The Researches on Planning of Airline Network under Flexible Airspace Usage

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Abstract. To relieve the present situation of increasingly saturated airline network flow, elicit the concept of flexible use of airspace and conditional route. Combined with relevant research about recent the air traffic airline network management and planning, establish an airline network planning model which objective function is to minimize total cost sum of flight operation cost, wait cost and delay cost. Propose an improved algorithm which combines the traditional genetic algorithm and simulated annealing algorithm to solve the model. Finally, a simple example is given to obtain the optimal route planning scheme in the state when airspace is flexibly used while applying the improved algorithm, which verifies the feasibility of the model. The result indicates that the model and algorithm can effectively solve airline network planning problem.

1. Introduction
At present, the existing fixed line capacity is becoming saturated, which often results in a heavy delay. To alleviate this contradiction, the concept of flexible airspace was first proposed and widely used in Europe. The temporary route is called "conditional route" (CDR) in Europe, that is, the non permanent air traffic service route which is planned and used under the given conditions [1]. It is the most representative and feasible part of the flexible use strategy of the airspace. Until now, our country needs to apply for temporary air route before use, but the future may use the rules of military aviation "active release" [2], or imitate the foreign free airspace routes (FRA) approach to share civil and military airspace[3], which means that the use of temporary routes will be more frequent. China's flexible use of airspace started late and had opened more than 140 temporary routes until 2014[4], which made a great contribution to solve the problem of air traffic congestion. However, because the cost of using the temporary route is slightly higher than the fixed route, and the capacity of the temporary air route is limited, blind route selection may not be optimal.

With regard to the flexible use of airspace, most of our countries are drawing on the mature theoretical research from abroad and extensive practical experience. In 1990, Europe promulgated the strategy of air route, and proposed the concept of flexible use of airspace (FUA), in April 2015, a more advanced form of airspace flexible use (AFUA) was published on the EUROCONTROL website, and several new viewpoints and theories were put forward to realize dynamic airspace management [5][6]. And the research of route network optimization based on special conditions has also received much attention and research. In 2009, Chen Xing proposed the opening of temporary routes, the establishment of diversion routes and the re-route airline network [7], but no specific options were proposed. In 2010, Zhang Lubin et al proposed a method based on the minimum cost stream to solve the airline network route choice problem [8], but the cost factor considered was relatively single. In
2012, Wang Lili used the car following theory, expanded the macro traffic model of air traffic flow [9], without the study of traffic assignment. In 2014, Lv Huanliang added the concept of conditional route to the mathematical model of dynamic airspace, and realized the dynamic management of sectors by Tyson polygon [10], which has certain reference significance. Zhang Dongman et al used genetic algorithms to solve the flexible use of airspace under the flight route selection problem[11] and on the basis of this algorithm, Zhang Zhaoning added heuristic algorithm to study the dynamic assignment of regional air traffic flow in 2015[12], but no consideration to flight priority.

Route planning under the flexible use of airspace is complex, the main difficulty is that the open-close state of the route is different, there is no unified planning method, resulting in the need to constantly re planning the airline network. The airline network model established in this paper is applicable to the route planning problem under various conditions, that is, the optimal plan can be obtained before and after opening the temporary routes. Combined the traditional route network planning model method, with the minimum cost as the optimization of the quantization condition, adding the passenger compensation loss caused by the flight delay on the basis of the total cost of the operation cost and the waiting cost as the objective function, and adding the flights priority restrictions in constraints, then using the improved genetic simulated annealing algorithm to get the optimal solution, the results show that using the method in this paper to obtain the new scheme under open temporary routes has saved the cost.

2. Establishment of Route Network Planning Model

2.1 Hypothetical Condition

Set a weighted directed graph \( D = (V, E, C) \), take waypoint as node \( V \), connecting line as leg \( E \), arc capacity as leg capacity \( C \), establishing airline network model. The following assumptions are made for the considered airline network model:

1. The flights of this group are kept in uniform speed;
2. The airline network consists of several starting points and several ending points;
3. If the flow exceeds the capacity of the leg, implement waiting strategy. In order to facilitate the calculation of flight capacity, only considering the longitudinal interval between each flight, without the vertical and horizontal interval;
4. The flight schedule and there are no flights in the airline network before the first flight takes off;
5. Flights with the same starting and ending points choose the same flight path;
6. The state of temporary routes whether opening is known, when not available, set the cost to a sufficiently large value, equivalent to remove those routes from the network;
7. The flights entering at the same time to the same leg implement avoidance according to the priority specify the flight priority rule, i.e. the order of flight, as shown in Table 1.

| Priority | Flight type               |
|----------|---------------------------|
| 1        | combat flight             |
| 2        | special plane flight,     |
| 3        | important mission flight  |
| 4        | schedule flight           |
| 5        | general mission flight    |
| 6        | Training flight           |

Note: the smaller the serial number, the higher the priority
2.2 Planning Model
Consider several flights \( f_k (k = 1, 2, \ldots, M) \), from the specified starting points \( A_x (x = 1, 2, \ldots, M_a) \), fly to the specified ending points \( B_y (y = 1, 2, \ldots, M_b) \), the rest via the route is intermediate points \( v_p (p = 1, 2, \ldots, M_v) \). In the network, there are several available legs \( R_{ij} (i, j \in \{ A_x, B_y, v_p \}, i \neq j) \).

The capacity of leg \( R_{ij} \) can be expressed as:

\[
C_{ij} = \frac{L_{ij}}{\text{Int}}
\]  
(1)

In formula (1), \( L_{ij} \) means the length of the leg, \( \text{Int} \) means the interval of the flights.

To judge whether flight \( f_k \) is on node \( h (h = i, j) \) or not, define identification variable:

\[
G_{ih} = \begin{cases} 
1 & \text{flight } f_k \text{ is on the knot } h \\
0 & \text{otherwise}
\end{cases}
\]  
(2)

To judge whether flight \( f_k \) passes leg \( R_{ij} \) or not, define identification variable:

\[
H_{ij} = \begin{cases} 
1 & \text{flight } f_k \text{ is on the leg } R_{ij} \\
0 & \text{otherwise}
\end{cases}
\]  
(3)

To judge whether flight \( f_k \) terminates at time \( t \) or not, define decision variable:

\[
T_{fh} = \begin{cases} 
1 & \text{flight } f_k \text{ continues flying at time } t \\
0 & \text{flight } f_k \text{ stops flying at time } t
\end{cases}
\]  
(4)

Let flight \( f_k \) estimated time of departure at node \( h \) is \( Etd^k_h \), estimated time of arrival is \( Eta^k_h \), actual time of departure is \( Atd^k_h \), actual time of arrival is \( Ata^k_h \), (default the estimated and actual time of arrival of starting points \( A_x \) are equal to the estimated time of departure, and the estimated and actual time of departure of ending points \( B_y \) are equal to the actual time of arrival) then the air waiting time at node \( h \) of flight \( f_k \) can represented as:

\[
W_{fh} = Atd^k_h - Ata^k_h = \sum_{t=0}^{T} T_{fh} \times G_{ih}
\]  
(5)

And the operating time on leg \( R_{ij} \) of flight \( f_k \) can represented as:

\[
O_{ij} = Ata^k_i - Atd^k_i = Eta^k_i - Etd^k_i = \sum_{t=0}^{T} T_{ij} \times H_{ij}
\]  
(6)

The total delay time on the whole route of flight \( f_k \) is:

\[
D_k = Ata^k_h - Etd^k_h = \sum_{t=0}^{T} T_{fh} \times \prod_{(i,j) \in V} (1 - H_{ij})
\]  
(7)

2.3 Objective Function
Although from the passengers view, the optimal route network is the minimum delay of a single flight, but on the whole, the minimum total cost of all flights is the best choice for airlines (airline operators). Therefore, considering two aspects of both airline benefits and passenger interests, the total cost of all flights include: air waiting costs, air routes costs and delay costs.

Assume the air waiting cost per unit time is \( C_{W_h} \), route operating cost per unit time is \( C_{O_{ij}} \), passenger delay compensation cost per unit time of flight \( f_k \) is \( C_{D_k} \), then the objective function can be represented as:

\[
Z = \min \sum_{(i,j) \in V} \sum_{k=1}^{M} (W_{fh} \times C_{W_h} + O_{ij} \times C_{O_{ij}} + D_k \times C_{D_k})
\]  
(8)
2.4 Constraint Condition
Although from the passengers view, the optimal route network is the minimum delay of a single flight, but on the whole, the minimum total cost of all flights is the best choice for airlines (airline operators). Therefore, considering two aspects of both airline benefits and passenger interests, the total cost of all flights include: air waiting costs, air routes costs and delay costs.

(1) Leg capacity constraint
Any moment $t$, the flight flow $F_{ij}^t$ on the leg satisfies:

$$F_{ij}^t = \sum_{k=1}^{M_i} H_{ij}^t, \quad 0 \leq F_{ij}^t \leq C_{ij}$$

(9)

(2) Flow balance condition
For starting points $A_p$, flight flow satisfies:

$$\sum_{p=1}^{M_p} \sum_{k=1}^{M} (F_{A_p}^t - F_{V_p}^t) = F$$

(10)

For ending points $V_p$, flight flow satisfies:

$$\sum_{p=1}^{M_p} \sum_{k=1}^{M} (F_{V_p}^t - F_{V_p}^t) = F$$

(11)

For ending points $B_y$, the inflow is equal to the outflow.

(3) Flight time calculation
Start clocking, moment $t$ satisfies:

$$\sum_{k=1}^{M} T_{k}^t = 1$$

(12)

Stop clocking, moment $t$ satisfies:

$$\prod_{k=1}^{M} (1 - T_{k}^t) = 1$$

(13)

3. Model Solving Algorithm Design

3.1 Improved Genetic Simulated Annealing Algorithm
The simulated annealing algorithm (SA) has stronger local search ability, but the ability to grasp the overall situation is poor; and the genetic algorithm (GA) has stronger global search ability, but prematurely converges [13], the two algorithms are complementary, can learn from each other. Therefore, this paper adopts a proposed algorithm which combines GA and SA, and the improved genetic simulated annealing algorithm (GASA) can effectively overcome the local convergence to optimum solution in large-scale data processing [14], so as to effectively and quickly solve this research problem.

The improved GASA in this paper, is starting from producing a random set of initial population, to search for global optimal solution: first through genetic operations of selection, crossover and mutation in the initial temperature to generate a new set of individuals, and then use SA to produce the next generation groups of individuals, after cooling operation, repeat the process of GA in the new temperature, repeated iteratively, until satisfies the termination condition.

3.2 Algorithm Flow Chart
The Algorithm flow chart of improved GASA used to solve this problem defined in Figure1.
3.3 Algorithm Parameter Specification
(1) Coding rule: start with 1 to number the airline network nodes from the left to right, top to bottom, and generate sort of numbers is the flight line of a certain flight;

(2) Initial population: a randomly generated initial population, individuals in the population describe all the flight routes set, expressed in the form of matrix, the number of rows is the product of starting point and ending points, columns number is the total number of nodes, for a flight, the starting and ending point is known, therefore, the matrix of the first and the last column are fixed number, just sort middle column, set the distance between two points infinite if not reachable, and ignore this leg of the last generated program.

(3) Fitness function: take the reciprocal of the objective function and the greater the fitness value, the better.

\[
\text{Fitness} = \frac{1}{\sum_{(i,j,h) \in V} \sum_{k=1}^{M_i} (W_{ik} \times CW_h + O_{ih} \times CO_g + D_k \times Cd_k)}
\]

(4) Selection operator (generation gap) \( \text{GGAP} \) : select individuals into progeny groups with certain probability from parent population, the probability of an individual being selected is related to fitness, the greater the fitness value, the easier it is to be selected.

(5) Crossover operator \( \text{cP} \) : divide parent individuals of groups in two, each group selects any column of one of the individuals in line with the other (except for the first and last columns), exchange according to a certain probability, if result in numbers repeated of line, change the repeated numbers.

(6) Mutation operator \( \text{mP} \) : use a heuristic mutation operator, select two columns of an individual matrix randomly (except for the first and last column) and exchange them under the control of mutation probability.

(7) Metropolis criterion: under temperature \( T_i \), in some way, get new status \( S' \)'according to the current solution \( S(k) \) to be candidate solution, and calculate energy difference \( \Delta C' = C(S') - C(S(k)) \), if \( \Delta C' < 0 \), accept \( S' \) as next current solution, otherwise, accept \( S' \) as next current solution in probability \( \exp\left(-\Delta C' / T_i\right) \).

(8) Termination rule: \( T_i < T_{\text{end}} \) or the optimal individual doesn’t change during several generations.
4. Example Analyses

Considering the route network model showed in Figure 2, starting points are \{A_1, A_2\}, ending points are \{B_1, B_2, B_3\}, intermediate points are \{v_1, v_2, v_3, v_4, v_5\}. The solid lines represent the original fixed routes, the dotted lines represent the temporary routes whose on-off state is known, and the number on line segment indicates the distance. Set flight interval as 1, flying speed as 1, the leg capacity and route running time can be calculated. Set operating cost factor per unit time that fixed route is 0.1, temporary route is 0.11, waiting cost on nodes is 0.1, and delay cost is 0.05.

Choosing a group of 20 flights which estimated departure time are known and the number of flights from each starting point to each terminal point and the flight priority are also known. Set population numbers as 20, maximum genetic algebra as 10, GGAP 0.9, Pm 0.1, To 100, Tmut 1, and q 0.8. Then use the improved GASA can obtain the optimized flight routes of the group before and after the opening the temporary routes as shown in Table 2. Simulation results show that total operating cost of the original route network is 22.5, the total operation cost of the optimized route network planning scheme is 21.11, which means after optimization, the total cost of the objective function is obviously reduced under the condition of the temporary route development. Each cost of the total cost after the temporary routes are opened is shown in Table 3.

![Fig.2 Route Network Model of an Area](image)

**Table 2 Material Properties of Steels**

| Starting points | Ending points | Flights number | Original flight path | Optimized flight path |
|-----------------|---------------|----------------|----------------------|-----------------------|
| \(A_1\)         | \(B_1\)       | 4              | \(A_1 \rightarrow v_1 \rightarrow v_4 \) \(\rightarrow B_1\) | \(A_1 \rightarrow v_1 \rightarrow v_4 \) \(\rightarrow B_1\) |
| \(A_1\)         | \(B_2\)       | 3              | \(A_1 \rightarrow v_1 \rightarrow v_2 \) \(\rightarrow v_4 \rightarrow B_2\) | \(A_1 \rightarrow v_2 \rightarrow v_4 \) \(\rightarrow B_2\) |
| \(A_1\)         | \(B_3\)       | 3              | \(A_1 \rightarrow A_2 \rightarrow v_3 \) \(\rightarrow B_3\) | \(A_1 \rightarrow v_2 \rightarrow v_5 \) \(\rightarrow B_3\) |
| \(A_2\)         | \(B_1\)       | 3              | \(A_2 \rightarrow v_2 \rightarrow v_4 \) \(\rightarrow B_1\) | \(A_2 \rightarrow v_2 \rightarrow v_4 \) \(\rightarrow B_1\) |
| \(A_2\)         | \(B_2\)       | 4              | \(A_2 \rightarrow v_2 \rightarrow v_5 \) \(\rightarrow B_2\) | \(A_2 \rightarrow v_3 \rightarrow v_5 \) \(\rightarrow B_2\) |
| \(A_2\)         | \(B_3\)       | 3              | \(A_2 \rightarrow v_3 \rightarrow B_3\) | \(A_2 \rightarrow v_3 \rightarrow B_3\) |
Table.3 Flight Cost before and after Optimization

|                | Operating cost | Waiting cost | Delay cost | Total cost |
|----------------|----------------|--------------|------------|------------|
| Before optimization | 21.45          | 0.7          | 0.35       | 22.5       |
| After optimization  | 20.81          | 0.2          | 0.1        | 21.11      |

5. Conclusions
Route network planning model proposed in this paper, with the cost as the objective function, considering both the flight operation cost and delay cost, and combine the genetic algorithm with simulated annealing algorithm to obtain an improved algorithm to solve the model, in the situation of known flight operation time, route opening and closing state, can obtain the air traffic route network planning scheme, the simulation results show that this model can apply to the flexible use of airspace conditions and in either the temporary route opened or closing, which select flight path effectively, and optimize the route network in order to save cost.

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