Pre-flight rerouting combining A* algorithm and AHP under severe weather

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Abstract. Delays due to bad weather have become common in recent years. When the delay occurs, in most cases, flights will choose ground-holding which results in the waste of airspace resources and reduces the operating efficiency of the entire air route network. In order to deepen the reform of the ATC operations, local rerouting strategy before flight is imperative. In this paper, based on the influence degree and scope of severe weather, historical meteorological data and flight plan data, the damage situation of the air route is comprehensively analyzed, and the segment that pilots need to avoid in route selection is defined. Taking the priority of different city pairs into consideration, the OD pair allocation order model based on AHP (analytic hierarchy process) was established. In addition, this paper establishes the evaluation index of navigation modification combined with the actual operation, and makes a comparative analysis with an example.

1. Introduction
Developed countries such as Europe and the United States have already begun to study how to arrange safe, orderly and efficient flights under the influence of severe weather, and put forward rerouting strategies. According to the difference of implementation time, relevant literatures are classified into pre-flight route change planning and real-time route change planning. About the rerouting before flight: in 1993, Dixon and Weidner established the navigation modification strategy under the grid navigation modification environment [1]. Sarah Stock Patterson established a relatively perfect mathematical model for static navigation strategy, and used Lagrange relaxation algorithm to solve the model [2]. In 1999, Krozel considered reducing the workload of pilots and ATC controllers, and increased the limit on the number of turning points [3]. Sridhar and Chatterji proposed a rerouting planning method based on polygon[4]. In 2018, Mayara Condeet al. studied the cooperative rerouting strategy in ATFM and proposed a route and airspace time slot resource allocation scheme, which minimized the disutility cost of flight delay and rerouting by airline operators [5]. About real-time route change planning: In 2008, Kees van Balen and Cees Bil[6], based on the previous studies, constructed the free flight reraneling software under the circumstance of partial airspace closure and verified the feasibility.

In 2009, Mark Hansen[7] studied the characteristics of route change and established a static ground waiting and dynamic route change model, in which the priority of flights was added into the model, and CPLEX9.1 was employed to solve the problem on SunfireV250. The model is suitable for flights with short flight times or when weather conditions are relatively stable. In 2017, Zhang and Mahadeva[8] studied a method based on simulation to optimize aircraft rerouting process by considering multiple uncertain sources.
Motivated by the analysis above, this paper puts forward the local pre-flight rerouting strategy combining A* algorithm and AHP. This method divides the complex rerouting problem into several sub-problems.

2. Rerouting problem description

For flight safety, rerouting in the event of a thunderstorm is necessary to bypass weather-affected areas. It is assumed that all levels are disabled in the weather-affected area. The area is represented by a flat, two-dimensional polygon, and no aircraft is allowed to fly through it. The fixed route of a flight is composed of airway points. It is assumed that the fixed route of a flight is $F$ and the airway point is $f_1, f_2, \ldots, f_N$.

The rectangular coordinate system as shown in the figure is established for these flights that need to be diverted, where the magnetic north is in the positive direction of $y$ axis and the magnetic north is 90 degrees east of $x$ axis. Assuming that each vertex of the polygon in the flight limit area is $p_i(x_i, y_i), i = 1, 2, \ldots, n$, the specific method to determine the rerouting point is described below:

![Figure 1 Diagram of rerouting model under adverse weather conditions](image)

**Step1:** For the affected flights, first determine the flight segment within the flight restriction zone. The initial influence point is the point where it intersects with the flight limit area at first along the route direction, $p_i(x_i, y_i), i = 1, 2, \ldots, n$; similarly, the final influence point is the point where it intersects with the flight limit area at last along the route direction, $q_i(x_i, y_i)$.

**Step2:** Determine the starting and ending points of rerouting flight segment. The airway points with the shortest selection distance to $q_i$ and not within the range affected by severe weather are defined as $q_i \cdot q_i = f_i$.

**Step3:** Determine the middle point of the rerouted section, and use A* algorithm to search the shortest path from the starting point and the ending point respectively to ensure that the rerouting part does not cross the FCA. What needs to be explained here is that the figure shows only some routes affected by severe weather, and some routes not affected will not be rerouted. This paper studies local rerouting affected by severe weather before flight.

3. Establishing the mathematical model

3.1 the mathematical model

$$\min D = \sum r \sum s \sum c^{rs}_k \quad (1)$$
Traffic volume conservation (2)

Non-negative flow condition (3)

Number of paths, $B=2$ (4)

Capacity constraint (5)

Node flow balance (6)

3.2 OD priority research

3.2.1 Possible Influencing factors
Various factors will affect the importance of OD pairs, such as OD volumes, affected segment number under serious weather, the following segment number, etc.

3.2.2 OD priority research
OD priority means the sequence of allocating traffic volumes. To make it specific, OD pair with more traffic volumes should have the priority to be rerouted. Three factors are considered, OD volumes, the following segment numbers and affected segment numbers. The flight data comes from August 2, 2016 and the meteorological information comes from 8:42 at that day. According to the vulnerable segment searching method mentioned, we can find the affected OD pair and the corresponding affected segments.

With the data mentioned above, AHP (Analytic hierarchy process) is applied into OD priority research. In this part, we put forward an alternative OD ordering method using AHP. The hierarchical model for OD priority is as follows.

| $r$ | All the starting points involved in an OD pair |
|---|---|
| $s$ | All the ending points involved in an OD pair |
| $x_a$ | The flow on segment $a$ |
| $d_a$ | The distance of segment $a$ |
| $f_{rs}^k$ | Traffic volume on $k$th path between OD pair $(r-s)$ |
| $\delta_{a,k}^{rs}$ | Represents the relationship between segments and paths, 0-1 variable |
| $W_{rs}$ | Set of all paths between OD pair $(r-s)$ |
| $C_{k}^{rs}$ | The distance of $k$th path between OD pair $(r-s)$ |
| $q_{rs}$ | Traffic demand between OD pairs $(r-s)$ extracted from the flight plan |
| $i$ | Airway point $i \in U$, $U$ represent set of all nodes |
| $\beta_i^a$ | Represents the relationship between nodes and flight segments, 0-1 variable |
As is shown in Figure 2, we have three levels of the hierarchical model for OD priority, the goal is to determine the sequence of OD pairs, the criteria level includes three factors mentioned and the alternative level are the OD pairs we should reroute.

### Table 1 Part of OD and 3 factors’ grades

| Departure | Arrival | OD volumes | The following segment | Affected segment | Grade 1 | Grade 2 | Grade 3 | Total grade |
|-----------|---------|------------|-----------------------|-----------------|---------|--------|--------|-------------|
| ZBAA      | ZSSS    | 40         | 54                    | 6               | 9       | 5      | 8      | 7.8519      |
| ZBAA      | ZSHC    | 24         | 43                    | 5               | 6       | 4      | 8      | 5.6912      |
| ZSSS      | ZGSZ    | 29         | 16                    | 2               | 7       | 1      | 9      | 5.6492      |
| ZBAA      | ZGGG    | 23         | 29                    | 4               | 6       | 3      | 9      | 5.5368      |
| ZBAA      | ZGSZ    | 24         | 29                    | 6               | 6       | 3      | 8      | 5.4307      |
| ZUCK      | ZBAA    | 23         | 16                    | 2               | 6       | 1      | 9      | 5.0158      |
| ZSSS      | ZGGG    | 23         | 10                    | 2               | 6       | 1      | 9      | 5.0158      |
| ZSSS      | ZSAM    | 20         | 34                    | 2               | 5       | 3      | 9      | 4.9034      |
| ZBAA      | VHHH    | 14         | 29                    | 6               | 4       | 3      | 8      | 4.1639      |
| ZBAA      | ZSPD    | 12         | 54                    | 6               | 3       | 5      | 8      | 4.0515      |
| ZBAA      | ZGHA    | 14         | 18                    | 4               | 4       | 2      | 9      | 4.0095      |
| ZSPD      | LEMD    | 1          | 116                   | 7               | 1       | 9      | 8      | 3.8267      |

According to the procedure of AHP, after constructing a judgment matrix and hierarchical single ordering and consistency checking, the data of three factors and the corresponding grades of three grades are listed. Considering the weight of three factors, each OD pair has a final score. The larger is the value, the higher is the priority of this OD.

#### 3.3 Rerouting based on A* algorithm

##### 3.3.1 Improved A Star Algorithm

In solving the problem of known starting and ending nodes and multiple target nodes, the improved A* algorithm takes A* algorithm as the basis, retains its original path-finding idea and increases the function of handling the traffic flow of air route nodes.

Due to the constant change of node capacity, when considering the connectivity between two points, it is necessary to judge according to the residual capacity of the node. Only when the residual capacity of the node is not zero, can the path pass through.
When the flight passes through the node, the remaining capacity of the node decreases by 1. In this way, capacity is regarded as a shared resource. After a flight decides the route, the capacity of certain nodes will be changed, thus affecting subsequent flights.

3.3.2 Searching process based on OD priority
- Select the affected OD pairs at the peak period for a test
- For the affected flights, we keep the departure point and the arrival points the same, start searching from the affected node.
- At first, find 2 nearest points outside the affected part fore and aft ends, keep finding the shortest path from both sides using A-star algorithm.
- When finding the departure point or the arrival point, the single-direction searching is over. When the departure point and the arrival point are both found, the searching is over.

4. Case Studies
The rerouting strategy in this study refers to the static local rerouting before flight. Our purpose is to make a prearranged plan before departure. The approach we are going to take is a combination of polygonal rerouting (to identify the affected sections) and rerouting based on existing route points (to find available routes on some other sections affected by severe weather).

4.1 Data collection
(1) Flight data
This study is based on the meteorological radar data and flight plan data from June to August in 2016. The data involved in the rerouting model include meteorological radar data, FPL (Flight Plan) data, traffic capacity data, thunderstorm statistics data, etc. Among them, we extracted FPL data on August 2, 2016. The information includes flight number, latitude and longitude, departure and landing airport, route, etc.

(2) Meteorological radar data
We get the reflectivity data based on the Doppler meteorological radar in the captured aviation weather data. Radar reflectivity is used to represent the intensity of a meteorological target. According to U.S. meteorological service center radar echo and dangerous weather grade\(^7\)\(^8\), the location of whose reflectivity data is more than 41 DBZ will be considered as a dangerous unit. Thus, we extract the affected flight and the corresponding vulnerable segments.

We collect the flight data on August 2, 2016 and sort the OD volumes according to different time. The overall distribution of the number of flights in a day increases first and then decreases. The flights are mainly focused on 9 AM-9 PM. Therefore, we take that period as the peak period for testing.

(3) Capacity data
According to the research of air route network node capacity\(^9\), based on different configurations, we figure out the capacity value of each node.

4.2 Discussions of Results
Safety, economy and the difference between route and flight plan are the basic factors to evaluate a route. In this paper, the rerouting results that does not cross the region affected by thunderstorm are regarded as meeting the requirements of safety. Combined with the common evaluation indexes of air route network and the requirements of actual operation, this section evaluates the rerouting results through the following indexes: non-linear coefficient, increased distance, increased time and operation cost.

(1) Non-linear coefficient
Non-linear coefficient is an important indicator in road network layout planning. The non-linear coefficient between two nodes of the network is defined as the ratio of the actual distance between the two nodes to the straight line distance between two points.
\[ R_{ij} = \frac{L_{ij}}{D_{ij}} \]  

(7)

\( D_{ij} \) is the straight line distance between OD-pair \( i \) and \( j \)

\( L_{ij} \) is the actual distance between OD-pair \( i \) and \( j \)

(2) Increased distance

The difference between the total length of the rerouting route and the total length of the original route is the increased distance.

\[ l_{ij} = D_{ij} - d_{ij} \]  

(8)

\( D_{ij} \) is the length of the rerouting route between OD-pair \( i \) and \( j \)

\( d_{ij} \) is the length of the original route between OD-pair \( i \) and \( j \)

(3) Increased time

Increased time reflects the delay cost. Assuming that the average flight speed is 800km/h, and the increased time is the ratio of increased distance to average speed.

\[ T_{ij} = \frac{l_{ij}}{800} \]  

(9)

\( l_{ij} \) is the increased distance after rerouting between OD-pair \( i \) and \( j \)

(4) Operation cost

The cost reflects the total flight mileage of rerouting route. Under the premise that ignores differences of aircraft types, operation cost can be expressed through total mileage.

\[ TOC = \sum_{i=1}^{n} f_i a_i \]  

(10)

\( a_i \) is the length of segment \( i \)

\( f_i \) is the traffic flow on segment \( i \)

| Non-linear coefficient of rerouting routes | Increased distance (km) | Increased time (min) | Operation cost (km·times) |
|-------------------------------------------|--------------------------|----------------------|---------------------------|
| AHP                                       | 1.18                     | 99.67                | 7.48                      | 855282                    |

Table 2 Weight priority data with AHP data

5. Conclusion

In this paper, through the polygonal region division of the impact range of severe weather, the static local rerouting under the condition of partial ARN damage is discussed, and the pre-flight local rerouting model is presented combining the Wardrop principle and the air traffic control program and aircraft performance are considered.

In addition, this paper defines the concept of OD priority, which can meet the requirements of different cities. The effectiveness and practicability of the local rerouting method combined with the analytic hierarchy process proposed are analyzed by examples. Meanwhile, relevant evaluation indexes are proposed based on the requirements of practical operation.

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