Study on Short-time Flight Timing Optimization of Airport Group Based on Weather Conditions

Jia-juan CHEN¹, Zheng-rong CHEN¹,*, Huai-yuan LIU¹ and Chuan-tao WANG²

¹School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China
²School of Mechanical-Electronic and Vehicle Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, China

*Corresponding author

Keywords: Airport group, Flight delay, Flight timing optimization, Tactical management of air traffic flow.

Abstract. During the execution of flight schedule, the capacity of airport and airspace is often reduced by external dynamic factors such as weather conditions and flow control, which makes it impossible to meet the flow demand of airport and airspace, resulting in flight delay. In order to better implement tactical management of air traffic flow and reduce flight delay time and delay cost, this paper considers the impact of weather conditions, and combines ground and air waiting strategies to construct a multi-objective short-term flight time optimization model based on weather conditions, and uses NSGA-II algorithm to solve it. Finally, the Yangtze River Delta Airport Group is taken as an example to verify.

Introduction

The planning and layout of regional airports has always been the core bottleneck of restricting the rapid development of regional air transport. With the single airport system becoming more and more difficult to meet the growing demand for air transport, multi-airport system (i.e. Airport group) with clear positioning and win-win cooperation in the region will inevitably become the future development trend. Because of the obvious air traffic interaction, limited airspace resources, strong demand for flight time and other reasons, airport groups are vulnerable to weather conditions, flow control and other external dynamic factors, resulting in lower than expected flight normal rate, large-scale flight delay, which seriously affects the sustainable and healthy development of airport groups. Therefore, the implementation of scientific and reasonable optimization of short-term flight time is particularly important.

At present, many researchers from all over the world have conducted research on airport group and flight time optimization issues. Rubin David (1976) began to study the airport group problem and first proposed the concept of an airport group, which briefly defined the airport group as "Multi Airport Region" [1]. Peter B (1994) analyzed the ground-holding policy of multiple airports in air traffic flow management and established a VBO model based on ground-holding policy [2]. Avijit Mukherjee (2007) established a dynamic random integer programming model based on weather forecast and ground-holding policy, and verified by example that the model can allocate flight time in different decision stages [3]. Husni Idris (2003) used the queuing model to analyze the collaborative operation of the New York airport group, focusing on the interaction of air traffic flows at airports within the airport group and the correlation of flight times at airports [4]. Alexandre Jacquillat (2013) used the delay value model and the Monte Carlo simulation model to approximate the dynamic characteristics of the airport queuing system, and analyzed the airport delay levels under different conditions, and optimized the flight time. [5,6]. Nikolas Pyrgiotis (2016) established a flight time optimization model considering the existing flight schedule and airline flight time requirements, and verified the model with New York Airport as an example [7]. Nuno Antunes (2018) established a multi-target flight time optimization model based on the flight time coordination mechanism and...
management strategy stipulated by the International Air Transport Association, and verified the example with the Portuguese airport [8].

Previous studies on flight schedule optimization have not fully considered the impact of weather conditions, and the description of flight delay is slightly inadequate. Starting from the short-term flight schedule, considering the impact of weather conditions on airport and airspace capacity, this paper establishes a model with the objective of minimizing flight delay, and optimizes and adjusts the short-term flight schedule taking into account the interests of air traffic control, airport and airlines.

Model Creation

Model Assumption

(1) Assumption 1
Different weather conditions can only affect the capacity of airports and airspace per unit time.

(2) Assumption 2
Airport group flight delay refers to the departure delay of departure flights and the landing delay of incoming flights of each member of the airport group.

(3) Assumption 3
In the optimization adjustment of short-term flight time, the adjusted take-off or landing time of each flight can only be delayed or not advanced compared with the expected take-off or landing time. The departure flights all adopt the ground-holding policy. The air-holding policy is used for the incoming flights which have taken off before the study period but have not yet landed. The other incoming flights also adopt the ground-holding policy.

Model Description

In this paper, the following four objective functions are proposed according to the actual situation:

\[
\begin{align*}
\min z_1 &= \sum_{k \in K_C} \left( \sum_{f \in F'_C} \sum_{i \in I_C} (t - d_f) \ast x_{fm}^{ki} + \sum_{f \in F'_C} \sum_{i \in I_C} (t - a_f) \ast y_{fm}^{kr} \right) \\
\min z_2 &= \sum_{k \in K_C} \left( \sum_{f \in F'_C} \sum_{i \in I_C} \beta_g \ast (t - d_f)^{1 + \epsilon} \ast x_{fm}^{ki} \ast \mu_{f,g} + \sum_{f \in F'_C} \sum_{i \in I_C} \beta_g \ast (t - a_f)^{1 + \epsilon} \ast y_{fm}^{kr} \ast \mu_{f,g} \right) \\
\min z_3 &= \sum_{k \in K_C} \left( \sum_{f \in F'_C} \sum_{i \in I_C} x_{fm}^{ki} \ast \sigma_{f,g} + \sum_{f \in F'_C} \sum_{i \in I_C} y_{fm}^{kr} \ast \mu_{f,g} + y_{fm}^{kr} \ast \mu_{f,a} \right) \\
\min z_4 &= \sum_{k \in K_C} \left( \sum_{f \in F'_C} \sum_{i \in I_C} x_{fm}^{ki} \ast \sigma_{f,g} + \sum_{f \in F'_C} \sum_{i \in I_C} y_{fm}^{kr} \ast \sigma_{f,g} + y_{fm}^{kr} \ast \sigma_{f,a} \right)
\end{align*}
\]

The constraints are as follows:

\[
\begin{align*}
\sum_{i \in I_C} x_{fm}^{ki} &= 1 \\
\sum_{i \in I_C} y_{fm}^{kr} &= 1 \\
\sum_{i \in I_C} tx_{fm}^{kr} - \sum_{i \in I_C} ty_{fm}^{kr} &\geq \bar{t}^{\min}_{im}
\end{align*}
\]
\[ \sum_{t \in T^O_k} t x_{f_m}^{k_t} - \sum_{t \in T^O_k} t y_{f_m}^{k_t} \leq t_{L_m}^{\text{max}} \] 

(8)

\[ \sum_{f \in F^O_k} x_{f_m}^{k_t} + \sum_{f \in F^O_k} y_{f_m}^{k_t} \geq C^t_k \cdot \zeta \quad \forall k \in K, \forall t \in T^O_k \cap T^J_k \] 

(9)

\[ \sum_{f \in S, t \in T} w_{f}^{s, t} - w_{f}^{s, t-\epsilon} \leq C^t_s \cdot \zeta \] 

(10)

\[ \sum_{t \in T} w_{f_m}^{S^i, t} - w_{f_m}^{S^i, t-\epsilon} \leq 0 \] 

(11)

In the above formula, \( \zeta \) is the weather influence factor. \( T \) is the time slice set. \( F \) is the flight set. \( L \) is the continuous flight pair set \( \{ (f, f') : (f') \text{ is a follow-up flight to } f \} \). \( K \) is the airport set. \( K_C \) is the airport set of selected airport group. \( F^O_k \) is the of departure flights set for the airport \( k \). \( F^J_k \) is the of arrival flights set for the airport \( k \). \( S \) is the route points set. \( S' \) is the set of route points through which flight \( f \) passes. \( S^i \) is the \( i \) route point through which flight \( f \) passes. \( d_f \) is the departure time of the original flight schedule. \( a_f \) is the landing time of flights in the original flight schedule. \( t_{L_m}^t \) is the acceptable take-off time range for airport \( k \). \( t_{L_m}^t \) is the acceptable landing time range for airport \( k \). \( l_i^t \) is the time it takes for flight \( f \) to fly from point \( i \) to the next point. \( C^t_k \) is the capacity value of the airport \( k \) in the time slice. \( C^t_s \) is the capacity value of the route point \( s \) in the time slice. \( \beta_g \) is the ground waiting cost coefficient, which is usually 15. \( \beta_a \) is the air waiting cost coefficient, which is usually 75. \( t_{L_m}^{\text{min}} \) is the minimum transit time for continuous flights of selected aircraft type \( m \). \( t_{L_m}^{\text{max}} \) is the maximum transit time for continuous flights of selected type \( m \). \( \epsilon \) is the delay factor, which is usually 0.2.

\( x_{f_m}^{k_t}, \ y_{f_m}^{k_t}, \ w_{f_m}^{s, t}, \ \mu_{f,g}, \ \mu_{f,a}, \ \sigma_{f,g} \) and \( \sigma_{f,a} \) are all 0-1 decision variables. When the flight \( f \) chooses the type \( m \) to adjust to the time slice \( t \) to leave the airport \( k \), \( x_{f_m}^{k_t} \) is 1, otherwise 0. When the flight \( f \) chooses the type \( m \) to adjust to the time slice \( t \) to arrive at the airport \( k \), \( y_{f_m}^{k_t} \) is 1, otherwise 0. When the flight \( f \) chooses the type \( m \) to enter the route point \( s \) at the time slice \( t \) or before, \( w_{f_m}^{s,t} \) is 1, otherwise 0. When the flight \( f \) executes the ground-holding policy, \( \mu_{f,g} \) is 1, otherwise 0. When the flight \( f \) executes the air-holding policy, \( \mu_{f,a} \) is 1, otherwise 0. When the flight \( f \) executes the ground-holding policy for more than 15 minutes, \( \sigma_{f,g} \) is 1, otherwise 0. When the flight \( f \) executes the air-holding policy for more than 15 minutes, \( \sigma_{f,a} \) is 1, otherwise 0.

Formula (1) denotes the least total delay time. Formula (2) denotes the least total delay cost. Formula (3) denotes the least total flight sorties to execute ground and air holding policy. Form (4) denotes the least total flight sorties for irregular flights (ground and air holding exceeding 15 minutes). Formula (5) and Form (6) ensure that each flight has only one assigned flight time. Formula (7) and Formula (8) ensure that continuous flights meet the minimum and maximum transit time requirements of the airport. Form (9) and Form (10) ensure that the flow of airports and route points within each time period can’t exceed the capacity limit. Form (11) ensure that flight \( f \) can reach the next route point \( s^i \) only if it reaches route point \( s^j \) and flight \( l_j^i \) first.
Model Algorithm

In this paper, the NSGA-II algorithm [9] is used to solve the problem of short-time airport group flight time optimization based on weather conditions.

This paper sets the selection method to the binary tournament method. The crossover operation is set to two points crossing. The specific steps are as follows:

Step 1: Read the flight time data in the flight schedule, including flight number, take-off airport, landing airport, expected take-off time, expected landing time, etc.

Step 2: Set the population size \( N=2000 \). Randomly generate the initial parent population \( P_0 \). Set the reproductive algebra \( W=200 \), and initialize the population algebra \( w=0 \);

Step 3: When the population algebra is greater than the termination algebra, the algorithm ends, otherwise jump to step 5;

Step 4: According to the selection, crossover, and mutation settings in the previous article, the parent population is operated to generate the sub-population \( Q_0 \). The crossover probability is set to 1, the mutation probability is set to 0.05, and the intersection and the variation point are all randomly selected;

Step 5: Combine the parent population and the sub-population into a new group, and calculate the fitness of each individual in the new group;

Step 6: Perform non-dominated sorting on the new group, construct all its boundary sets, and then calculate the aggregation distance of each individual in the boundary set;

Step 7: Establish a partial order set of the new population, and select \( N \) individuals from the partial order to form a new population;

Step 8: Increase the population algebra by 1 and jump to Step 4.

Example and Analysis

The data in this paper are from the "China Civil Aviation Flight Plan for Summer and Autumn 2019". 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 Shuofang International Airport) from 8:00 to 12:00 on April 8, 2019 (On April 8, 2019, from 8:00 to 9:00, the Yangtze River Delta region is in light rain.) are selected, totaling 931 flights.

According to the related research, the weather influence factor under the light rain condition is 0.8. According to the NSGA-II algorithm, the total flight delay time of the optimized Yangtze River Delta airport group is 1565 min, the total delay cost is 11235 min. The total number of delayed flights and irregular flights is 130 and 18 respectively. Delays at airports are shown in table 2. Compared with the actual flight delay, the total flight delay time is reduced by 626 minutes, 39 sorties were reduced for delayed flights, and 6 sorties are reduced for irregular flights.

| Airport                                | Delay time(min) | Delay cost(min) | Delayed flight sorties | Irregular flight sorties |
|----------------------------------------|-----------------|-----------------|------------------------|--------------------------|
| Shanghai Pudong International Airport  | 725             | 5178            | 61                     | 6                        |
| Shanghai Hongqiao International Airport| 215             | 1553            | 18                     | 3                        |
| Hangzhou Xiaoshan International Airport| 180             | 1295            | 15                     | 3                        |
| Nanjing Lukou International Airport     | 170             | 1242            | 14                     | 2                        |
| Ningbo Qushe International Airport     | 145             | 1035            | 12                     | 2                        |
| Wuxi Shuofang International Airport     | 130             | 932             | 10                     | 2                        |
| **Total**                              | **1565**        | **11235**       | **130**                | **18**                   |
Table 2. Comparison of flight delay of airport group in Yangtze River delta

|                         | Total delay time (min) | Total delayed flight sorties | Total irregular flight sorties |
|-------------------------|------------------------|-------------------------------|-------------------------------|
| Actual operation        | 2191                   | 169                           | 24                            |
| After model optimization| 1565                   | 130                           | 18                            |

Summary

Based on the optimization of flight schedules, considering the influence of weather conditions, combined with the ground-holding policy and air-holding policy, this paper constructs a short-time flight time optimization model based on weather conditions and solves it using NSGA-II algorithm. The results show that the flight delay is effectively controlled.

Acknowledgement

This research was financially supported by the National Key R&D Program of China (No. 2018YFB1601603).

References

[1] Rubin, David, and L. N. Fagan. "FORECASTING AIR PASSENGERS IN A MULTIAIRPORT REGION." Transportation Research Record (1976).

[2] Vranas, Peter B., and B. A. R. Odoni. "The Multi-Airport Ground-Holding Problem in Air Traffic Control." Operations Research 42.2(1994): 249-261.

[3] Hansen, Mukherjee Mark. "A Dynamic Stochastic Model for the Single Airport Ground Holding Problem." Transportation Science 41.4 (2007):444-456.

[4] Idris, Husni. "Queuing Analysis of Interdependencies Between Multi-Airport System Operations." Aiaa Aviation Technology, Integration, & Operations Conference 2013.

[5] Jacquillat, Alexandre. A queuing model of airport congestion and policy implications at JFK and EWR. Diss. Massachusetts Institute of Technology, 2012.

[6] Jacquillat, Alexandre, and Amedeo R. Odoni. "Congestion Mitigation through Schedule Coordination at JFK: An Integrated Approach." (2013).

[7] Pyrgiotis, Nikolas, and Amedeo Odoni. "On the impact of scheduling limits: A case study at newark liberty international airport." Transportation Science 50.1 (2015): 150-165.

[8] Ribeiro, Nuno Antunes, et al. "An optimization approach for airport slot allocation under IATA guidelines." Transportation Research Part B: Methodological 112 (2018): 132-156.

[9] Deb, Kalyanmoy, et al. "A fast and elitist multiobjective genetic algorithm: NSGA-II." IEEE transactions on evolutionary computation 6.2 (2002): 182-197.