Flight Schedule Strategy of Airport Group

Li Lei¹, Dan Zhao²*, Huaiyuan Liu³ and Dong Guo⁴

¹,²School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China
³No. 745, Heping Avenue, Yangyuan, Wuchang, Wuhan, Hubei 430063, China
⁴School of Mechanical-Electronic and Vehicle Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, China

*Corresponding author

Abstract. Overall consideration of airport group flight schedule optimization can make air traffic flow management more efficient and reasonable. The research features of this paper fully considers the matching of airport, airspace capacity and flow. It took into account the functional positioning of each member airport in the airport group and the airline's need for "golden hour" during the flight adjustment process and established a seasonal flight time optimization model which targets the minimum flight time adjustment. And taking the Yangtze River Delta Airport Group as an example to carry out a case study.

Keywords: Airport group; Airspace capacity; Air traffic flow; Flight schedule optimization.

1. Introduction
With the steady growth of the national economy, the development of China's civil air transport industry is rapid and the airport clusters have begun to appear. Optimizing the flight schedule of the airport group is crucial to improve the overall operating efficiency and service level of the airport group. Scholars at home and abroad have begun to study airport flight schedule optimization.

As early as 1995, Richard de Neufville systematically proposed the relevant theory of the airport group, focusing on the management strategies and cooperative operation mechanisms of the member airport group. But these are only theoretical studies and have not been applied to practice. In 2014, Simaiakis Ioannis and Balakrishnan, Hamsa optimize flight schedules to address air traffic demand management. The optimization goal is to reduce the difference between the required flight time of the aircraft operator and the final assigned flight time [1]. But did not consider airport capacity issues. In 2015, Alexandre Jacquillat and Amedeo Odoni analyzed and quantified the relationship between flight schedules, airport capacity and flight delays. They combined the capacity utilization strategy and queuing strategy to establish an airport congestion model, and proposed a flight time management method to alleviate the problem of airport congestion[2]. But did not take into account the existing flight schedule of the airline. In 2016, Nikolas Pyrgiotis and Amedeo Odoni established a flight schedule optimization model after taking into account existing flight schedules and airline flight schedule requirements. And using New York Airport as an example to validate the model [3]. China's research on the planning, construction, and operation of airport clusters is still in its infancy, and related theories and management techniques are scarce. Experts classify optimization efforts. In 2016, Ping Xie and his colleagues divided the airline's flight plan optimization work into local optimization and season optimization, and summarized the optimization methods into three categories: flight increase and decrease, aircraft type changes, and time adjustment. And using Xiamen Airlines as an example to validate their theory [4]. But only for single airport issues. In response to the flight
schedule optimization problem of Shanghai’s "City of Two Airports", Tianyuan Yi established a multi-airport flight schedule optimization model based on historical flight schedule operation data. He designed an improved Hungarian algorithm to solve the problem, instead of considering only a single airport optimization problem, but taking into account the needs of multiple airports[5].

This article combines the above work progress to solve the problem that the capacity of the airport or airspace in the airport group does not match the flow, considering the matching of the capacity of the airport, airspace and flow, establishing a flight schedule optimization model with the goal of minimum flight schedule adjustment.

2. Model Building

2.1. Model assumptions

- In order to prevent the situation that the flight time is too intensive during non-hours, this model selects a time slice with a time interval length of 5 minutes as the unit time slice.
- Each flight time has a maximum adjustment limit. This model assumes that the maximum adjustment time (the difference between the existing time and the optimized time) is the same for all flight times.
- The research scope of this paper is defined in the area of an airport group. Therefore, except for the capacity limitation of the airports and airspaces within this airport group, the capacity of the remaining airports or airspace are positive.

2.2. Symbol description

- $F$: Flight collection, $\forall f \in F$;
- $T$: Time slice collection, $t \in T$;
- $A$: Airline collection;
- $L$: Continuous flight pair collection, $L = \{(f, f'): (f')$ is the subsequent flight of $f), f, f' \in F\};$
- $K$: Airport collection, $\forall k \in K$;
- $K_c$: A collection of all airports in the Airport Group;
- $\eta_k$: The synergy coefficient of airport $k$;
- $F_k^D$: Collection of airport $k$ departure flights;
- $F_k^A$: Collection of airport $k$ approach flights;
- $S$: Waypoint collection, $\forall s \in S, S' \subseteq S$;
- $S_f'$: The set of waypoints that flight $f$ passed;
- $S_i'$: The $i$th waypoint that flight $f$ passed;
- $d_f$: Departure time of flight $f$ in the original flight schedule;
- $a_f$: Landing time of flight $f$ in the original flight schedule;
- $T_k^D$: Acceptable departure time range for airport $k$;
- $T_k^A$: Acceptable landing time range for airport $k$;
- $T_h$: Golden hour time slice collection(9:00-11:00,15:00-17:00,19:00-21:00);
- $T_r$: Golden regular periods time slice collection(7:00-9:00,17:00-19:00);
- $T_p$: Peak hours time slices collection during peak hours(5:00-7:00,11:00-15:00,21:00-24:00);
- $T_r$: Red eye period time slice collection(0:00-5:00);
- $t_f$: is the time it takes to fly from waypoint $i$ to the next waypoint;
- $C_k^t$: Capacity of airport $k$ at time slice $t$. 
$C_s^t$ - Capacity of waypoint $s$ at time slice $t$;

$t_{Lm}^{\min}$ - Select minimum transit time for consecutive flights of model $m$;

$t_{Lm}^{\max}$ - Maximum transit time for consecutive flights with model $m$;

$G_t = \begin{cases} 
1 & t \in T_h \\
0.8 & t \in T_g \\
0.4 & t \in T_c \\
0.1 & t \in T_s, G_t \text{ is Flight time factor} 
\end{cases} 
$

$x_{fm}^{kt} = \begin{cases} 
1 & \text{Flight } f \text{ selects model } m \text{ and adjusts to time slice } t \text{ to leave airport } k \\
0 & \text{Otherwise} 
\end{cases} 
$

$y_{km}^{kt} = \begin{cases} 
1 & \text{Flight } f \text{ selects model } m \text{ and adjusts to time slice } t \text{ leaves airport } k \\
0 & \text{Otherwise} 
\end{cases} 
$

$w_{fm}^{st} = \begin{cases} 
1 & \text{Flight } f \text{ selects model } m \text{ to enter waypoint } s \text{ at or before time slice } t \\
0 & \text{Otherwise} 
\end{cases} 
$

2.3. Objective function

The objective function consists of two parts. The first part is the maximum flight adjustment time $\theta$ of all flights in the airport group, and the second part is the total flight after weighted adjustment time $\delta$ of each airport in the airport group. The two are added as the objective function value. Golden hour usually refers to the three periods of 9:00-11:00, 15:00-17:00, and 19:00-21:00. Air transport demand is highest and flight takeoffs and landings are highest during this time.

$$\theta = \max_{k \in K} \left\{ \max_{f \in F} \sum_{t \in T^k} (t - d_1 y_{fm}^t G_t) \max_{f \in F} \sum_{t \in T^k} (t - a_1 y_{fm}^t G_t) \right\}$$  (1)

$$\delta = \sum_{k \in K} \left( \sum_{f \in F} \sum_{t \in T^k} (t - d_1 y_{fm}^t G_t) + \sum_{f \in F} \sum_{t \in T^k} (t - a_1 y_{fm}^t G_t) \right)$$  (2)

$$\min z = \theta + \delta$$  (3)

2.4. Constraint condition

- Uniqueness restrictions of flight time. $\forall f \in F$, Each flight has one and only one assigned flight time.

$$\sum_{t \in T^k} x_{fm}^{kt} = 1$$  (4)

$$\sum_{t \in T^k} y_{km}^{kt} = 1$$  (5)

- Consecutive flight restrictions $\forall(f, f^*) \in L$. $f^*$ is next of $f$. Consecutive flights must meet the time limit requirements of the minimum transit time and maximum transit time at the airport, so that the restrictions of continuous flight transfer can be met.

$$\sum_{t \in T^k} t x_{fm}^{kt} - \sum_{t \in T^k} t y_{km}^{kt} \geq t_{Lm}^{\min}$$  (6)
\[ \sum_{i \in T^Q_k} tx^k_{jm} - \sum_{i \in T^t_k} ty^k_{jm} \leq t^\text{max}_{LM} \quad (7) \]

- Capacity limitation. The flow of each member airport in the regional airport group and the waypoints in the airspace in each time slice cannot exceed the high capacity limit.

\[ \sum_{f \in F^k_m} x^k_{fm} + \sum_{f \in F^t_m} y^k_{fm} \geq C^f_k \quad \forall k \in K, \forall t \in T^Q_k \cap T^t_k \quad (8) \]

\[ \sum_{f \in S^t_i, t \in T} w^f_{jm} - w^f_{j, t-1} \leq C^f_s \quad (9) \]

- Flight restrictions. First the flight \( f \) must arrive at waypoint \( S^f_i \), then flight \( f \) to the next waypoint \( S^f_{i+1} \).

\[ \sum_{t \in T} w^{f, i}_{jm} - w^{f, t-1}_{jm} \leq 0 \quad (10) \]

- Flight adjustment restrictions. Limit maximum flight adjustment time and weighted total flight adjustment time.

\[ \theta \leq \theta^\text{max} \quad (11) \]

\[ \delta \leq \delta^\text{max} \quad (12) \]

3. Algorithm Design

Optimization is an integer programming problem and involves a large amount of data. In this chapter, we used a tabu search algorithm to solve the airport flight season flight schedule optimization model.

The essence of the tabu search algorithm is an extension of local domain search. The tabu search algorithm uses a taboo strategy to mark and avoid the searched solutions by simulating the memory mechanism of human intelligence. The key links of algorithm design include:

- Generate the initial solution. In this paper, the original flight schedule is used as the initial feasible solution.
- Construct neighborhood. The tabu search algorithm is an extension of domain search. This paper uses full permutation: N flights arrange M flight times.
- Construct taboo tables. In this article, the contraindication object is set to the previous combination of contraindications, which can prevent the occurrence of "circulation"; the contraindication period is set to 100; The amnesty rule is: if a banned neighbor makes the current optimal value drop, that neighbor can be made optional again.
- Evaluation function. The objective function of the airport group flight time optimization model is an evaluation function. The smaller the evaluation function value, the better the solution.
- Termination conditions. Setting the maximum number of iterations of the algorithm to 5000 can enable the model to reach a solution in a certain time.

The flowchart of this algorithm is shown in Figure 1.
4. Empirical Analysis

4.1. Data sources
The data in this article comes from the “National Civil Aviation 2019 Summer and Autumn Season Flight Plan”. Selecting the flight schedule of the Yangtze River Delta Airport Group (Shanghai Pudong International Airport, Shanghai Hongqiao International Airport, Hangzhou Xiaoshan International Airport, Nanjing Lukou International Airport, Ningbo Lishe International Airport and Wuxi Sunan Shuofang International Airport) on April 1, 2019, a total of 3838 flights.

Based on the documentation and operating experience of the approach control room, the flow restrictions of 41 points, including AND, SHZ, REMIM, JTN, NXD, KAKIS, and ELNEX, were calculated for 5 minutes, 15 minutes, and 60 minutes. And the synergy coefficient of the airports calculated from the airport positioning. Among them, the synergy coefficient reflects the priority status of each member airport in the airport group. The larger the airport's synergy coefficient, the higher the priority of the airport in the airport group, and the greater the impact of flight timing adjustments.

The calculation shows that the synergy coefficient of the airports in the Yangtze River Delta Airport Group are: Shanghai Pudong International Airport is 0.8; Shanghai Hongqiao International Airport is 0.5; Hangzhou Xiaoshan International Airport is 0.3; Nanjing Lukou International Airport is 0.3; Ningbo Lishe International Airport is 0.2; Wuxi Sunan Shuofang International Airport is 0.2. The synergy coefficients of the first, second, and third-level hub airports and non-junction airports are 0.8, 0.5, 0.3, and 0.2, respectively.

4.2. Result analysis
1) Flight adjustment: According to tabu search algorithm, the weighted total flight adjustment time of each airport in the Yangtze River Delta Airport Group after optimization is 1568.2 min, and the largest flight adjustment time is 44 min. Table 1 shows the adjustments of flights at each airport.
Table 1. Flight adjustment of airport group in Yangtze River delta.

| Airport | Flight adjustments (sorties) | Maximum flight adjustment time(min) | Total flight adjustment time(min) |
|---------|------------------------------|-------------------------------------|----------------------------------|
| ZSPD    | 109                          | 44                                  | 947                              |
| ZSSS    | 69                           | 35                                  | 606                              |
| ZSHC    | 89                           | 36                                  | 785                              |
| ZSNJ    | 64                           | 35                                  | 577                              |
| ZSNB    | 21                           | 20                                  | 300                              |
| ZSWX    | 20                           | 15                                  | 195                              |
| Total   |                              |                                     | 1568.2                           |

a. ZSPD is the ICAO code of Shanghai Pudong International Airport
b. ZSSS is the ICAO code of Shanghai Hongqiao International Airport
c. ZSHC is the ICAO code of Hangzhou Xiaoshan International Airport
d. ZSNJ is the ICAO code of Nanjing Lukou International Airport
e. ZSNB is the ICAO code of Ningbo Lishe International Airport
f. ZSWX is the ICAO code of Wuxi Sunan Shuofang International Airport

Figure 2. Flight schedule before and after optimization of Shanghai Pudong International Airport.

Figure 3. Flight time distribution before and after optimization of Shanghai Hongqiao International Airport.
Figure 4. Flight time distribution before and after the optimization of Hangzhou Xiaoshan International Airport.

Figure 5. Flight time distribution before and after the optimization of Nanjing Lukou International Airport.

Figure 6. Flight time distribution before and after the optimization of Ningbo Lishe International Airport.

Figure 7. Flight time distribution before and after optimization of Wuxi Sunan Shuofang International Airport.
2) Airport traffic situation: Using MATLAB to plot the flight time distribution of the Yangtze River Delta Airport Group before and after optimization in 5min and 15 min time units (map of changes in total flight arrivals and departures). As shown in Figures 2 to 7.

3) It is not difficult to see from the comparison of the flight time before and after optimization that the flight schedules of the member airports of the Yangtze River Delta Airport, during the prime time and peak hours before optimization fluctuated greatly, and the flight schedules in some time slices exceeded the airport capacity limit which seriously affected the orderliness and safety of flight operations. After the optimization, the number of flights in each time period has been effectively controlled, and the distribution is more even, which is more in line with the basic idea of "Peak Load Shifting" in flight adjustment.

4) Waypoint flow: Using MATLAB to draw saturation of route points in the Yangtze River Delta region before and after the optimization, during the golden time (10:00-11:00). Among them, the redder the color, the higher the waypoint saturation, and the bluer the color, the lower the waypoint saturation. As shown in Figures 8 to 9.

5. Conclusion
Based on the shortcomings of current airport group flight schedule management, this paper starts from the flight schedule to optimize and adjust the airport group flight schedule. It not only considered the matching of airport, airspace capacity and flow, but also took into account the demand for golden moments in the flight adjustment process of each member airport in the airport group, and established a flight timing optimization model with the minimum flight timing adjustment as the goal. And using Yangtze River Delta Airport Group as an example to carry out case studies. It is concluded that the weighted total flight adjustment time of each airport in the Yangtze River Delta Airport Group is 1568.2 min, and the largest flight adjustment time is 44 min. The results show that the optimization effect of this model and algorithm is good. The model and algorithm of this article can be applied to airport flight schedule optimization, and can also solve the problem of matching capacity and flow between airport and airspace. Protecting the interests of airports and airlines.
Acknowledgment
This research is supported by National Key Research and Development Plan (2016YFE0201700).

References
[1] Simaiakis I, Sabdberg M, Balakrishnan H. Dynamic control of airport departures: algorithm development and field evaluation [J]. IEEE transactions on intelligent transportation systems, 2014, 15 (1): 285-295.

[2] Jacquillat A, Odoni A R. Endogenous control of service rates in stochastic and dynamic queuing models of airport congestion[J]. Transportation Research Part E Logistics and Transportation Review, 2015, 73:133-151.

[3] Pyrgiotis N, Odoni A. On the Impact of Scheduling Limits: A Case Study at Newark Liberty International Airport [J]. Transportation Science, 2016, 50:150112072345006.

[4] Ping Xie. The Analysis of Flight Schedule Optimization in Xiamen Airlines [D]. Lanzhou University of Technology, 2016. (In Chinese).

[5] Tianyuan Yi. Research on Flight Schedule Optimization of Shanghai Airports[D]. Nanjing University of Aeronautics and Astronautics, 2018. (In Chinese).