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Optimization of Aircraft Pushback Slot Allocation under Multi-hotspot Restriction

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Abstract. Serious congestions and frequent delay are hitting the most major airports in the world. In order to improve the operation efficiency of airports and reduce the flight delay, some factors such as runway capacity, wake interval, and hotspot restriction are considered, an optimization method for aircraft pushback slot allocation under multi-hotspot restriction is proposed in this work. Firstly, multi-runway departure scheduling problem is regarded as an NP-Hard combinatorial optimization problem. Secondly, aiming at minimizing delay time and conflict times simultaneously, the optimization model of aircraft pushback slot allocation is established. Finally, in order to solve the problem, an elitist non-dominated sorting genetic algorithm (NSGA-II algorithm) is designed combined with the multi-objective optimization theory and applied to solving the problem of pushback slot allocation to search for Pareto solutions. Experimental results verify that the above model and algorithm can achieve optimized slot allocation for aircraft pushback, effectively reduce the delay time and conflict times as opposed to historical model. The proposed method can significantly improve the punctuality rate and operation efficiency of large busy airports.

Keywords: flight delay, multi-objective optimization, pushback slot allocation, multi-hotspot.

1. Introduction

With the rapidly increasing demand, serious congestions and frequent delays are hitting the most major airports. Airports are becoming the major bottleneck in China. It is vital to seek methods to better use the existing airport infrastructure and to better manage aircraft movements. The optimization of aircraft pushback slot allocation is a key factor to improve the performance.

Airport surface scheduling optimization has been an active field for research. Ioannis Simaiakis et al. developed a queuing model of the departure process in order to describe quantitatively how queues form on the surface and what factors lead to the increased taxi-out times [1].Andrea D' Ariano et al. studied the problem of sequencing aircraft take-off and landing operations at congested airports, but the real time of the solution was not good [2].Ying Dong et al. proposed that the airport ground system can be regarded as an airport network topology and established an optimization model [3].Gautam Gupta et al. evaluated the effect of uncertainty on a deterministic runway scheduler [4].Atkin et al. used a model to predict the delays at the stands or the runway in order to absorb this time at the stand, but they did not analyze the delays at hotspot [5]. Christofas Stergianos et al. investigated the importance of the pushback process in the routing and scheduling problem [6]. Yun Wei et al. built a launch time model of departure flights on a multi-runway airport, but this model did not consider mutli-hotspot restriction [7]. Jianan Yin et al. proposed an method for multi-runway spatio-temporal resource scheduling in the mode of independent departures [8]. Yuanyuan Ma et al. established an optimized model for collaborative arrival sequencing and scheduling in metroplex terminal area [9]. Lili Wang et al. established an optimization model of arrival and departure resource allocation in terminal area [10].

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Obviously, the great majority of the research has analysed single runway and focused on the runway schedule, there were few studies on the pushback slot allocation, especially on the multi-runway. Based on the multi-runway departure scheduling problem, this paper proposed an optimization approach of aircraft departure schedule and pushback slot allocation under multi-runway airport. Through comprehensively considering runway capacity, wake interval, hotspot restriction and other factors, the model of aircraft pushback slot allocation aiming at minimizing delay time and frequency simultaneously are established. Also, the genetic algorithm is designed, and example verification is carried out by using the real operation data of Shanghai HongQiao Airport.

2. Problem Description

The current mode of pushback and taxi is to release aircrafts from the stands as soon as reaching the schedule time and the ground controller permits in order to avoid adjacent aircrafts pushing back at the same time, require the pilot who finds other aircraft on the left side of the cockpit to stop and wait, finally get them to the runway holding area and wait, allow the runway controller to perform the take-off sequencing.

However, that can cause long waiting queue before the runway in the peak hour of departure. Long queue leads to congestion on the taxiway and an increase in both fuel consumption and emissions. In addition, this kind of operation that let aircrafts wait frequently at hotspot have high risk of collision. In fact, departure aircraft waiting at the gate can stop its engines and avoid some conflicts. But at the same time, that can also cause delay the take-off time, which in turn reduces the capacity and passenger satisfaction. So how to balance the reducing of delay time and the number of conflicts has not only theoretical significance, but also very important practical importance.

The structure of apron is complex, especially for large busy airports. Combining different safety separation between different plane models that should be satisfied, an optimized flight pushback sequence can be calculated. According to ICAO, the safety separation among different plane models must be satisfied, turning safety separation into time, we can achieve the minimum safety separation time.

The departure aircrafts push back from the stands, taxi on the network of taxiways to the runway holding area and wait to take off. Taxiing on the network occupies most of the departure process. In order to improve the punctuality rate, a large number of aircrafts often taxi on the airport surface in the peak hour of operation, which leads to congestion and conflicts. The conflicts can be divided into cross-conflicts, rear-end collision and the pushback conflicts between adjacent aircrafts.

3. Optimization Algorithm for Aircraft Pushback Slot Allocation Model

3.1 Objective Function

Through analysing the process of departure, this paper assumes that all departure flights are waiting to be released from the stands, the departure process refers to the entire process from pushing back from stands to waiting at runway holding area. Due to the interaction between flights, the departure flight might conflict with others, at this moment, the departure flight must wait at the hotspot in order to avoid the congestion and conflict. Define the delay time as the result of the actual take-off time minus the scheduled take-off time. Let F denote the set of flights, where A represents the arrival flight set, D represents the departure flight set.

The first goal of the model is to make the delay as small as possible. The delay in the model refers to the delay time. The delay includes conflict waiting, threshold waiting and pushback waiting. Here, optimization objective is to minimize the total delay time after reprogramming the pushback schedule, as follows:

$$\text{Min} \quad \sum_{i=1}^{N}\sum_{r=1}^{R}\left(AT_{ir} - ET_{ir}\right)x_{ir} \quad , \quad i \in D \tag{1}$$

where, let $i \in F$ denote departure flight i, $r \in R$ denote the runway r, ET_{ir} denote the scheduled departure time of flight i which will take off on runway r, AT_{ir} denote the actual departure time of flight i which takes off on runway r, and x_{ir} denote the 0-1 variable indicating whether flight i takes off on the runway r.

Define the decision variable: $x_{ir} = \begin{cases} 1, \text{if the flight } i \text{ takes off on the runway } r \\ 0, \text{otherwise} \end{cases}$

The second objective of the model is to minimize the conflict number. When the separation between two aircrafts that reach the same hotspot is less than one minute, the conflict occurs, remember the conflict frequency. The smaller conflict number can effectively reduce the total delay time.

$$\text{Min} \quad \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{K} f_{ijn_k} \quad , \quad i \in D \tag{2}$$

In order to consider the taxiing collision between flights, the network diagram $G=(V,E)$ is used to describe the taxiing process, where n_k represents the hotspot on the taxiway. Let f_{ijn_k} denote the 0-1 variable indicating whether there is a conflict, that is:

$$f_{ijn_k} = \begin{cases} 1, \text{if the flight } i \text{ and } j \text{ conflict at hotspot } n_k \\ 0, \text{otherwise} \end{cases}$$

3.2 Model Constraint

- Runway uniqueness constraint

There is only one runway for each flight that can take off, so:

$$\sum_{i=1}^{N}\sum_{r=1}^{R} x_{ir} = 1, \quad \forall i \in F \tag{3}$$

where x_{ir} denotes the 0-1 variable indicating whether flight i takes off on the runway r.

- Wake interval constraint

The safety separation must be met, in another word, the separation between two aircrafts that take off on the same runway must be greater or equal to the allowed separation, while the separation between two aircrafts that take off on the different runways must also meet another separation, as follows:

$$AT_j - AT_i \geq S_{ij} y_{ij} + D_{ij}\left(1 - y_{ij}\right) \tag{4}$$

For any ordered pair of aircraft i and j, where i takes off before j, let S_{ij} denote the minimum safety separation on the same runway, D_{ij} denote the minimum safety separation on the different runways. y_{ij} represents the 0-1 variable indicating whether flight i and flight j takes off on the same runway. AT_i denotes the actual departure time of the leading flight i, while AT_j denote the actual departure time of the trailing flight j,that is:

$$y_{ij} = \begin{cases} 1, \text{if the flight } i \text{ and } j \text{ takes off on the same runway} \\ 0, \text{otherwise} \end{cases}$$

- Taxiing separation constraint

In any common taxiway unit, the separation between two aircrafts that reach one hotspot should meet the surface taxiing separation standard, as follows:

$$t_{n_k}^{i} - t_{n_k}^{j} \geq t_0 \tag{5}$$

where $t_{n_k}^{i}$ denotes the time when flight i reaches the hotspot n_k^i, t_0 denotes the minimum safety separation when conflicts occur. According to the taxiing separation standard, aircraft taxiing speed and other parameters, t_0 can be acquired by turning separation into time.

- Non-negative constraint

The scheduled departure time, the actual departure time, the time when reaching the hotspot and the safety separation are all non-negative, which is:

$$ET_{ir},\ AT_{ir},\ S_{ij},\ D_{ij},\ t_{n_k},\ t_0 \geq 0 \tag{6}$$

3.3 Solving Algorithm Design

- Chromosome encoding

The delay times of each flight at every hotspot are used as the genes, that is, in the above model the real value is used in the process of encoding. The delay times of each flight at every hotspot are used as the genes, and arranged in a fixed order which corresponding for the different flight. For example, for a time window, there are three hotspot and three area, at the same time, only one aircraft can push back in each area.

- Calculation of the objective function

The economic efficiency and the simplicity of the strategy are considered, which the economic target is characterized by the total delay time and the simplicity target is characterized by the conflict number. The economic objective is the minimum total delay time and the simplicity target is the minimum conflict number in each time slot, so the fitness function for the targets are as follows:

$$EC = \frac{1000}{\sum_{p\in K}\sum_{i\in F} DL_{ip} + \varepsilon} \tag{7}$$

$$SC = \frac{1000}{\sum_{p\in K}\sum_{i\in F} CL_{ip} + \varepsilon} \times \sigma \tag{8}$$

where ε is a small positive number, which ensuring the fitness function meaningful, when the total delay time is 0, the value in this paper is 1.

4. Simulation and Analysis

Shanghai HONGQIAO Airport has two parallel runways, and the apron is divided into 6 regions and 7 hotspots. The structure of the airport is shown in Fig 1. In order to speed up convergence, the concept of time window is introduced, pushback slot is allocated in every 15 minutes, such as in 00, 15, 30, 45 minute per hour. Tab .1 shows part of flight schedule for this period from 12:00 to 12:15, which includes departure and landing flights.

Table 1: Part of flight schedule

Serial	Fight	Type	Apron	In/Out	Time
1	CA158	B738/M	4	Out	12:00
2	CZ369	B737/M	4	In	12:00
3	CZ6799	B738/M	1	In	12:06
4	CZ3095	A321/M	1	Out	12:00
5	KE898	A333/H	2	Out	12:05
6	MU503	A320/M	5	Out	12:05
7	MH389	B772/H	2	In	12:08
8	AC026	B763/H	5	In	12:10
9	MU5820	B737/M	6	Out	12:10
10	CZ6534	A321/M	3	Out	12:10
11	HO1132	A321/M	2	In	12:15
12	MU5301	B738/M	5	Out	12:15

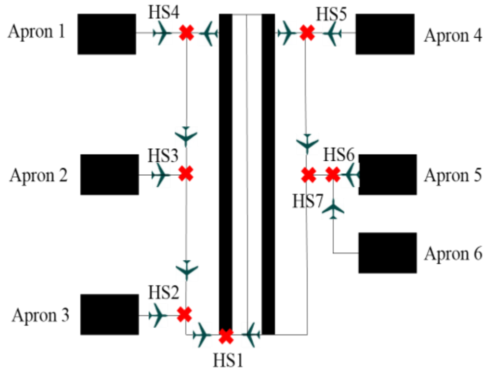

Fig. 1: Structure of the airport.

Table 2: Simulation result of departure flights

Serial	Fight	Type	Apron	Time①	Time②
1	CZ3095	A321/M	1	12:09	12:04
2	KE898	A333/H	2	12:08	12:05
3	CZ6534	A321/M	3	12:10	12:15
4	CA158	B738/M	4	12:07	12:02
5	MU503	A320/M	5	12:10	12:08
6	MU5820	B737/M	6	12:12	12:11

①Total delay time=26min, Conflict times=4

②Total delay time=15min, Conflict times=7

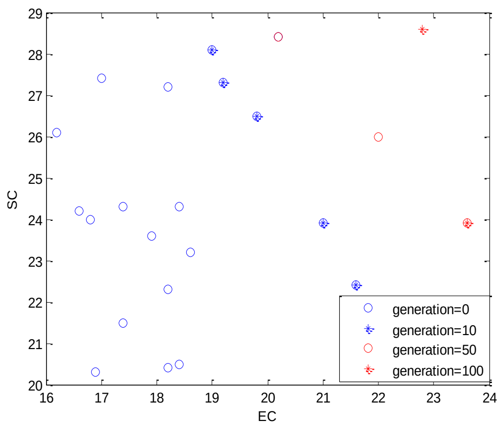

Fig. 2: Schematic diagram of the population distribution.

NSGA-II algorithm is used to solve the above model, calculation parameters is as follows: The number of individuals is set to 20, the maximum genetic generation is 100, the length of chromosome is 24, the use of the generation gap is 0.8, the crossover probability is 0.8, the mutation probability is 0.1. Calculation and analysis of the model with the NSGA-II algorithm is shown in Fig. 2 by the use of MATLAB.

Tab.2 shows the comparison of the optimization results, and the conclusions can be drawn as follows. The total delay time of pushback Time-Set 1 is the highest while it has the least conflict frequency. The conflict frequency of Time-Set 2 is the highest while it has the shortest total delay time. Therefore, the total delay time and conflict frequency cannot reach superior in the meantime, in the two types of pushback slot set, each efficiency and simplicity target has advantages and disadvantages; air traffic controllers or traffic flow management staff can make collaborative decisions according to the actual situation in the airport area and select the appropriate pushback strategy.

5. Conclusions and Discussion

The plan of flight pushback schedule is the most common part in airport surface operation. Flight pushback schedule has impacts on the safe operation and airport capacity. However, it is not so effective in the current mode of operations that is to release aircrafts from the stands as soon as reaching the schedule time. Considering that the delay is a strict restriction of capacity and the conflicts have bad impact on safe operation, the optimization of aircraft pushback slot allocation is very necessary. Through comprehensively considering runway capacity, wake interval, and hotspot restriction, the model of aircraft pushback slot allocation aiming at minimizing delay time and conflict times simultaneously is established. A Multi-Objective Genetic Algorithm is proposed to search Pareto solutions for multi-objective optimization model. Experimental results verify the effectiveness of the method.

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