stochastic optimization model was used to determine the number of arrival slots that should be allocated to airlines at a congested airport during different time intervals across the course of a single day. The innovation of their approach takes into account the long-term uncertainty induced in arrival or departure capacities because of weather conditions [18]. A demand smoothing (DS) optimization model was established that can generate a new feasible flight schedule that obeyed the scheduling limits without canceling any flights. By applying the DS model, on the one hand, substantial delay reductions could be achieved and, on the other, interference with airline scheduling preferences could be reduced [19].

However, none of the above studies considered taking the increase of airport transfer opportunities as one of the objectives while optimizing airport flight schedules. In this study, we propose to optimize flight schedules at one airport considering both the operational efficiency (delay) and hub airport competitiveness (transfer opportunities). We use Urumqi airport as a case study to demonstrate the proposed method and evaluate potential benefits.

# 2 Flight schedule optimization mechanism

The objective of this paper is to develop a mathematical model to optimize flight schedules at the strategic level of air traffic demand management to increase transfer opportunities and improve on-time performance for hub airports. The number of feasible flight connections is used to quantify transfer opportunities. The feasible flight connections refer to those connections that are competitive, operationally feasible, and sufficiently convenient transfer opportunities between arriving and departing flights including coordinated transfers and self-help transfers. The coordinated transfers are those planned by airlines for passengers. The self-help transfer means passengers use the advantage of available flights at a particular airport to create their own connection. Assuming that the original flight schedule is the most desired setting for all

airlines, the proposed flight schedule optimization model considers minimizing total slot displacements as one objective and maximizing the number of feasible flight connecting seats as the other objective. While optimizing flight schedules to increase the airport's transfer opportunities, a "demand smoothing model" [19] is introduced into the flight schedule optimization model to reduce the number of flights during peak hours to a certain extent, and to reduce the queuing delay of departure and arrival flights. The "demand smoothing model" aims at spreading departures and arrivals more evenly throughout the day by placing slot limits on the number of movements that airlines may schedule per unit time at an airport. Slot limits, i.e. the maximum total number of departures and arrivals, at the congested airport in China usually are set on a 60 min basis and they are for both departures and arrivals. For example, slot limits at Beijing Capital Airport were 88 in any 60 min period in 2017. There are two disadvantages of these simple slot limits. First, slot limits set on a 60 min basis cap the total operations scheduled in that hour, but within that hour, there is possibly a surge of scheduled flights that could cause significant delays. Refining the resolution of the slot limit time unit, e.g. from every 60 to 15 min, could alleviate such a problem. Second, the current slot limits do not consider the runway capacity trade-off while serving different fleet mixes of arrivals and departures. Even the total scheduled operations do not exceed slot limits, there might be delays if there are significant more arrivals or departures in one hour because runway capacity is lower under this circumstance compared to when the mix is more balanced. Thus, besides slot limits on the total operations, we may add constraints limiting the number of scheduled arrivals and departures within the refined time unit, every 15 min. The setting of the constraints will be based on the analysis of historical operational throughput of every 15 min, which will be elaborated on in later sections.

However, the adjustment of flight schedules will interfere with the competitive environment of airlines. To ensure equity among airlines, we need to set a threshold of maximum displacement for each operation and take that as one of the constraints. The threshold of the maximum displacement is a parameter that can be varied to test how the optimal solutions would change accordingly. The other constraint while modeling the flight schedule optimization is to maintain aircraft flight task connection. A minimal connecting time needs to be maintained to ensure the feasibility of aircraft and passenger itineraries. With the outputs of the optimization model, we can calculate the increase of the number of feasible flight connections and available flight connecting seats, and the decrease in arrival and departure queuing delays compared to the status quo. Figure 3 shows the flow chart of the flight schedule optimization scheme.



Figure 3: Flight schedule optimization mechanism.

# 3 Flight schedule optimization model

In this paper, we take the flight schedule of 1 day in the summer and autumn flight seasons of airport *W* as the research object and establish the flight data set, time interval data set, and flight slot data set for airport flight schedule optimization problem. The main sets involve the set of departure and arrival flights  $F = \{1,...,f\}$ , the set of time intervals  $P = \{1,...,p\}$ , and the set of flight slots  $T = \{1,...,t\}$ . In the set *P*, the length of each time interval is assumed to be equal to 15 min, so there are 96 periods in this set. We define 00:00–00:15 as the first period, 00:15–00:30 as the second period, and so on until 23:45–24:00 as the 96th period. In set *T*, the flight slot is defined as an interval of 5 min. We define 00:00 as slot 1, 00:05 as slot 2, and so on until 23:55 as slot 288.

## 3.1 Parameters and variables

Every flight *i* or *j* is associated with a departure slot, a departure period, a departure airport, an arrival slot, an arrival period, and an arrival airport. We define the following parameters  $\forall i, j \in F, i \neq j, \forall p \in P, \forall t \in T$ .

Parameters:

$$S_{ip}^{a} = \begin{cases} 1, & \text{if flight } i \text{ is originally scheduled to arrive in period } p; \\ 0, & \text{otherwise;} \end{cases}$$

$$S_{ip}^{d} = \begin{cases} 1, & \text{if flight } i \text{ is originally scheduled to departure in period } p; \\ 0, & \text{otherwise;} \end{cases}$$

 $t_i^a$ : the arrival slot of flight *i* in the original schedule;

 $t_i^d$ : the departure slot of flight *i* in the original schedule;

 $N_{ij}$ : the number of feasible flight connections;

*R*<sub>*ij*</sub>: the detour factor;

 $A_{iW}$ : the distance between the origin airport and the transfer airport W of flight *i*;

 $D_{Wj}$ : the distance between the transfer airport W and the destination airport of flight *j*;

 $D_{ij}$ : the great circle distance between the origin airport of flight *i* and the destination airport of flight *j*;  $T_{ij}$ : the connecting time between flight *j* and flight *i*;

 $C_a^a/C_a^t/C_a^t$ : arrival/departure/total flight slots number available for allocation in 15 min;

 $m_{ij}^{\min}$ : the minimum aircraft turnaround time between flight *j* and flight *i* when they use the same aircraft;

 $m_{ij}^{\text{mins}}$ : the minimum connecting time between flight *j* and flight *i* when flight *j* is a coordinated connecting flight of flight *i* with the same flight number;

 $m_{ij}^{\text{minc}}$ : the minimum connecting time between flight *j* and flight *i* when flight *j* is a coordinated connecting flight of flight *i* with different flight numbers;

 $m_{ij}^{\text{maxs}}$ : the maximum connecting time between flight *j* and flight *i* when a flight *j* is a coordinated connecting flight of flight *i* with the same flight number;

 $m_{ij}^{\text{maxc}}$ : the maximum connecting time between flight *j* and flight *i* when a flight *j* is a coordinated connecting flight of flight *i* with different flight numbers;

MCT: the minimum connecting time for passengers to make the transfer;

MaxCT: the maximum connecting time for passengers to make the transfer;

 $\delta$ : the maximum displacement of any single flight acceptable to airlines;

 $p_{ij}$ : the maximum number of seats provided to passengers when passengers transfer from flight *i* to flight *j*;

*qi*: the displacement weighted coefficient;

*a*: a positive weighted coefficient in the objective function;

The decision variables of this optimization model are as follows:

$$R_{ip}^{a} = \begin{cases} 1, & \text{if flight } i \text{ is assigned to arrive in period } p; \\ 0, & \text{otherwise;} \end{cases}$$

$$R_{ip}^{d} = \begin{cases} 1, & \text{if flight } i \text{ is assigned to departure in period } p; \\ 0, & \text{otherwise;} \end{cases}$$

 $\mu_i$ : the slot displacement of flight *i*.

## 3.2 Objective function

This paper takes the airport's maximum transfer opportunities and minimum total weighted flight slot displacements as the objective function. Hence, the objective function is to maximize

$$\sum_{\substack{i \in F, j \in F \\ i \neq j}} p_{ij} N_{ij} - \alpha \sum_{i \in F} q_i |\mu_i|$$
(1)

$$N_{ij} = \begin{cases} 1, & 1 \le R_{ij} \le 1.4 \text{ and } MCT \le T_{ij} \le MaxCT; \\ 0, & \text{otherwise;} \end{cases} \quad \forall i, j \in F, i \neq j$$

$$(2)$$

$$R_{ij} = \frac{A_{iW} + D_{wj}}{D_{ij}}, \quad \forall i, j \in F, i \neq j,$$
(3)

$$T_{ij} = [(t_i^d + 3\mu_i) - (t_i^a + 3\mu_i)] \times 5, \ \forall i, j \in F, i \neq j.$$
(4)

The objective function is divided into two parts. The first part is the number of feasible connecting flight seats that is used to represent transfer opportunities of an airport. The feasible connecting flight seats are calculated as the summation of  $p_{ij}$  if the connection between flights *i* and *j* is feasible. The variable  $p_{ij}$  is introduced to represent the maximum number of seats provided to passengers when passengers transfer from flight *i* to flight *j*. It is determined by the minimal number of seats while comparing flight *i* and *j*. Compared with direct flights, it will take longer travel times for passengers traveling by indirect flights, consisting of connecting time and detour time. Feasible flight connections are flight connections that meet the constraints of the detour time and the connecting time. The detour time passengers can accept is related to the range, so we introduce a detour factor. The detour factor  $R_{ij}$  means the in-flight time for an indirect flight compared to the direct flight time. We assume that the distance is proportional to the flight time, so we define the detour factor as the ratio of the sum of the flight distance of flight *i* and flight *j* to the distance in the great circle between the origin airport of flight *i* and the destination airport of flight *j*. The connecting time  $T_{ij}$  is the time difference between the arrival time of flight *i* and the departure time of flight *j* in the schedule. The maximum detour factor is usually less than or equal to 1.4 [16]. In addition, the connecting time  $T_{ii}$  should be greater than the minimum connecting time MCT required for passengers to make the transfer and be less than the maximum connecting time MaxCT that passengers are willing to wait when making the transfer. The minimum connecting time MCT that needs to be feasible for both passengers and baggage depends on the terminal building layout, the capacity of BHS (baggage handling system), and the availability of transport means. Usually, small airports tend to have significantly shorter MCT and they can provide faster transfer connections. Large airports, on the other hand, are usually much more constrained and can only offer relatively slow connections. The maximum connecting time, MaxCT, should be appropriate for different hub airports based on the main connection type such as long haul-short/medium haul or short/medium-short/medium haul, etc. Many different proposals exist as parameters for MaxCT: Doganis and Dennis propose a standard value of 90 min for all types of connections [20]. Danesi suggests a differentiated set of values ranging from 90 to 180 min [21]. For the sake of model simplicity, we refer to fixed maximum connecting times.

The second part of the objective function is the total weighted flight slot displacements, multiplication of  $q_i$ , and absolute value of  $\mu_i$ . The slot displacement of flight  $\mu_i$  is expressed as the number of 15 min periods. For example, if the slot displacement of flight *i* is 15 min, then we set the corresponding value of  $\mu_i = 1$ . The variable  $q_i$  is introduced to represent the weighted coefficient based on the difficulty level of schedule coordination. For the purposes of airport schedule coordination, airports are categorized into three levels by IATA (International Air Transport Association) according to congestion conditions at the airports. In China, airports are categorized by CAAC (Civil Aviation Administration of China) according to the relationship between flight demand and airport supply including main schedule coordinated airports, secondary schedule coordinated airports, and non-schedule-coordinated airports. For each flight, depending on if it is an arrival flight or a departure flight,  $q_i$  is determined by the schedule coordination level of the origin airport for the arrival flight and the destination airport for the departure flight. In terms of the subject airport where we apply the schedule optimization, those airports are called related airports. For international flights, if the related airport is the level 3 airport specified by IATA, then the schedule coordination difficulty coefficient is defined as  $q_i = 10^5$ , i.e. with a very large number so that these flights' schedules should not be replaced. If the related airport is specified by IATA as an other level airport, the schedule coordination difficulty coefficient is equal to 1. For domestic flights in China, if the related airport is one of Beijing/Capital airport, Guangzhou/Baiyun airport, Shanghai/Pudong airport, and Shanghai/ Hongqiao airport, then the schedule coordination difficulty coefficient is of the highest level because these airports are the most congested airports. We define  $q_i = 10^5$ . In the process of adjusting flight schedules, these flight schedules in these busiest airports will not be displaced. If the related airport is one of the main coordination airports specified by CAAC other than the four airports described above, we define  $q_i = 4$ . If the related airport is the secondary coordination airport, we define  $q_i = 2$ . If the related airport is one of the nonschedule-coordinated airports specified by CAAC, we define  $q_i = 1$ . It is preferred to displace the flight slot of the related airport as a non-schedule-coordinated airport when adjusting the flight schedule so that we can ensure the feasibility of flight schedule optimization.

## 3.3 Constraints

(1) Ensure that each arrival fight is assigned to exactly one scheduled arrival time. Then,

$$\sum_{p \in P} R_{ip}^a = 1, \quad \forall i \in F.$$
(5)

(2) Ensure that each departure fight is assigned to exactly one scheduled departure time. Then,

$$\sum_{p \in P} R_{ip}^d = 1, \quad \forall i \in F.$$
(6)

(3) The arrival flight i in the original flight schedule is displaced to a time period p. Then,

$$\sum_{p \in P} pR_{ip}^a = \sum_{p \in P} pS_{ip}^a + \mu_i, \quad \forall i \in F.$$
<sup>(7)</sup>

(4) The departure flight *i* in the original flight schedule is displaced to a time period *p*. Then,

$$\sum_{p \in P} pR_{ip}^d = \sum_{p \in P} pS_{ip}^d + \mu_i, \quad \forall i \in F.$$
(8)

The combination of Constraints (3) and (4) ensures that scheduled block times are left unchanged. (5) Ensure that the displacement of any single flight does not exceed the maximum displacement of any single flight acceptable to airlines  $\delta$ . The maximum displacement  $\delta$  is also expressed as the number of 15 min periods. For example, if the maximum displacement is 30 min, then we set the corresponding value of  $\delta = 2$ :

$$|\mu_i| \le \delta, \quad \forall i \in F \tag{9}$$

(6) Meet the limit of airport flight slot numbers available for allocation in 15 min, so that

$$\sum_{i\in F} R^a_{ip} \le C^a_q, \quad \forall p \in P,$$
(10)

$$\sum_{i\in F} R_{ip}^d \le C_q^d, \quad \forall p \in P,$$
(11)

$$\sum_{i\in F} R^a_{ip} + \sum_{i\in F} R^d_{ip} \le C^t_q, \quad \forall p \in P.$$
(12)

Constraints (10) ensure to meet the arrival flight slot limits in 15 min, Constraints (11) ensure to meet the departure flight slot limits in 15 min, and Constraints (12) ensure to meet the total flight slot limits in 15 min.

(7) Aircraft connections maintained.

The flights in the flight schedule optimization model include all flights that arrive at airport W or that leave from airport W. Sometimes the flight that arrives at airport W and the flight that leaves from airport W are executed by the same aircraft. For instance, if an aircraft flies the itinerary  $A \rightarrow W \rightarrow B$ , then both flights  $A \rightarrow W$  and  $W \rightarrow B$  are included in the model. The rescheduling of flight  $A \rightarrow W$  might require a change in the scheduled time of flight  $W \rightarrow B$  to maintain a feasible connection between both flights. Just like the above instance, the situation that an aircraft has two flight slots in the flight schedule may include the following four scenarios.

(1) Given subject airport W, if the aircraft is used for flight *i* coming from airport A to airport W, and then flight *j* leaving from airport W to airport B, the itinerary of the aircraft is  $A \rightarrow W \rightarrow B$ . If flights *i* and *j* have the same flight number, then the connecting time between flights *i* and *j* should meet the following constraints considering both aircraft connection and passenger connection because they are coordinated connecting flights planned by airlines:

$$m_{ij}^{\min}X_{ij} \le T_{ij}X_{ij} \le m_{ij}^{\max}X_{ij}, \quad \forall i, j \in F, \ i \neq j,$$

$$(13)$$

where

 $X_{ij} = \begin{cases} 1, & \text{if flight } j \text{ is a coordinated connecting flight of} \\ & \text{flight } i \text{ with the same flight number;} \\ 0, & \text{otherwise;} \end{cases}$ 

(2) If similar to that described in Scenario 1 but flights *i* and *j* have different flight numbers, then the connecting time between flights *i* and *j* should meet the following constraints considering both aircraft connection and passenger connections because they are coordinated connecting flights planned by airlines:

$$m_{ij}^{\min}Y_{ij} \le T_{ij}Y_{ij} \le m_{ij}^{\max}Y_{ij}, \quad \forall i, j \in F, i \neq j,$$

$$(14)$$

where

$$Y_{ij} = \begin{cases} 1, & \text{if flight } j \text{ is a coordinated connecting flight of} \\ 1, & \text{flight } i \text{ with different flight numbers;} \\ 0, & \text{otherwise;} \end{cases}$$

(3) In this scenario, flight *i* comes from airport A to airport W, and then flight *j* leaves from airport W back to airport A. The itinerary of the aircraft is A → W → A and uses two flight slots at airport W including one arrival slot and one departure slot. The duration between the departure time and the arrival time in airport W should be larger than the minimum aircraft turnaround time:

$$m_{ij}^{\min}Z_{ij} \le T_{ij}Z_{ij}, \quad \forall i, j \in F, \ i \neq j,$$
(15)

where

$$Z_{ij} = \begin{cases} 1, & \text{if flight } j \text{ is the return flight of flight } i \text{ and the departure slot of } \\ 1, & \text{flight } j \text{ at airport W is later than the arrival slot;} \\ 0, & \text{otherwise;} \end{cases}$$

(4) The last scenario is that flight *i* leaves airport W and arrives at airport A, and then flight *j* departure from airport A and comes back to airport W. The itinerary of the aircraft is  $W \rightarrow A \rightarrow W$  and uses two flight slots at airport W including one departure slot and one arrival slot. The duration between arrival time and the departure time in airport W should be longer than the sum of the flight time from airport W to airport A, the minimum aircraft turnaround time at airport A, and the flight time from airport A to airport W. We force aircraft connecting time in the new flight schedule at airport A to be larger than the minimum aircraft connecting time because the flight times of flight *i* and flight *j* are not changed:

$$AT_{ij} = \{ [(t_j^a + 3\mu_j) - FT_j] - [(t_i^d + 3\mu_i) + FT_i] \} \times 5, \quad \forall i, j \in F, i \neq j$$
(16)

$$m_{ij}^{\min}Q_{ij} \le AT_{ij}Q_{ij}, \quad \forall i, j \in F, i \neq j,$$
(17)

where

*FT<sub>i</sub>*: flight time of flight *i*;

 $AT_{ij}$ : the connecting time between flight *i* and flight *j* at airport A;

$$Q_{ij} = \begin{cases} & \text{if flight } j \text{ is the return flight of flight } i \text{ and the arrival slot of} \\ & \text{flight } j \text{ at airport W is later than the departure slot;} \\ & \text{0, otherwise.} \end{cases}$$

 $FT_i$  is expressed as the number of 5 min. For example, if the flight time of the flight *i* is 60 min, then we set the corresponding value of  $FT_i$  = 12.

## **4** Numerical experiment

We take Urumqi International Airport (IATA: URC, ICAO: ZWWW) as the case for demonstrating the optimization model. URC is currently one of the Chinese eight regional hub airports and is planned to become one of the Chinese national gateway hub airports. Same as many other airports in China, there is no dominant airline operating at URC. Thus, to improve the competitiveness of URC as a hub airport, it is needed to increase its transfer opportunities and passenger self-help hubbing.

### 4.1 Input data

We obtained 1 day flight schedule of the Urumqi airport used in both summer and autumn flight seasons of 2017, which included 236 arrival and 237 departure flights. Figure 4 shows the scheduled arrivals, departures, and total operations in every 15 min for that day. To obtain the airport capacity profile, we utilized the capacity evaluation method based on historical data to determine the airport operational throughput envelope. Such method includes quantile regression and Graham scanning method to determine the convex hull inflection point, with which the airport operational throughput envelope of URC based on the actual operating data from June to September 2017 was obtained, as shown in Figure 5. The capacity envelopes of 95% confidence interval and 85% confidence interval are, respectively, described in Figure 5. Based on the current slot limits, there are 32 operations per hour in the Urumqi airport, and the capacity envelope with an 85% confidence interval is determined as the operating capacity envelope. The seat numbers of different types of aircraft in the flight schedule for that day are shown in Table 1. The minimum aircraft turnaround



Figure 4: Arrival and departure flight slots distribution in every 15 min in the Urumqi airport original flight schedule.

time  $m_{ij}^{\min}$  at the Urumqi airport is 45 min. We calculated  $m_{ij}^{\min}$ ,  $m_{ij}^{\min}$ ,  $m_{ij}^{\max}$ , and  $m_{ij}^{\max}$  of the in the flight schedule. The  $m_{ii}^{\text{mins}}$  is 45 min and the  $m_{ii}^{\text{maxs}}$  is 160 min; the  $m_{ii}^{\text{minc}}$  is 45 min and the  $m_{ii}^{\text{maxc}}$  is 240 min. There are three terminal buildings T1, T2, and T3, 111 check-in counters, 12 self-service check-in counters, 47 security channels, 12 outbound luggage turntables, and 9 inbound luggage turntables at the Urumgi airport. It is very convenient for passengers to transfer at the Urumgi airport. It takes passengers about 10 min to walk between different terminals. According to the regulations of the operation department of the Urumqi airport, the first baggage must appear in the carousel within 10 min after the flight arrives, the last one should appear in the carousel within 40 min, and the average time for passengers to take the luggage is 25 min. While waiting for luggage, passengers can complete self-service check-in through a mobile app, and then check in luggage within 10 min. According to the regulations of the security department in the Urumqi airport, the security staff needs to ensure that 95% of the passengers enter the security queue and complete the security inspection within 10 min. It usually takes passengers 15 min from entering the security queue to the boarding gate. If passengers need to transfer to an international flight, it will take about 15 min to go through the customs. Considering the interference of uncertain factors, we add a 15 min time margin. Usually, 90 min is enough for passengers to transfer at the Urumqi airport. So in this model, we assume that the minimum connecting time MCT is 90 min, and the maximum connecting time MaxCT is



Figure 5: Operational throughput envelope within 15 min in the Urumqi airport.

**Table 1:** Seats numbers in aircraft types in the flight schedule

Aircraft type	B738	B737	B752	B772	B763	A320	A319	A332	A321	E195	E190
Number of seats	162	149	239	550	269	150	124	293	186	122	114

180 min as passengers for self-connections not only wait between flights but have to be processed. We also determine if flight *j* is the immediate successor of flight *i* based on the tail number of aircraft performing flight *i* and flight *j*. The maximum displacements of any single flight acceptable to airlines are  $\delta = 1$  and  $\delta = 2$ . Based on the operational throughput envelope within 15 min in the Urumqi airport shown in Figure 5, we designed three test scenarios with different flight slot limits in 15 min (shown in Table 2). Together with the two levels of the maximum displacement, we have a total of 6 settings for implementing the flight schedule optimization.

## 4.2 Optimization results

We implemented the flight schedule optimization model in GAMS 25.1 using CPLEX MIP on an Intel(R) Core

Table 2: Schemes for the number of flight slots that can be allocated within 15 min

	Scheme 1	Scheme 2	Scheme 3
No. of arrival flight slots	5	6	5
No. of departure flight slots	5	5	6
Total no. of arrival and departure flight slots	8	9	9

(TM) i7 running at 2.71 GHz and 16 GB RAM. For  $\delta = 1$  and  $\delta = 2$  and 3 slot allocation schemes, we obtained 6 optimized flight schedules. We analyzed feasible flight connections and delays of optimized flight schedules.

#### 4.2.1 Feasible flight connections

The number of feasible flight connections, the number of feasible connecting flight seats, and flight slot displacements of every scheme are shown in Table 3. When  $\delta = 1$ , the number of feasible flight connections and the number of feasible connecting flight seats optimized by Scheme 3 are increased the most, by 27.2 and 27.9% respectively. When  $\delta = 2$ , the number of feasible flight connections and the number of feasible connecting flight seats optimized by Scheme 3 are increased the most, by 27.2 and 27.9% respectively. When  $\delta = 2$ , the number of feasible flight connections and the number of feasible connecting flight seats optimized by Scheme 1 are increased the most, by 32.6 and 33.8%, respectively.

#### 4.2.2 Flight queuing delay

We take the optimized flight schedule and airport operational throughput as the input. We model the arrival queue and the departure queue by means of two distinct  $M(t)/E_k(t)/1$  queuing systems. We take the runway as a single server and the demand processes are modeled as Poisson processes, and the service processes are modeled as Erlang processes of order *k* where k = 3 as used in the existing literature [22]. In this runway queuing system, demand rates are calculated from the number of landings and takeoffs in the flight schedule. Service rates are determined by the airport operational throughput envelope. Flight queuing

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	UIBIIIdi value		т = <b>0</b>			0 = 2	
		Scheme 1	Scheme 2	Scheme 3	Scheme 1	Scheme 2	Scheme 3
Optimal value of the objective function			191,769	189,640	198,126	202,312	195,216
		183,988					
No. of feasible flight connections	1,375		1,573	1,519	1,624	1,635	1,611
		1,535					
No. of feasible connecting flight seats	187,950		215,624	208,490	223,216	225,127	221,606
		210,313					
Arrival queue length (aircraft)	52		47	7	0	41	80
		0					
Departure queue length ( aircraft)	147		19	87	0	17	84
		0					
Total queue length (aircraft)	199		66	94	0	58	92
		0					
Flight slot displacements	0		201	160	282	255	247
		220					

Table 3: Optimization results by every scheme

delay is represented by the arrival and departure queue lengths at the end of the period *p*. Some new parameters as follows are introduced. We define  $\forall p \in P$  in these parameters.

- $a_p$ : the arrival queue length at the end of period p;
- $d_p$ : the departure queue length at the end of period p;
- $\mu_n^a$ : the arrival service rate selected during period *p*;
- $\mu_n^d$ : the departure service rate selected during period *p*;
- $\alpha_s/\beta_s/\gamma_s$ : parameters defining each linear segment of the envelope;

So, the arrival and departure queue lengths can be calculated by the following formulation:

$$a_p = a_{p-1} + \sum_{i \in F} R^a_{ip} - \mu^a_p, \quad \forall p \in P,$$
 (18)

$$d_p = d_{p-1} + \sum_{i \in F} R_{ip}^d - \mu_p^d, \quad \forall p \in P,$$
(19)

The service rates are represented by means of a piece-wise linear operational throughput envelope as shown in Figure 5. We suppose that air traffic controllers adopt tactics of "service arrival aircraft first." This is consistent with the actual air traffic control method. The arrival and departure service rates are selected among the set of achievable service rates determined by the operational throughput envelope. The operational throughput envelope can then be expressed by the following set of linear inequalities (20):

$$\alpha_{s}\mu_{n}^{a}+\beta_{s}\mu_{n}^{d}\leq\gamma_{s},\quad\forall p\in P,$$
(20)

Arrival and departure queuing delays and flight slot displacements in the optimized flight schedule for every scheme are shown in Table 3. When we use Scheme 1 to optimize flight schedule, the arrival queuing delay and departure queuing delay are decreased to 0. The flight queuing delay distribution in every 15 min of the optimized flight schedule by every scheme when  $\delta = 1$  is shown in Figure 6. From the comparison of feasible flight connections, queuing delay, and flight slot displacements in Table 3, it can be seen that with  $\delta = 1$ , the feasible flight connections have been optimized to a certain extent and an increase of the maximal displacement  $\delta$  led to more total flight slot displacements but only slight improvement of feasible flight connections and connecting flight seats. Similarly, when  $\delta$  is relaxed from 1 to 2, the queuing delays of the optimized flight slot displacements are 220 15 min periods, and the number of feasible flight connections is increased by 11.6%, the number of feasible connecting flight seats are increased by 11.9%, and the arrival queuing delay and the departure queuing delay are both decreased to 0. If we take  $\delta = 2$ , the total flight slot displacements are 282 15 min periods, and the number of feasible flight connections is increased by 18.1%, the number of feasible connecting flight seats are increased by 18.8%, and the arrival periods are increased by 18.8%, and the arrival periods are increased by 18.8%.



**Figure 6:** Flight queuing delays distribution in every 15 min of the optimized flight schedule by every scheme when  $\delta = 1$ .

queuing delay and the departure queuing delay are also both decreased to 0. When we take  $\delta = 1$ , it is possible to significantly reduce the arrival and departure queuing delay with fewer flight slot displacements, and at the same time increase the number of feasible flight connection seats at the airport. Schemes 2 and 3 both have higher total slot limits. Scheme 2 gives more flexibility of scheduling arrival flights while Scheme 3 gives the flexibility to scheduled departure flights. The optimized outcomes show that Scheme 3 will lead to more arrival and departure queuing delays compared to other Schemes (see Figure 6). The arrival and departure slot distributions within every 15 min in the optimized flight schedule by Scheme 1 and Scheme 2 when  $\delta = 1$  are shown in Figures 7 and 8. In this study, we only show the optimized flight schedule for six settings of slot limits and maximal displacement. More settings can be generated and the optimized outcomes could be analyzed and visualized. It provides decision support so that the airport, airlines, and the air traffic control department can work collaboratively to determine the optimal flight schedule.



Figure 7: Arrival and departure flight slot distribution in every 15 min in the optimized flight schedule by Scheme 1 when  $\delta$  = 1.



Figure 8: Arrival and departure flight slot distribution in every 15 min in the optimized flight schedule by Scheme 2 when  $\delta = 1$ .

# **5** Conclusion

We have studied how to improve the hub network temporal configurations of the airport by adjusting flight schedules. We propose to refine the resolution of slot limits from every 60 to 15 min and add arrival and departure specific slot limits to assist the flight schedule adjustment. A multiobjective optimization model is proposed to maximize transfer opportunities of the airport and control the total schedule displacements.

Considering that rescheduling flight slots would interfere with airlines' competitive environment, we also put restrictions on maximal schedule displacement. The optimization model was applied for the flight schedule at the Urumqi international airport. Based on the different number of arrival and departure flight slots available for allocation, obtained from analyzing historical operational data and flight schedule displacement limits acceptable to the airlines, different testing scenarios have been designed and corresponding optimized flight schedules were obtained. The increase of the number of feasible flight connections and available flight connection seats, and the decrease in flight queuing delays for every testing scenario were calculated. The results show that the proposed flight schedule adjustment, i.e., demand management of flight schedules at a strategic level, can reduce the queuing delays for arrival and departure flights to improve the airport's operating efficiency and airport transfer opportunities at the same time without reducing the number of flights and affecting the mission connection of the aircraft. We also observed that for the Urumgi airport case, an increase of maximal schedule displacement did not lead to a significant improvement in the performance metrics that we calculated. The proposed model can be easily implemented in other hub airports as well. Our research provides a decision support tool so that airlines, airports, and air navigation service providers can work collaboratively to adjust the schedule to improve the competitiveness of hub airports.

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