Collaborative slot allocation for arrival flights in multi-airport terminal area based on the traffic flow pattern: a case study of Shanghai terminal, China

Lina Ma 1*, Yong Tian 1 and Songtao Yang 2

1 College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing, Jiangsu, 211106, China
2 School of Mechanical Engineering, University of Leeds, Leeds, LS2 9JT, UK
*Corresponding author’s e-mail: malinacca@nuaa.edu.cn

Abstract. In order to solve the increasingly serious congestions and delays in busy airports, the problem of collaborative arrival slot allocation for the multi-airport terminal area is investigated in this paper. With the premise of ensuring operation safety and the goal of minimizing total delay, the specific pattern of arrival traffic flow in the terminal area is considered in optimization modelling, and an improved genetic algorithm is designed for effective solution, followed which a simulation experiment of Shanghai terminal in China is conducted based on analysing the spatiotemporal characteristics of the arrival traffic flow in it. Results show that the proposed method in this paper is able to reduce the total arrival delay in Shanghai terminal by 18.67%, and the delays on three runways in the terminal are cut down by 14.56%, 19.35% and 25.37% respectively, indicating a significant improvement in operation efficiency of the total system.

1. Introduction
With the development of global air transport industry, the issue of flight delay is increasingly rigorous and has caused huge losses in the overall benefits of society, including the dissatisfaction of civil aviation passengers, reduction of airlines operation profits, and decrease of the industry competitiveness. The cumulation and propagation effect of flight delay in the multi-airport terminal area is more potentially amplified[1]. Considering the long time and high cost of airport reconstruction or expansion, the most economical and efficient way to ameliorate the on-time rate of flights in the multi-airport terminal area is to improve the utilization efficiency of existing slot resources through reasonable allocation strategy.

The slot resources are widely allocated based on the principle of first come first service (FCFS) according to the flight schedule[2]. This method emphasizes the fairness of flight operations, but there is still an improvement room for resource utilization ratio from the overall perspective[3]. In this regard, many researchers have carried out a series of effective researches. The problem of collaborative sequencing for arrival flights in the multi-airport terminal area was effectively solved by introducing the concept of ‘multiple restricted time windows’[4]. Apart from the goal of reducing total delay, the utilization fairness of space and time resources between airports was also considered to obtain a fair strategy for arrival slot allocation[5]. Additionally, many other scholars used the conflict detection and resolution methods to address the problems of terminal airspace management and airport congestions at the macroscopic level through the integrated control of arrivals[6-7].
In short, the existing researches have theoretically obtained many methods with better performance than the original strategy of FCFS. Most of them have discussed and deepened the slot allocation strategy under the general airspace conditions and limitations, while lacking analysis and consideration of the air traffic flow pattern in the multi-airport terminal area. In this paper, a case study based on the real operation data of Shanghai terminal, one of the busiest multi-airport systems in China, is carried out considering the specific traffic flow pattern, so as to improve the reliability and practicability of the research results.

2. Arrival traffic flow pattern of Shanghai terminal

2.1. Airspace operation for arrival flights
There are two civil airports in Shanghai terminal: Shanghai Pudong International Airport (ZSPD) and Shanghai Hongqiao International Airport (ZSSS), and three main runways for arrival aircrafts to land on: Runway 34 and Runway 35L in ZSPD, and Runway 36R in ZSSS, each of which adopts the isolated parallel operation principle. According to the operation rules approved by Civil Aviation Administration of China (CAAC), SASAN is the waypoint that flights flying to both ZSSS and ZSPD can use to enter the terminal. DUMET and MATUN are mainly used for international flights, except the few flights flying to ZSSS through DUMET. As for BK and AND, they serve the arrival flights to ZSPD and ZSSS respectively.

2.2. Statistics of the typical daily arrival flights
To identify the traffic flow pattern of arrival flights in Shanghai terminal, the typical day of January 7, 2019, when there was no special event or extreme weather, is selected for analysis. Figure 1 shows the hourly statistical data of arrival flights to ZSSS and ZSPD on January 7, 2019, and the data collection was strongly supported by CAAC East China Regional Administration.

![Figure 1. Number of arrival flights from various waypoints to two airports during each hour.](image)

It can be seen that there were 1,072 arrival flights in Shanghai terminal on January 7, 2019. The flights to ZSPD were generally more than that to ZSSS, and 14:00-16:00 and 18:00-20:00 were the two busiest periods in Shanghai terminal. From 15:00 to 18:00, the waypoints of SANSA and DUMET, which served the two airports simultaneously, were relatively busy and more likely to generate congestions and delays. That contributes to the need of exploring an effective allocation strategy for arrival slot resources.

2.3. Spatiotemporal characteristics of the arrival traffic flow
The spatiotemporal characteristics of the arrival flight flow in Shanghai terminal are analysed using the total occupied time of the approaching route in this paper. The route direction and occupied
seconds are simultaneously illustrated in a polar histogram as figure 2 shows, the shaded parts represent the total occupied time of different approaching routes from the corresponding waypoints to the different airports. The numerical results of all approaching routes, along with the corresponding waypoints and airports, are marked using text in the figure.

Figure 2. Spatiotemporal distribution of the arrival flights in Shanghai terminal.

According to the results, the total approaching time of arrival flights was 15,775 minutes. SASAN was the busiest waypoint with the largest percentage of 38.9%. The occupied times of DUMET and MATUN were relatively shorter and accounted for 22.6% in total. As for BK and AND, which have clear function division, they made up 38.5% together. It can be concluded that the multi-airport terminal area has an unique traffic flow pattern for its specific mode in business development. In addition to the structural capacity limitation of the air route, it is necessary to consider the specific traffic flow pattern in the sequencing for the arrival flights, and take the matching constraint into account based on the occupied proportion of each route. That will help to better accord with the actual operation and improve the practical value of theoretical results.

3. Mathematic model

This paper aims to explore an allocation strategy of arrival slot in the multi-airport terminal area considering the traffic flow pattern. Given that the expected arrival times of all flights are available, the specific model is presented as follows:

3.1. Basic parameters

- \( F \): the set of arrival flights to be rearranged;
- \( A \): the set of airports;
- \( W \): the set of runways;
- \( P \): the set of arrival waypoints;
- \( S \): the set of approaching routes;
- \( e'^{af} \): the expected time when the flight \( f \) arrives at the airport \( a \);
- \( r'^{af} \): the actual time when the flight \( f \) arrives at the airport \( a \);
- \( d'^{af} \): the delay of the flight \( f \) arriving at the airport \( a \), and \( d'^{af} = r'^{af} - e'^{af} \);
- \( t'^{af}_{aw} \): the time when the flight \( f \) lands on the runway \( w_j \) at the airport \( a \);
- \( C_s \): the capacity of the approaching route \( s_i \);
- \( C_{w_j} \): the capacity of the runway \( w_j \);
- \( C_{p_m} \): the capacity of the waypoint \( p_m \);
3.2. Decision variables
There are four decision variables as follows. For each one, when the described condition is satisfied, it values 1, otherwise it values 0.

- $\chi_{f,s_i} = \{0,1\}$, the flight $f$ flies along the route $s_i$;
- $\lambda_{f,p_m} = \{0,1\}$, the flight $f$ passes the waypoints $p_m$;
- $\gamma_{f,w_j} = \{0,1\}$, the flight $f$ lands on the runway $w_j$;
- $\beta_{f,f'} = \{0,1\}$, the flight $f$ arrives earlier than flight $f'$.

3.3. Objective and constraints

\[
Y = \text{Min} \left( \sum_{a \in A} \sum_{f \in F} d_{af}^f \right) \tag{1}
\]
\[
\sum_{f \in F} \chi_{f,s_i} \leq C_{s_i}, \forall s_i \in S \tag{2}
\]
\[
\sum_{f \in F} \lambda_{f,p_m} \leq C_{p_m}, \forall p_m \in P \tag{3}
\]
\[
\sum_{f \in F} \gamma_{f,w_j} \leq C_{w_j}, \forall w_j \in W \tag{4}
\]
\[
\beta_{f,f'} \left(t_{a,p_m}^f + SEP_{p_m}^{f'}\right) \leq t_{a,p_m}^{f'}, \forall f \in F, a \in A, p_m \in P \tag{5}
\]
\[
\sum_{p_m \in P} \lambda_{f,p_m} = 1, \forall f \in F \tag{6}
\]
\[
\sum_{w_j \in W} \gamma_{f,w_j} = 1, \forall f \in F \tag{7}
\]
\[
\delta_s \sum_{s_i \in s_i \subset f \in F} \lambda_{f,s_i} \leq \sum_{f \in F} \gamma_{f,w_j} \leq \delta_s \sum_{s_i \in s_i \subset f \in F} \lambda_{f,s_i}, \forall s_i \in S \tag{8}
\]

The goal of minimizing total delay is achieved through equation (1); equation (2)-(4) are the capacity constraints for approaching routes, waypoints, and runways respectively; equation (5) means safe wake separations between aircrafts; equation (6) and equation (7) ensure that each flight enters the terminal area through one approaching waypoint and arrives at one airport. Equation (8) makes the occupied proportion of each approaching route is within a given range.

4. Solution approach
The conducted model belongs to a NP-hard problem and cannot find the optimal solution in polynomial period. Therefore, an improved genetic algorithm is designed to solve it in this paper.
4.1. Algorithm design

The chromosome coding is conducted in a dual way as the decision-making variables of the model include the route selection variables: one indicates the flight to be arranged; the other indicates the approaching route of the flight. And the sequential scheme of generating the initial population is based on the FCFS principle, which can ensure that all individuals in the initial population are able to meet the operation requirements. The fitness function is constructed based on the goal of minimizing total delay. Considering the possibility that the total flight delay values 0, the fitness function is constructed as equation (9).

\[
F = \sum_{a \in A} \sum_{f \in F} \frac{1}{d^a_f + 1}
\]  

(9)

4.2. Implementation process

- Step 1: read the data of the flights to be rearranged;
- Step 2: generate the initial population of arrival sequence based on FCFS;
- Step 3: calculate the individual fitness according to equation (9);
- Step 4: determine whether the termination condition is satisfied. If it is, the process will end, and the optimal allocation scheme can be obtained according to the optimal individual; otherwise, perform Step 5;
- Step 5: select and make some individuals enter the next generation using elitist retention strategy;
- Step 6: find the best individual among a randomly selected set and execute the championship strategy for it to generate a new population;
- Step 7: perform the two-point crossover based on a predefined probability;
- Step 8: discretely mutate the individuals to a new population according to a predefined probability. Return to Step 3.

5. Simulation and comparison

5.1. Experiment design

Arrival flights to Shanghai terminal during the peak period of 15:00-16:00 on January 7, 2019 were used for simulation. The arrival interval constraints on runways followed the standards about wake separation and safe speed provided by International Civil Aviation Organization (ICAO). In the implementation of the improved genetic algorithm, the population size and the maximum generation were both set as 100, the probabilities for crossover, mutation and retention were defined as 0.85, 0.85, and 0.01 respectively.

5.2. Result analysis

Comparing the optimized strategy (OS) proposed in this paper with the initial one of FCFS, the arrival delays of 51 flights are shown in figure 3. It can be seen that OS can effectively alleviate or eliminate the delays of most flights though the on-time performance of individual flights is sacrificed. From the cumulative results that figure 3 shows, there is a significant reduction of about 18.67% in total delay when using OS (2875s) compared with FCFS (3535s). Additionally, the growth of the cumulative delay using OS is more gradual than using FCFS. When the flight number is less, OS cannot reflect obvious superiority; with the increase in the flight number, it can effectively reduce the total delay and the reduction degree is getting higher and higher; while this effect will not be enhanced when the flight number climbs to a certain extent, for the flight flow has reached the capacity upper limit.
Figure 3. Respective and cumulative arrival delays.

Figure 4 illustrates the sequence adjustments of arrival flights on each runway. It can be seen that the number of flights adjusted on ZSPD/34, ZSPD/35L and ZSSS/36R are 8, 8 and 9 respectively. The arrival delays of flights on various runways in each 10-minute interval using different strategies are shown in table 1.

Table 1. Delays on various runways in different durations using two strategies.

| Duration  | ZSPD/34 | ZSPD/35L | ZSSS/36R |
|-----------|---------|----------|----------|
|           | FCFS(s) | OS(s)    | FCFS(s)  | OS(s)    | FCFS(s)  | OS(s)    |
| 15:00-15:10 | 280     | 210      | 250      | 190      | 90       | 90       |
| 15:10-15:20 | 460     | 480      | 30       | 30       | 370      | 250      |
| 15:20-15:30 | 330     | 250      | 60       | 60       | 180      | 140      |
| 15:30-15:40 | 40      | 40       | 90       | 110      | 195      | 145      |
| 15:40-15:50 | 180     | 140      | 250      | 170      | 180      | 130      |
| 15:50-16:00 | 290     | 230      | 250      | 190      | 10       | 10       |
| Sum       | 1580    | 1350     | 930      | 750      | 1025     | 765      |

After optimization, most of the results in table 1 are effectively reduced with few unchanged or slightly increased. Generally speaking, the total delays on the three runways are decreased by 14.56%, 19.35% and 25.37% respectively. Summarization can be drawn that the proposed arrival slot allocation strategy is able to alleviate the delays of the whole terminal as well as each runway in the multi-airport terminal area.
6. Conclusions
For flight delay mitigation and operation efficiency improvement in the multi-airport terminal area, an arrival slot allocation method considering the specific pattern of traffic flow is proposed in this paper based on the concept of collaborative decision making. And it is effectively solved using the designed improved genetic algorithm with dual coding and elite retention strategy. A case study of Shanghai terminal is presented, including identifying the spatiotemporal distribution of the arrival traffic flow, and reallocating the arrival slot resources using the proposed optimization method. Results show that the optimized strategy is able to reduce flight delay at different decision horizons whether for the whole terminal area, the airport or the runway, when ensuring safety and matching the traffic flow pattern. Future studies can be conducted by taking fairness allocation of delay and different weights of flights into consideration to obtain a more comprehensive framework of collaborative management in the multi-airport terminal area.

Acknowledgments
This work was funded by the National Nature Science Foundation of China (Grant no. 61671237), and the Graduate Open Foundation of Nanjing University of Aeronautics and Astronautics (Grant no. kfjj20200735).

References
[1] Qi, Y., Wang, Y., Liang, Y., Yao, D. (2019) Two-stage programming model for time slot allocation problem under uncertain capacity. J. Ei. Journal of Beijing University of Aeronautics and Astronautics., 45: 1747-1756.
[2] Liu, J.X., Jiang, H., Dong, X.F., Lan, S.J., Wang, H.Z. (2020) Dynamic collaborative sequencing method for arrival flights based on air traffic density. J. Ei. Acta Aeronautica et Astronautica Sinica., 41: 285-300.
[3] Huang, J.B. (2019) Flight sequencing model for multi-airport terminal area based on delay allocation. J. Sci. Command Information System and Technology., 10: 37-42.
[4] Ma, Y.Y., Hu, M.H., Zhang, H.H. (2015) Optimized method for collaborative arrival sequencing and scheduling in metroplex terminal area. J. Ei. Acta Aeronautica et Astronautica Sinica., 36: 2279-2290.
[5] Wang, Z., Wu, Y., Wan, L.L. (2016) Collaborative arrival aircrafts scheduling strategy aimed at common resources utilization fairness in metroplex terminal area. J. Cnki. Journal of Wuhan University of Technology (Transportation Science & Engineering.), 40: 585-591.
[6] Sidiropoulos, S., Majumdar, A., Han, K. (2018) A framework for the optimization of terminal airspace operations in Multi-Airport Systems. J. Sci. Transportation Research Part B: Methodological., 110: 160-187.
[7] Ma, J., Delahaye, D., Sbihi, M., Scala, P. (2019) Integrated optimization of terminal maneuvering area and airport at the macroscopic level. J. Sci. Transportation Part C: Emerging Technologies., 98: 338-357.