Bi-level Programming Model for Joint Scheduling of Arrival and Departure Flights Based on Traffic Scenario

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Abstract: In order to meet the needs of collaborative decision making, considering the different demands of air traffic control units, airlines, airports and passengers in various traffic scenarios, the joint scheduling problem of arrival and departure flights is studied systematically. According to the matching degree of capacity and flow, it is determined that the traffic state of arrival / departure operation in a certain period is peak or off-peak. The demands of all parties in each traffic state are analyzed, and the mathematical models of arrival / departure flight scheduling in each traffic state are established. Aiming at the four kinds of joint operation traffic scenarios of arrival and departure, the corresponding bi-level programming models for joint scheduling of arrival and departure flights are established, respectively, and the elitism genetic algorithm is designed to solve the models. The results show that: Compared with the first-come-first-served method, in the scenarios of arrival peak & departure off-peak and arrival peak & departure peak, the departure flight equilibrium satisfaction is improved, and the runway occupation time of departure flight flow is reduced by 38.8%. In the scenarios of arrival off-peak & departure off-peak and departure peak & arrival off-peak, the arrival flight equilibrium delay time is significantly reduced, the departure flight equilibrium satisfaction is improved by 77.6%, and the runway occupation time of departure flight flow is reduced by 46.6%. Compared with other four kinds of strategies, the optimal scheduling method can better balance fairness and efficiency, so the scheduling results are more reasonable.

Key words: air traffic management; arrival and departure flight scheduling; bi-level programming; departure flight equilibrium satisfaction; arrival flight equilibrium delay time

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0 Introduction

Under the situation of stable and good economic operation in China, the aviation industry has developed rapidly, and the main transportation indicators of civil aviation have maintained steady and rapid growth. In 2019, the total transportation turnover of the whole civil aviation industry was 129.325 billion ton kilometers, an increase of 7.2% over the previous year[1]. The continuous growth of air traffic demand and the long-term limitation of available airspace and airport resources bring new opportunities and challenges to air traffic management. At present, the civil aviation authorities have invested heavily in building new runways and updating air traffic control equipment at busy airports. However, solely relying on this method to improve the operational capacity of the airport and terminal area is limited by many factors (such as time and money) and cannot be an effective measure to improve the traffic flow. Therefore, in order to improve the utilization of airspace and airport available capacity, optimizing the scheduling of spatio-temporal resources has become a research hotspot in the field of air traffic management. The optimal scheduling of arrival and depar-

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ture flights in runway system is a typical problem in this field.

The optimal scheduling of arrival and departure flights refers to the rational and efficient allocation of runways for arrival and departure flights under the condition of the safety isolation and combined with operational constraints, and the optimal departure and landing sequence and time are provided so as to improve the runway capacity and reduce flight delay or the workload of controllers, etc.[2] Relevant scholars have carried out a lot of studies on flight scheduling problems, and the research perspective has experienced the gradual development from arrival[3-10] to departure[11-14], and from arrival / departure to arrival & departure[15-19]. However, the existing single-level programming models of arrival & departure joint scheduling are difficult to reflect the hierarchical relationship between arrival and departure flights: (1) From the perspective of air traffic control unit, the decision makers of arrival flight scheduling and departure flight scheduling are different, they are the approach control unit and the tower control unit, respectively. (2) In different traffic scenarios, the relative importance between arrival and departure flights is different. For example, the importance of arrival flight is higher than that of departure flight in scenario of arrival peak & departure off-peak; on the contrary, departure flight is more important. In recent years, under the development trend of collaborative decision making in the civil aviation transportation industry, there have been relevant studies on the optimal scheduling of arrival flights[8], in which the scheduling scheme is selected according to the different demands of the flight operation participants in each traffic state, while the joint scheduling of arrival and departure flights is lack of such consideration.

In view of the existing problems in the above analysis, this paper focuses on the joint scheduling of arrival and departure flights under different traffic scenarios in an airport with a single runway. The research focuses on the "customization" and "hierarchy". By analyzing the demands of air traffic control units, airlines, airports and passengers in different traffic status, the objective functions and constraints are selected in a "customized" way to establish the scheduling model of arrival / departure flights in each traffic state. The bi-level programming method has been applied to the optimization of airport surface resources scheduling[20-21] and air route generation and repair[22-23]. Considering the different hierarchical relationship between the arrival and departure flights, the "hierarchy" is reflected in the establishment of a bi-level programming model for joint scheduling of arrival and departure flights in each traffic scenario. The bi-level programming model can reflect the difference in the relative importance of arrival and departure flights under different traffic scenarios and the role and performance of different decision makers in the decision-making process.

1 Model Establishment

Using 80% of the capacity as the threshold[8], according to the relationship between the arrival / departure traffic flow and the threshold in the scheduling period, the arrival / departure traffic state is determined as peak or off-peak. If the traffic state of scheduling period is arrival peak & departure off-peak (Scenario 1), the bi-level programming model is established with the arrival flight scheduling model as the upper level model and the departure flight scheduling model as the lower level model; if the traffic state of scheduling period is arrival peak & departure peak (Scenario 2) or arrival off-peak & departure off-peak (Scenario 3), according to the principle of "arrival priority", the arrival flight scheduling model is taken as the upper level model; if the traffic state of scheduling period is departure peak & arrival off-peak (Scenario 4), the departure flight scheduling model is taken as the upper level model.

1.1 Definition of symbols

The basic symbols and corresponding definitions used in the model are shown in Table 1.

Table 1 Definition of symbols

Symbol	Definition
$F^{\mathrm{A}}/F^{\mathrm{D}}$	Arrival/departure flight set
G	Departure flow direction set of departure flight
F_f^{D}	Departure flight set with departure flow direction f, $\bigcup_{f \in G} F_f^{\mathrm{D}} = F^{\mathrm{D}}$
$\nabla^{\mathrm{A}}/\Delta^{\mathrm{A}}$	Set of lower/upper bound of the maximum acceptable delay time for arrival flight
ε^{A}	Set of the maximum position shifting of arrival flight
Δ^{D}	Set of the maximum acceptable delay time of departure flight
$T_a^{\mathrm{sch}}/T_d^{\mathrm{sch}}$	Scheduled landing time of arrival flight a/scheduled departure time of the departure flight d
$T_a^{\mathrm{opt}}/T_{a_1}^{\mathrm{opt}}/T_{a_2}^{\mathrm{opt}}$	Optimized landing time of arrival flight $a/a_1/a_2$
$T_d^{\mathrm{opt}}/T_{d_1}^{\mathrm{opt}}/T_{d_2}^{\mathrm{opt}}/T_{d_3}^{\mathrm{opt}}/T_{d_4}^{\mathrm{opt}}$	Optimized departure time of departure flight $d/d_1/d_2/d_3/d_4$
$L_a^{\mathrm{sch}}/L_a^{\mathrm{opt}}$	Scheduled/optimized landing sequence of arrival flight a
$L_d^{\mathrm{sch}}/L_d^{\mathrm{opt}}$	Scheduled/optimized departure sequence of departure flight d
$S_{d_1d_2}^{\mathrm{wak}}/S_{a_1a_2}^{\mathrm{wak}}$	Wake separation minima that should be met between the departure flights d_1 and d_2 / arrival flights a_1 and a_2
$S_{d_3d_4}^{\mathrm{del}}$	Delivery separation minima that should be met between the departure flights d_3 and d_4 with departure flow direction f
$S_{a_1a_2}$	Separation minima that should be met when both the leading and subsequent flights are all arrival flights
S_{da}	Separation minima that should be met when the leading and subsequent flights are departure flight d and arrival flight a, respectively
v_a/v_{a_2}	Speed at the latest position receiving landing clearance of arrival flight a/a_2
y	Distance between the latest position of landing clearance received by the arrival flight and the runway threshold
t_a/t_{a_1}	Runway occupation time from landing to vacating runway of arrival flight a/a_1
t_d	Take-off run time of the departure flight d
c_a/c_d	Priority level of arrival flight a/ departure flight d, with the highest level, the second highest level and the lowest level corresponding to 1, 2 and 3, respectively
δ_d/γ_d	Delay time/departure sequence deviation of departure flight d, which is used to reflect time deviation / space deviation
δ_a	Delay time of arrival flight a, $\delta_a = \left\| T_a^{\mathrm{sch}} - T_a^{\mathrm{opt}} \right\|$
ρ_d/σ_d	Time satisfaction factor/space satisfaction factor of departure flight d corresponding to time deviation / space deviation
θ_d	Flight satisfaction evaluation index of departure flight d
x_a	The 0-1 discrete variable, which is used to reflect the sequence adjustment state of arrival flight a, x_a takes 1 when $L_a^{\mathrm{sch}} \neq L_a^{\mathrm{opt}}$, otherwise x_a takes 0
$\eta_{a_1a_2}$	The 0-1 discrete variable, which is used to reflect the chronological order of landing time of arrival flights a_1 and a_2, $\eta_{a_1a_2}$ takes 1 when the landing time of arrival flight a_1 is earlier than that of a_2, otherwise $\eta_{a_1a_2}$ takes 0
η_{da}/η_{ad}	The 0-1 discrete variable, which is used to reflect the chronological order of departure time of departure flight d and landing time of arrival flight a, when the leading flight is a departure flight and the subsequent flight is an arrival flight, η_{da}/η_{ad} takes 1/0, otherwise η_{da}/η_{ad} takes 0/1

Continued

Symbol	Definition
$\eta_{d_1d_2}$	The 0-1 discrete variable, which is used to reflect the chronological order of departure time of departure flights d_1 and d_2, $\eta_{d_1d_2}$ takes 1 when the departure time of flight d_1 is earlier than that of d_2, otherwise $\eta_{d_1d_2}$ takes 0
$\eta_{d_3d_4}$	The 0-1 discrete variable, which is used to reflect the chronological order of departure time of departure flights d_3 and d_4 with departure flow direction f, $\eta_{d_3d_4}$ takes 1 when the departure time of flight d_3 is earlier than that of d_4, otherwise $\eta_{d_3d_4}$ takes 0

1.2 Arrival flight scheduling as the upper model

Three different bi-level programming models are established, which take the arrival flight scheduling as the upper level model and the departure flight scheduling as the lower level model, corresponding to the above three traffic scenarios: Scenario 1, Scenario 2 and Scenario 3. The objective functions and constraints of bi-level programming model under various traffic scenarios are described as follows.

1.2.1 Scenario 1—Arrival peak & departure off-peak

In the period of arrival peak, air traffic controllers' workload is high. To reduce the fatigue risk caused by high workload and avoid the negative impact on aviation safety, the objective function of the upper level programming model is to minimize the air traffic controllers' workload. The objective function and constraints of the upper level programming model in Scenario 1 are as follows

$$\min Z_1=\sum_{a\in F^{\mathrm{A}}} x_a \tag{1}$$

s.t.

$$T_{a_2}^{\mathrm{opt}}\geqslant \eta_{a_1a_2}(T_{a_1}^{\mathrm{opt}}+S_{a_1a_2}^{\mathrm{wak}})\quad \forall a_1,a_2\in F^{\mathrm{A}} \tag{2}$$

$$T_{a_2}^{\mathrm{opt}}\geqslant \eta_{a_1a_2}(T_{a_1}^{\mathrm{opt}}+t_{a_1}+S_{a_1a_2})\quad \forall a_1,a_2\in F^{\mathrm{A}} \tag{3}$$

$$T_{a}^{\mathrm{opt}}\geqslant \eta_{da}(T_{d}^{\mathrm{opt}}+S_{da})\quad \forall a\in F^{\mathrm{A}},d\in F^{\mathrm{D}} \tag{4}$$

$$T_{d}^{\mathrm{opt}}\geqslant \eta_{ad}(T_{a}^{\mathrm{opt}}+t_a+t_d)\quad \forall a\in F^{\mathrm{A}},d\in F^{\mathrm{D}} \tag{5}$$

$$T_a^{\mathrm{sch}}-\nabla^{\mathrm{A}}(c_a)\leqslant T_a^{\mathrm{opt}}\leqslant T_a^{\mathrm{sch}}+\Delta^{\mathrm{A}}(c_a)\quad \forall a\in F^{\mathrm{A}} \tag{6}$$

$$L_a^{\mathrm{sch}}-\varepsilon^{\mathrm{A}}(c_a)\leqslant L_a^{\mathrm{opt}}\leqslant L_a^{\mathrm{sch}}+\varepsilon^{\mathrm{A}}(c_a)\quad \forall a\in F^{\mathrm{A}} \tag{7}$$

$$S_{da}=\frac{y}{v_a}\quad \forall a\in F^{\mathrm{A}},d\in F^{\mathrm{D}} \tag{8}$$

$$S_{a_1a_2}=\frac{y}{v_{a_2}}\quad \forall a_1,a_2\in F^{\mathrm{A}} \tag{9}$$

Eq.(1) represents the objective function of the upper level programming model. The adjustment of the arrival flight's landing sequence in the queue will directly increase the workload of the air traffic controller. The optimization objective of reducing air traffic controllers' workload is achieved by minimizing the number of arrival flights adjusted by landing sequence. Inequality (2) indicates that the arrival flights should meet the wake separation minima. Inequality (3) and inequality (4) correspond to the situations of "both leading and subsequent flights are arrival flights" and "leading and subsequent flights are departure flight and arrival flight respectively", respectively. After the leading flight vacate runway or depart from runway, the distance between the subsequent flight and the runway threshold should meet the requirement of the latest distance for issuing landing clearance[24]. Inequality (5) corresponds to the situation of "leading and subsequent flights are arrival flight and departure flight respectively", and the subsequent aircraft should take off in line at least after the leading aircraft vacate runway. The T_d^{opt} in inequalities (4) and (5) comes from the lower level programming model, reflecting the data transmission from the lower level programming model to the upper level programming model. Inequality (6) is the acceptable delay time window of arrival flight and inequality (7) is the constrained position shifting of arrival flight. The objective function Eq.(1) only optimizes the total number of arrival flights with landing sequence adjustment. Using constrained position shifting aims to coordinate with the objective function to limit the position shifting within a certain range in the period of arrival peak. Eqs.(8) and (9) are the separation minima converting methods from distance to time according to the requirements of the latest distance from the runway threshold for issuing landing clearance and the flight speed at that position.

In the period of departure off-peak, the operation pressure of the tower control unit is relatively small, and the safety objective of the air traffic control unit is achieved through the separation constraints. At this time, more attention is paid to the demands of the airlines, airports and passengers. The airlines and the airports will determine the start time and sequence of flight support service according to the departure time of departure flights. In order to ensure the smooth, orderly and efficient implementation of departure flight support services by airlines and airports, the deviation between the optimized departure time and the scheduled departure time should be as small as possible. In addition, passengers are not only concerned about flight delay time, but also sensitive to flight departure sequence deviation. According to the time deviation and space deviation of departure flight, the concept of "flight satisfaction" is proposed and the corresponding evaluation index is given in Ref.[17]. Therefore, this paper considers the average flight satisfaction and flight satisfaction deviation of departure flights in the period of departure off-peak, and puts forward the evaluation index of "departure flight equilibrium satisfaction", so as to achieve the goal of improving departure flight satisfaction and scheduling fairness by maximizing departure flight equilibrium satisfaction. The objective function and constraints of the lower level programming model in Scenario 1 are as follows

$$\max Z_2 = \frac{\sum_{d \in F^{\mathrm{D}}} \theta_d}{|F^{\mathrm{D}}|} - \max_{d_1, d_2 \in F^{\mathrm{D}}, d_1 \neq d_2} \left(\left| \theta_{d_1} - \theta_{d_2} \right| \right) \tag{10}$$

s.t.

$$T_{d_2}^{\mathrm{opt}} \geqslant \eta_{d_1 d_2} (T_{d_1}^{\mathrm{opt}} + S_{d_1 d_2}^{\mathrm{wak}}) \quad \forall d_1, d_2 \in F^{\mathrm{D}} \tag{11}$$

$$T_{d_2}^{\mathrm{opt}} \geqslant \eta_{d_1 d_2} (T_{d_1}^{\mathrm{opt}} + S_{d_1 d_2}^{\mathrm{rwy}}) \quad \forall d_1, d_2 \in F^{\mathrm{D}} \tag{12}$$

$$T_{d_4}^{\mathrm{opt}} \geqslant \eta_{d_3 d_4} (T_{d_3}^{\mathrm{opt}} + S_{d_3 d_4}^{\mathrm{del}}) \quad \forall d_3, d_4 \in F_f^{\mathrm{D}}, \forall f \in G \tag{13}$$

$$T_a^{\mathrm{opt}} \geqslant \eta_{ad} (T_d^{\mathrm{opt}} + S_{da}) \quad \forall a \in F^{\mathrm{A}}, d \in F^{\mathrm{D}} \tag{14}$$

$$T_d^{\mathrm{opt}} \geqslant \eta_{ad} (T_a^{\mathrm{opt}} + t_a + t_d) \quad \forall a \in F^{\mathrm{A}}, d \in F^{\mathrm{D}} \tag{15}$$

$$T_d^{\mathrm{sch}} \leqslant T_d^{\mathrm{opt}} \leqslant T_d^{\mathrm{sch}} + \Delta^{\mathrm{D}}(c_d) \quad \forall d \in F^{\mathrm{D}} \tag{16}$$

$$\delta_d = \left| T_d^{\mathrm{sch}} - T_d^{\mathrm{opt}} \right| \quad \forall d \in F^{\mathrm{D}} \tag{17}$$

$$\gamma_d = \left| L_d^{\mathrm{sch}} - L_d^{\mathrm{opt}} \right| \quad \forall d \in F^{\mathrm{D}} \tag{18}$$

$$\rho_d = \frac{1}{2 \times (\delta_d + 1)} \quad \forall d \in F^{\mathrm{D}} \tag{19}$$

$$\sigma_d = \frac{1}{2 \times (\gamma_d + 1)} \quad \forall d \in F^{\mathrm{D}} \tag{20}$$

$$\theta_d = \rho_d + \sigma_d \quad \forall d \in F^{\mathrm{D}} \tag{21}$$

Eq.(10) represents the objective function of the lower level programming model. If the departure flight average satisfaction is higher and the deviation of flight satisfaction between departure flights is smaller, the departure flight equilibrium satisfaction is higher. Inequalities (11) and (12) indicate that the departure flight should meet the wake separation minima and runway operation separation minima, respectively. Inequality (13) indicates that departure flights with the same departure flow direction should meet the delivery separation minima. Inequality (14) is the same as Inequality (4) and Inequality (15) is the same as Inequality (5), in which T_a^{opt} comes from the upper level programming model, reflecting the data transmission from the upper level programming model to the lower level programming model. Inequality (16) is the acceptable delay time window of departure flight. Departure flight is different from arrival flight and it is difficult to accept departure before scheduled departure time. Eqs.(17) and (18) are the calculation methods of departure flight delay time and departure sequence deviation, respectively. Eqs.(19) and (20) are the calculation methods of departure flight time satisfaction factor and space satisfaction factor, respectively. Eq.(21) is the departure flight satisfaction calculation method.

1.2.2 Scenario 2—Arrival peak & departure peak

Section 1.2.1 has established the arrival flight scheduling model during the period of arrival peak, that is, the objective function of the upper level programming model in Scenario 2 is Eq.(1), and the constraints are formulas (2—9).

In the period of departure peak, it is the most concerned problem of the tower control unit to make as many departure flights depart as possible in a short time. Therefore, the objective function of the lower level programming model in Scenario 2 is to minimize the runway occupancy time of departure flight flow, shown as

$$\min Z_3=\max_{d\in F^{\mathrm{D}}}(T_d^{\mathrm{opt}})-\min_{d\in F^{\mathrm{D}}}(T_d^{\mathrm{opt}}) \tag{22}$$

In Scenario 2, the constraints of the lower level programming model are formulas (11—21).

1.2.3 Scenario 3—Arrival off-peak & departure off-peak

As during the departure off-peak, more attention should be paid to the demands of airlines, airports and passengers during the period of arrival off-peak. Different from the departure flight scheduling problem, passengers in the air do not pay much attention to the deviation of flight arrival sequence, and the common concern of these three parties is the flight delay time. Therefore, for arrival flight scheduling problem under the period of arrival off-peak, only the time deviation is concerned, but the space deviation is not concerned. Meanwhile, considering the average delay time and delay time deviation of the arrival flight, the evaluation index of "arrival flight equilibrium delay time" is proposed (Eq.(23)), the upper level programming model of Scenario 3 achieves the goal of reducing arrival flight delay and improving scheduling fairness by minimizing the arrival flight equilibrium delay time.

$$\min Z_4=\frac{\sum_{a\in F^{\mathrm{A}}}\delta_a}{|F^{\mathrm{A}}|}+\max_{a_1,a_2\in F^{\mathrm{A}},a_1\neq a_2}\left(\left|\delta_{a_1}-\delta_{a_2}\right|\right) \tag{23}$$

At this time, constrained position shifting is no longer used, and the constraints of the upper level programming model in Scenario 3 are inequalities (2—6) and Eqs.(8—9).

Section 1.2.1 has established the departure flight scheduling model during the period of departure off-peak, that is, the objective function of the lower level programming model in Scenario 3 is Eq.(10), and the constraints are formulas (11—21).

1.3 Departure flight scheduling as the upper model

There is only one applicable scenario in the bi-level programming model, which takes departure flight scheduling as the upper level programming model and the arrival flight scheduling as the lower level programming model, namely, the scenario of departure peak & arrival off-peak (Scenario 4).

Section 1.2.2 has established the departure flight scheduling model during the period of departure peak, that is, the objective function of the upper level programming model in Scenario 4 is Eq.(22), and the constraints are formulas (11—21).

Section 1.2.3 has established the arrival flight scheduling model during the period of arrival off-peak, that is, the objective function of the lower level programming model in Scenario 4 is Eq.(23), and the constraints are inequalities (2—6) and Eqs.(8—9).

2 Algorithm

In Ref.[8], Elitism genetic algorithm (EGA) is used to efficiently solve the single-level programming model of arrival flight scheduling. The elite strategy ensures that the optimal solution found in the process of evolution will not be abandoned, which is the basic guarantee of population convergence to the optimal solution of the optimization problem. The flowchart of EGA is shown in Fig.1.

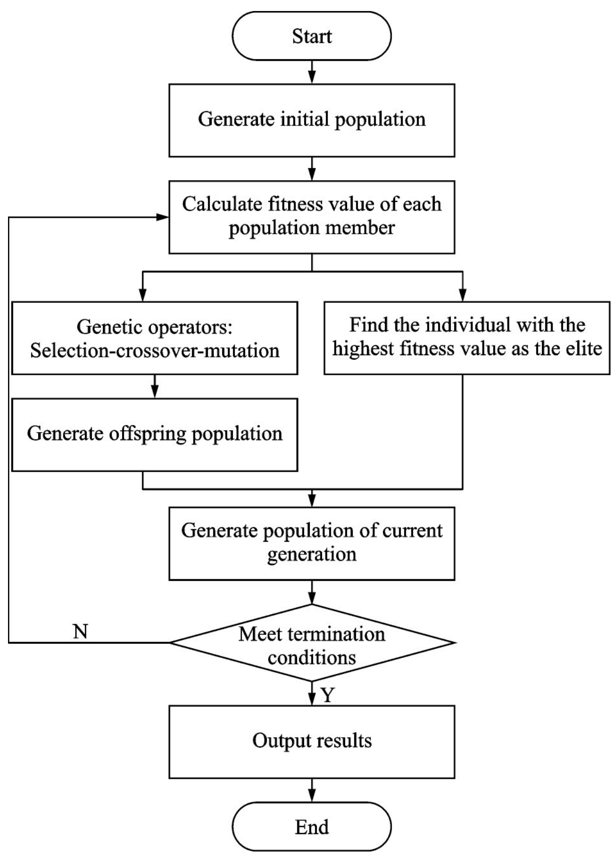

Fig.1 Flowchart of EGA

2.1 Coding

Coding is the process of mapping the solution space of a problem into the coding space. In this paper, we use integer coding method to code chromosomes. The length of chromosomes (i.e. the number of genes in each chromosome) is equal to $|F^{A}|$ or $|F^{D}|$, and each chromosome corresponds to a solution of the optimal scheduling problem of arrival / departure flights. The value of each gene in chromosome represents the real value of decision variable (optimized landing / departure time). Fig.2 shows an example of a chromosome with eight genes. The values of A1—A8 represent the optimized landing time of arrival flights.

A1	A2	A3	A4	A5	A6	A7	A8

Fig.2 Chromosome coding

2.2 Fitness value

For the established mathematical model, the fitness value is obtained by properly transforming the objective function value of population member. The fitness value must be a non-negative real number, and the increasing direction of fitness value is consistent with the optimization direction of the objective function value.

In EGA, the objective function value of each population member is obtained by linear scale transformation

$$F=\phi\times Z+\varphi \tag{24}$$

where F is the fitness value, Z the objective function value, φ a constant, and ϕ the parameter of controlling the transformation scale. For the maximized optimization objective (Objective 2 in this paper), the value of ϕ is greater than 0. For the minimized optimization objectives (Objectives 1, 3 and 4 in this paper), the value of ϕ is less than 0.

In this paper, before calculating the objective function value Z of each population member, we first judge the constraint compliance. If the population member violates any constraint, the objective function value is set to 0 / an arbitrary large number according to the maximization / minimization of the objective function. If the population member satisfies all constraints, the objective function value is calculated according to the formula of objective function.

In order to ensure that the expected replication number of an individual whose objective function value is equal to the average value is 1 in the next generation, the average fitness value after transformation should be equal to the average objective function value. At the same time, the maximum fitness value after transformation is set to be equal to the specified multiple of the average objective function value, so as to control the replication number of the individual with the optimal objective function value in the next generation. After this linear transformation, the fitness value of individuals with better objective function value decreases in equal proportion, while the fitness value of individuals with worse objective function value expands in equal proportion, which is beneficial to the diversity of the population.

2.3 Selection

The selection operator adopted by EGA is binary tournament selection. Based on the idea of elimination, this selection operator randomly selects two individuals from the population each time, and then selects the individuals with the higher fitness value to join the selected individuals.

Repeat the operation until the size of the selected individual reaches the set number.

2.4 Crossover

The crossover operator adopted by EGA is two-point crossover. This crossover operator randomly sets two crossover points in the chromosomes of two paired father individuals, and then exchanges the chromosome segments between the two crossover points to generate two offspring chromosomes. Fig.3 shows an example of two-point crossover.

2.5 Mutation

The mutation operator of EGA is the same as that of breeder genetic algorithm (BGA)[25]. This mutation operator uses Mutshrink and Gradient to control the mutation distance (Ref.[25]).

Since the values of decision variables in this pa-

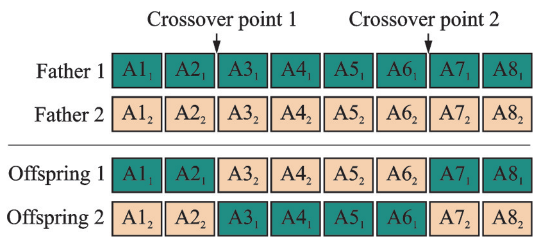

Fig.3 Two-point crossover

per are all integers, real numbers are first used as the mutation operator, and then the rounding method is used to convert the mutation results into integers.

2.6 Process of proposed algorithm

Based on EGA, this paper designs an algorithm for solving the bi-level programming model for joint scheduling of arrival and departure flights. Firstly, the decision variables of the upper level programming model are initialized and each flight is given a random initial solution in a reasonable range, that is, the landing/departure time of arrival/departure flights. Then, in the lower level programming, the optimal departure/landing time is obtained by using EGA to optimize objective function within the constraints of landing/departure time and parameters transferred by the upper level programming, and the optimal scheduling scheme is fed back to the upper level programming. After that, according to the optimal scheduling scheme fed back by the lower level programming, the upper level programming uses EGA to optimize, then the new optimal scheduling scheme is passed to the lower level for adjustment. Repeat the iteration process until the maximum number of simultaneous iterations. The pseudo code of the proposed algorithm is presented in Algorithm 1.

Algorithm 1 The procedure of proposed algorithm

Input Parameters of the model & parameters of EGA & the maximum number of simultaneous iterations T

Output Optimal objective function value and corresponding flight landing & departure time

(1) $t=0$

(2) Determine traffic scenario

(3) Determine landing & departure time windows according to inequalities (6) and (16)

(4) Randomly generate initial population of the upper level based on time window

(5) Calculate fitness values of each member in the initial population of the upper level

(6) Transfer the maximum fitness value and corresponding solution of the upper level to the lower level

(7) while $t<T$ do

(8) Obtain the maximum fitness value and corresponding solution of the lower level using EGA

(9) Transfer the results of the lower level to the upper level

(10) Obtain the maximum fitness value and corresponding solution of the upper level using EGA

(11) Transfers the results of the upper level to the lower level

(12) $t=t+1$

(13) end while

The specific steps of the proposed algorithm are as follows:

Step 1 Determine the input parameters of the model: The capacity of the airport, the base airlines and the departure points; wake separation minima and priority level of arrival / departure flights; the runway occupation time, the distance between the latest position of receiving the landing clearance and the runway threshold and the flight speed at this position, the lower bound and the upper bound sets of the acceptable maximum delay time, and the maximum position shifting set of arrival flights; take-off run time, runway operation separation minima, delivery separation minima, acceptable maximum delay time set of departure flights, etc. Determine the input parameters of the algorithm: The maximum number of simultaneous iterations, the maximum evolutionary generations, the population sizes, the crossover and mutation probabilities of EGA of the upper / lower level programming, etc.

Step 2 Determine the arrival and departure joint operation traffic scenario of the scheduling period, and select the bi-level programming model for joint scheduling of arrival and departure flights for the specific scenario.

Step 3 Initialization. According to inequality (6) / (16), the landing / departure time windows of all arrival / departure flights are determined, and the landing / departure time windows are taken as the upper and the lower bounds of the decision variables of the upper level programming model to generate the initial population randomly. The fitness values of all individuals in the initial population are calculated, and the maximum fitness value and corresponding landing / departure time of each flight are transferred to the lower level programming model.

Step 4 The lower level programming model uses EGA to obtain the maximum fitness value and the corresponding departure / landing time of each flight under the conditions of each flight landing / departure time transferred by the upper level programming model, and then transfers them to the upper level programming model.

Step 5 The upper level programming model uses EGA to obtain the maximum fitness value and the corresponding landing / departure time of each flight under the conditions of each flight departure / landing time transferred by the lower level programming model, and then transfers them to the lower level programming model.

Step 6 Increase the number of simultaneous iterations by 1. If the number of simultaneous iterations is not less than the maximum number of simultaneous iterations, the cycle ends. Otherwise, returns to Step 4.

Step 7 Output the optimal objective function values of the upper and lower level programming model and the corresponding each flight departure / landing time under the current number of simultaneous iterations.

3 Simulation

Taking a large airport with a single runway as an example, the flight data of the airport on a typical day is selected. Taking 15 min as the time scale, the bi-level programming model for joint scheduling of arrival and departure flights is verified under the four traffic scenarios described in Section 2, respectively. The basic situation of the airport is as follows: The capacity is 25 flights / h, there are three base airlines, and the number of departure points is five, two in the north, two in the south and one in the west.

Combined with the actual operation of the airport, the parameters in the model are set as follows: The wake separation minima of arrival / departure flights is determined according to the standard[24] issued by Civil Aviation Administration of China (CAAC); the runway occupation time of arrival flight is 70 s; the distance between the latest position of arrival flight receiving landing clearance and runway threshold is 4 km, and the flight speed of arrival flight at this position is 240 km / h; the take-off run time of departure flight is 65 s; runway operation separation minima of departure flight is 3 min for medium aircraft in front and heavy aircraft in rear, otherwise 2 min; delivery separation minima of departure flight is 5 min for two departure points in the south and 2 min for others; according to Ref.[8], the priorities of arrival / departure flights are determined, the lower and upper bound sets for the maximum acceptable delay time of arrival flights are [15, 10, 15] and [0, 10, 15], respectively, the set of maximum acceptable delay time of departure flight is [10, 20, 40], and the set of maximum position shifting of arrival flight is [1, 2, 3].

Considering the running time and convergence of the algorithm, several simulation experiments are carried out to adjust the parameters. The effective algorithm control parameters for the established bi-level programming model are as follows: The maximum number of simultaneous iterations is 10; the maximum evolution generation of EGA for the upper / lower level programming problem is 100 / 150; the population size of EGA for the upper / lower level programming problem is 50 / 100; the EGAs for both level programming problems adopt two-point crossover and BGA mutation operator; the crossover probability is 1, the compression ratio is 0.5, and the gradient is 20.

This paper compares the scheduling methods based on the first come first served (FCFS) strategy and other four kinds of strategies proposed scheduling method based on the bi-level programming model for joint scheduling of arrival and departure flights (hereinafter referred to as the optimal method), so as to evaluate the optimization effect of the proposed method. This paper uses Python programming to solve the bi-level programming problem for joint scheduling of arrival and departure flights.

3.1 Scenario 1—Arrival peak & departure off-peak

Fig.4 shows the trend of optimal objective function values of the upper and lower level programming models in Scenario 1 during iterations. As can be seen from Fig.4, with the increase of the number of iterations, the objective function value of the upper level programming model gradually decreases, and tends to be stable after the second simultaneous iteration. In the first six iterations, the objective function value of the lower level programming model rises rapidly; from the seventh to the eighth iteration, the objective function value rises gently; after the eighth iteration, the objective function value tends to be stable, which shows that the maximum number of simultaneous iterations selected in this paper is enough.

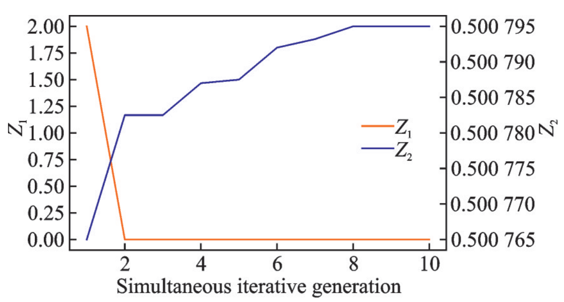

Fig.4 Trend of upper / lower level programming model objective function value in simultaneous iteration process (Scenario 1)

In Scenario 1, the corresponding objective function values of FCFS method result are $Z_1 = 0$ and $Z_2 = 0.500\,2$. The performance of FCFS method in the objective function Z_1 is constant and optimal because it does not change the sequences of arrival flights. After the completion of 10 simultaneous iterations, the optimal objective function values of the upper and lower level programming results are $Z_1 = 0$ and $Z_2 = 0.500\,8$ obtained by the optimal method, respectively. Compared with FCFS method, the value of the objective function Z_2 of the optimal method increases, so the departure flight equilibrium satisfaction improves.

In order to verify the effectiveness of the proposed "departure flight equilibrium satisfaction" evaluation index, the scheduling results of the optimal method are compared with those of three other strategies, namely, FCFS method, the objective function of the lower programming model is to maximize the departure flight average satisfaction (Strategy 1), and the objective function of the lower programming model is to minimize the departure flight satisfaction deviation (Strategy 2). The values of departure flight average satisfaction (Index 1), departure flight satisfaction deviation (Index 2) and departure flight equilibrium satisfaction (Index 3) of various scheduling strategies are shown in Table 2. When Strategy 1 is adopted, the value of Index 1 is greatly improved compared with the other three strategies, but the value of Index 2 is the largest. As a result, the scheduling efficiency is the highest among the four strategies, but Strategy 1 is difficult to ensure the fairness of departure flight scheduling. When Strategy 2 is adopted, the value of Index 2 is the smallest of the four strategies, but Index 1 is the lowest. Strategy 2 overoptimizes the fairness, making it difficult to ensure the efficiency of departure flight scheduling. Each evaluation index value of FCFS method results has no advantage in the four strategies. The result of the optimal method has the highest value of Index 3, and the value of Index 2 is second only to the scheduling result of Strategy 2. Although the value of Index 1 is inferior to the

Table 2 Performance of each scheduling strategy (Scenario 1)

Strategy	Index 1	Index 2	Index 3
Optimal	0.500 9	0.000 1	**0.500 8**
FCFS	0.502 5	0.002 3	0.500 2
Strategy 1	**0.877 0**	0.491 8	0.385 2
Strategy 2	0.500 4	**0.000 03**	0.500 4

FCFS method result, the optimal method balances fairness and efficiency, so the scheduling result is more reasonable.

3.2 Scenario 2—Arrival peak & departure peak

Fig.5 shows the trend of optimal objective function values of the upper and lower programming models in Scenario 2 during iterations.

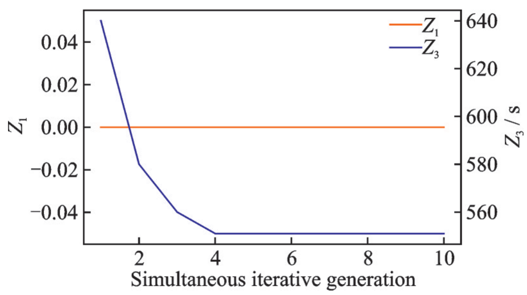

Fig.5 Trend of upper / lower level programming model objective function value in simultaneous iteration process (Scenario 2)

The upper level programming model of Scenario 2 is the same as Scenario 1. The objective function values corresponding to FCFS method are $Z_1 = 0$ and $Z_3 = 900$ s, respectively, and the performance of the objective function Z_1 is also constant and optimal. After 10 simultaneous iterations, the optimal method obtains the optimal objective function value $Z_1 = 0$ of the upper level programming model, and the optimal objective function value of the lower level programming model is $Z_3 = 551$ s. Compared with FCFS method, the value of objective function Z_3 of the optimal method is reduced by 38.8%. The runway occupancy time of departure flight flow shortens, so the efficiency of departure operation improves.

The comparison between the optimal departure sequences and FCFS departure sequences of departure flights is shown in Fig. 6. The difference between the optimal departure sequences and the FCFS departure sequences is that the departure sequences of departure flights D3 and D4 exchange. Departure flights D4 and D5 leave from the same departure point in the south, where the delivery separation minima is 5 min. According to FCFS method, the departure sequences of departure flight flow are determined as D1—D2—D4—D3—D5, in which D4 and D5 are adjacent departure flights. The optimal departure sequences of departure flight flow are D1—D2—D4—D3—D5, in which departure flights D4 and D5 are not adjacent departure flights. Departure flight D3 is after D4 and before D5, making the required 5-minute separation minima between D4 and D5 be fully utilized.

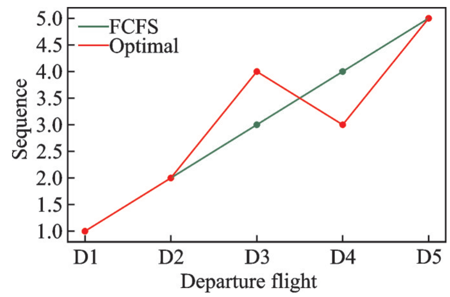

Fig.6 Optimal departure sequences and FCFS departure sequences for departure flights (Scenario 2)

3.3 Scenario 3—Arrival off-peak & departure off-peak

Fig.7 shows the trend of optimal objective function values of the upper and lower programming models in Scenario 3 during iterations.

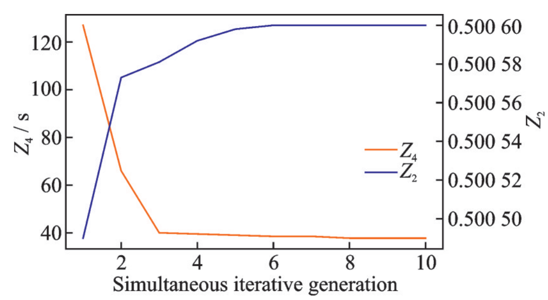

Fig.7 Trend of upper / lower level programming model objective function value in simultaneous iteration process (Scenario 3)

In Scenario 3, the corresponding objective function values of FCFS method result are $Z_4 = 87.5$ s and $Z_2 = 0.281\,9$, respectively. After 10 simultaneous iterations, the optimal method obtains the optimal objective function value $Z_4 = 37.75$ s of the upper level programming model, and the optimal objective function value of the lower level programming model is $Z_2 = 0.500\,6$. Compared with

FCFS method, the value of the objective function Z_4 of the optimal method is reduced by 56.9%, which reduces the arrival flight equilibrium delay time; the value of the objective function Z_2 of the optimal method is increased by 77.6%, which improves the departure flight equilibrium satisfaction.

In order to verify the effectiveness of the proposed "arrival flight equilibrium delay time" evaluation index, the scheduling results of the optimal method are compared with the scheduling results of other three strategies, namely, FCFS method, the objective function of the upper programming model is to minimize the arrival flight average delay time (Strategy 3), and the objective function of the upper programming model is to minimize the arrival flight delay time deviation (Strategy 4). The values of arrival flight average delay time (Index 4), arrival flight delay time deviation (Index 5) and arrival flight equilibrium delay time (Index 6) of various scheduling strategies are shown in Table 3. The scheduling results of FCFS method and Strategy 3 show that the value of Index 4 among the four strategies is the same and the smallest, but the values of Index 5 are the highest two among the four strategies. Though the scheduling efficiency is high, these two strategies are difficult to ensure the fairness of arrival flight scheduling. When Strategy 4 is adopted, the value of Index 5 is the smallest among the four strategies, but the values of Index 4 and Index 6 are the highest. Strategy 4 overoptimizes the fairness, making it difficult to ensure the efficiency of arrival flight scheduling. The result of the optimal method has the smallest value of Index 6, and the value of Index 5 is second only to the scheduling result of Strategy 4. The optimal method balances fairness and efficiency, so the scheduling result is more reasonable.

Table 3 Performance of each scheduling strategy (Scenario 3)

Strategy	Index 4 / s	Index 5 / s	Index 6 / s
Optimal	34.75	3	**37.75**
FCFS	**17.50**	70	87.50
Strategy 3	**17.50**	49	66.50
Strategy 4	318.00	**1**	319.00

3.4 Scenario 4—Departure peak & arrival off-peak

Fig.8 shows the trend of optimal objective function values of the upper and lower programming models in Scenario 4 during iterations.

In Scenario 4, the corresponding objective function values of the FCFS method result are $Z_3 = 1\,035$ s and $Z_4 = 160$ s, respectively. After 10 simultaneous iterations, the optimal method obtains the optimal objective function value $Z_3 = 553$ s of the upper level programming model and the optimal objective function value $Z_4 = 1$ s of the lower level programming model. Compared with FCFS method, the value of objective function Z_3 of the optimal method is reduced by 46.6%, which shortens the runway occupation time of departure flight flow and improves the departure operation efficiency. The optimization effect of objective function Z_4 is remarkable, which greatly reduces the arrival flight equilibrium delay time. The optimization method balances fairness and efficiency, and the scheduling result is more reasonable and feasible.

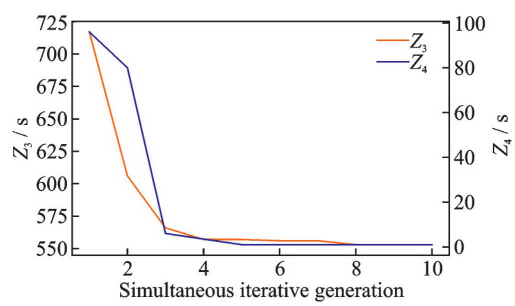

Fig.8 Trend of upper / lower level programming model objective function value in simultaneous iteration process (Scenario 4)

4 Conclusions

(1) Considering the demands of efficiency and fairness, this paper proposes "arrival flight equilibrium delay time" and "departure flight equilibrium satisfaction" evaluation indexes for arrival and departure flight scheduling, respectively.

(2) According to the matching degree between capacity and flow, aiming at the four kinds of joint operation traffic scenarios of arrival and departure, the corresponding bi-level programming models for

joint scheduling of arrival and departure flights are established, respectively, and the elitism genetic algorithm is designed to solve the problem.

(3) The simulation results show that: On the premise of ensuring safety, the departure flight equilibrium satisfaction improves, and the runway occupation time of departure flight flow and the arrival flight equilibrium delay time reduce when using the optimal method. The proposed method can provide theoretical support for air traffic managers to make arrival and departure flight scheduling plans.

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Author contributions Mr. **JIANG Hao** designed the study and wrote the manuscript. Dr. **LIU Jixin** interpreted the results and conducted the analysis. Mr. **ZHOU Wenshen** contributed to the discussion and background of the study. All authors commented on the manuscript draft and approved the submission.

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基于交通场景的进离场航班联合调度双层规划模型

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摘要:为适应协同决策需要,考虑进离场运行不同交通场景下空管、航司、机场和旅客的诉求差异,对进离场航班联合调度问题进行了系统的研究。根据容流匹配程度,判定进场/离场运行的交通状态为高峰或非高峰,分析不同交通状态下进场/离场运行各方诉求的差异,分别建立了各交通状态下进场/离场航班调度的数学模型;针对进场/离场运行交通状态组合所得的4种进离场联合运行交通场景,分别建立了相应的进离场航班联合调度双层规划模型并设计精英保留的遗传算法求解。结果表明:较先到先服务方法,在进场高峰/离场非高峰和进场高峰/离场高峰场景下,优化调度结果中离场航班均衡满意度得到提升,离场航班流的跑道占用时间减少了38.8%;在进场非高峰/离场非高峰和离场高峰/进场非高峰的场景下,优化调度结果中进场航班均衡延误时间大幅减少,离场航班均衡满意度提升了77.6%,离场航班流的跑道占用时间减少了46.6%。与其他4种策略相比,优化调度方法更好地权衡了公平与效率,调度结果更加合理可行。

关键词:空中交通管理;进离场航班调度;双层规划;离场航班均衡满意度;进场航班均衡延误时间