An Air Network Risk Control Method Based on Airport Location and Throughput*

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Abstract. An aviation network risk control measure considering airport location and throughput is proposed to reduce the risk loss. Firstly, the relationship between cost input and risk residual rate is determined, and then the importance of airport node is determined by combining kernel degree and importance evaluation matrix. Then, based on the linear programming method, the minimum residual risk loss is used as the objective function to obtain the residual risk loss minimization deployment scheme, and the minimum control cost is taken as the objective function by controlling the cost minimization operation. Comparative experiments show that ALTRCM method has great advantages in risk control efficiency and cost control.

Keywords: risk residual rate, aviation network, safety risk control, linear programming, control costs.

1. Introduction

With the rapid development of the world economy and aviation industry, the aviation network has become busy and irreplaceable. At the same time, the aviation industry is becoming more and more information, aviation information system has become the key infrastructure of the country, aviation network is closely related to the development of national politics, economy, science and technology, so the risk control of aviation network is particularly important, which is not only related to safe flight, cargo transportation, but also threatens national security and social stability.

In recent years, the challenges of aviation network are also increasing, and the internal and external risks seriously affect the stable operation of aviation network system. Therefore, the aviation network risk control work is paid more and more attention. Aviation network is a typical complex network, which is not only the carrier of aviation information, but also the guarantee of aviation business. At present, the academic circles have carried out more in-depth research on the ability of anti-destruction and risk control of aviation networks.

After 2000, many scholars have proved that the world aviation network conforms to the characteristic of small world network model [1,2]. Cascade failure models were proposed in 2002 to study the propagation and diffusion process failure in networks [3]. Then, Crucitti and so on further consider the influence of dynamic update of transmission efficiency between nodes on failure model, put forward CLM model, and solve the importance evaluation of nodes when transmission efficiency changes [4]. By studying 20 Chinese airlines in 2011, Gergana et al proved that dynamic traffic on the route has a
greater impact on network survivability [5]. A network vulnerability assessment method based on network efficiency is proposed by Lordan et al in 2014, and a reverse adaptive strategy is constructed to sort nodes and predict the network impact range [6]. By comparing the European airspace network model, the joint airport network and route network with the existing airspace division, the Gerald Gurtner and others put forward corresponding suggestions on the European airspace planning in 2014[7]. In the same year, Lordan et al. proposed a critical airport identification method for the global air transport network (ATN) based betweenness-centricity [8].

From 2010 to 2014, Dang Yaru and others made a series of studies on various aviation networks, analyzed the hierarchical structure and characteristics of aviation networks, and made in-depth analysis on the invulnerability of flight flow networks from different aspects [9-13]. A heuristic particle swarm optimization algorithm based on meso-guided is proposed in 2011 to optimize the route intersection layout (CWLP) to maximize flight efficiency under the condition of airspace congestion, and to construct a multi-objective optimization model composed of total route cost and meso standard deviation. The non-persistent solution set of route convergence point layout problem is obtained [14]. In 2012, Ren Xinhui and others used the analysis method of social network to evaluate the degree centrality, proximity centrality and intermediary centrality of each airport in the aviation network. A new study on the importance of nodes in the network was carried out to evaluate the impact of airport node failure on network connectivity directly and indirectly [15]. In 2013, Xu Weiju and others analyzed the cascaded failure invulnerability of U.S. airport network and compared the cascaded failure processes of small world and scale-free network [16]. In 2015, based on the complex network theory, Du studied the delay propagation process of the city under the three network configurations of route network, hub route network and line route network, and explored the influence of topology on the stability of route network [17]. Kang Jinxia and others analyzed the network characteristics of the route network in 2014, simulated the failure of single and multi-route points, and simulated the distribution of traffic to nearby nodes and nodes with large values when the nodes failed. The characteristic parameters in these cases were compared with the parameters before the failure to evaluate the survivability of the route network. Finally, the dynamics process of the aircraft during the failure of the route point was studied by using the cellular automata model. Article [18,19] from the actual situation of the route, compared with the airport as the node of the aviation network closer to the real operation. In 2016, Peng Ting and others divided China's domestic aviation network into trunk and branch networks to evaluate the value of risk control in the event of external interference by introducing punishment factors [20]. In 2017, Sun Mengdan combined data mining and complex network theory to analyze China's aviation network from the aspects of basic structure, cluster analysis and risk control [21]. In 2017, Wu Xiping and others established the air traffic delay propagation model based on the load-capacity cascade failure model to analyze the impact of risk control on delay [22]. Zhang Yuxiang and others constructed the weighted network and put forward the multi-index evaluation method of aviation network risk control. At the same time, from the network throughput, the transportation reliability measurement of the network is given. Based on the connection between nodes, a measure of accessibility is proposed to accurately reflect the network connection; In the case of segment failure, a flow redistribution optimization model considering route cost and node cost is proposed [23-25]. In 2018, Jiang Yisen studied the risk control strategy of route network based on the centrality and central potential of route network [26]. Gao Jingdong et al put forward the concept of sector network in 2018, and studied the structural characteristics, static invulnerability, cascade failure and its optimization strategy of sector network in central and southern regions [27-28]. In 2020, Shao Jiajia and others analyzed the robustness of the route network of the three major aviation alliances, and pointed out that the alliance network has strong robustness under random attack, while the robustness of the alliance network under deliberate attack is weak. It provides a theoretical basis for the study of route network optimization design [29].

The research of aviation network risk control in the existing literature mainly focuses on the influence of node failure on the whole network in the fixed network structure, and lacks the pre-judgment of risk. In addition, in the aviation network, in addition to the innate importance of these hub nodes, the volume of business also reflects the importance of airports, routes, key equipment and so on in the network,
which must be considered. Because there are more dynamic factors in aviation network system, it is necessary to consider the feasibility and relevance of control measures more and reduce the cost of risk control.

In view of the above problems, an aviation network risk control method based on airport location and throughput is proposed (ALTRCM), deploy risk control measures to the most appropriate location according to the airport location and throughput of the aviation network.

2. Risk Quantification
Aviation network is a typical complex network, the risks are diverse, risk control measures are also multifaceted, generally mainly including personnel, equipment and management. In order to effectively realize the deployment of risk control measures, it is necessary to define the relevant parameters and analyze the relevant measures.

2.1. Parameter Definitions
The aviation network is abstracted into a complex network composed of \( N \) nodes (airports) and \( L \) edges (routes), in which the risk control measures that can be taken by the aviation network are combined into a set of \( K \), and the deployment cost of the risk control measures is defined as parameter \( \theta \).

Before the risk control measures are deployed, it is necessary to determine the effectiveness of the risk control measures, that is, how much the risk control measures have an impact on the security of the aviation network. Therefore, the parameter \( \beta_{nk} \) \( n \in N, k \in K \) is defined in the risk quantification phase, representing the risk residual rate of the node after node \( n \) deploys the risk control measure \( k \).

Its formal definition is:

\[
\beta_{nk} = \begin{cases} 
\left(1 - \frac{\theta_{nk}}{\max \theta_{nk}} \right)^{a_{i}} & \text{node } n \text{ deployed risk control measure } k \\
1 & \text{else}
\end{cases}
\]

(1)

In practice, with the increase of deployment risk control measures, the effect of each unit measure on the residual rate of node risk will continue to decrease, so the function model is used in this expression. Among them, \( \theta_{nk} \) is the cost of risk control measure \( k \) deployed at node \( n \) and \( \max \theta_{nk} \) is the cost of risk control measure \( k \) required to achieve the highest level of security at node \( n \). \( a_{i} \) is the power index corresponding to risk control measure \( k \); The power index of different measures is different.

Through statistical analysis and expert consultation, three kinds of risk control measures of personnel, equipment and management are fitted with curve of risk residual rate of node, the parameters are obtained \( a_{1} =2.1, a_{2}=2.5, a_{3} =1.8 \).

It is assumed that the failure of a certain risk control measure will cause the expected loss to the aviation network system, because the importance of the airport in the aviation network is different, so in the case of the same risk value, The more important nodes cause the greater the expected loss, setting node importance parameter \( V_{n} \), the expected risk loss of the node is:

\[
F_{nk} = V_{n} \phi_{nk}, \phi_{nk} = \omega_{k} V_{n}
\]

(2)

Among them, \( \phi_{nk} \) is the influence degree of risk control measure \( k \) after no-deployment or failure, \( \omega_{k} \) is the probability of failure of risk control measure \( k \) and \( \phi_{nk} \) is the probability of failure of risk control measure \( k \) at node \( n \).
2.2. Parameter Initialization

2.2.1. Node initialization. The nodes are randomly distributed in rectangular coordinates in a certain range, and the weights of the connection \( L_v \ (i, j \in N) \) between any two nodes are set to represent the route traffic in the actual aviation network. The sum of all traffic connected to the node is the throughput of the node.

2.2.2. Expected security risk initialization. In the deployment of actual aviation network security risk measures, the influence range of security risk is determined according to the security logs and statistical reports.

The risk of nodes in the network not only directly causes their own losses, but also has a radiation effect on their adjacent nodes, which is determined by network connectivity. In addition, the risk loss caused by different importance of nodes is different, so it is necessary to evaluate the importance of network nodes.

2.2.3. Node Importance Assessment Initialization. The importance of airport nodes determines the impact on aviation networks, so it is necessary to determine the importance of nodes. The methods of node importance determination are mainly based on degree, meso, centrality and so on. It is not difficult to find that the importance of airport nodes is mainly determined by airport location and throughput, so in this paper, an important degree evaluation matrix composed of node kernel degree and throughput is proposed:

\[
H_e = \begin{bmatrix}
C_{T_1} & C_{T_2} \delta_1 T_2 & \cdots & C_{T_n} \delta_n T_n \\
C_{T_1} \delta_1 T_1 & C_{T_2} \delta_2 T_2 & \cdots & C_{T_n} \delta_n T_n \\
\vdots & \vdots & \ddots & \vdots \\
C_{T_1} \delta_1 T_1 & C_{T_2} \delta_2 T_2 & \cdots & C_{T_n} \delta_n T_n
\end{bmatrix}
\]  

(3)

In the formula: \( C_i \) is the kernel degree of node \( n \) (delete all nodes and edges with a connectivity of 1 in the graph, if there are still nodes with a degree of 1 in the remaining nodes, continue to delete, and put these deleted nodes into the kernel with a kernel layer of 1, that is, the kernel degree of these nodes is 1); \( \delta_e \) indicates whether there is a route between i, j airport nodes, Being 1, does not exist as 0. \( \gamma_e \) is the ratio of node \( i \) to neighbor node output importance, \( \gamma_e = \frac{R_i}{\sum R_e} \), Where \( R_i \) is the degree of node \( i \). \( T_i \) is the throughput of node \( i \), \( T_i = \sum \gamma_j \), where \( \gamma_j \) is the flow from adjacent node \( j \) to node \( i \) (this flow is undirected weight because the airport node has the same function during flight departure or landing).

According to the importance evaluation matrix, the importance of node \( i \) can be expressed as

\[
v_i = \sum_{j=1,j\neq i}^{\delta_e} C_i \delta_e T_e \gamma_j
\]  

(4)

After standardization

\[
V_i = \frac{v_i}{\sum_{i=1}^{N} v_i}
\]  

(5)
Obviously \( V_i \) is the weighted kernel centrality of node \( i \), which well reflects the importance of node \( i \) in the network. The importance evaluation matrix fully considers the location and throughput of airport nodes, and comprehensively and accurately expresses the importance of airport nodes.

2.2.4. Cost control initialization. Cost control is the basic requirement for the healthy development of modern aviation industry, and the deployment of risk control measures also has cost limitation, that is \( \sum \sum \theta_{nk} \leq M \) is the risk control cost ceiling, the cost of risk control is mainly composed of manpower expenditure, management cost, equipment consumption and processing delay in actual management.

2.2.5. Residual risk loss initialization. Residual risk loss refers to the risk loss that still exists in the node after the deployment of risk control measures. It is mainly determined by the expected loss of risk and the residual rate of risk.

Residual risk loss:

\[
f_{sk} = F_{sk} \cdot \beta_{sk} = V_n^2 \phi_k \omega_k \beta_{sk}, \quad n \in N, k \in K
\]

As safety risk control measures do not fully avoid losses, there are: \( 0 \leq f_{sk} \leq F_{sk} \)

Deploying risk control measures \( k \) in a network of nodes \( N \), the total residual risk loss of the network is:

\[
f = \sum_{n=1}^{N} \sum_{k=1}^{K} f_{sk} = \sum_{n=1}^{N} \sum_{k=1}^{K} V_n^2 \phi_k \omega_k (1 - \frac{\theta_{sk}}{\max \theta_{nk}})^{\omega_k}
\]

3. Risk Control

The main goal of risk control is to deploy the most reasonable risk control measures under the limitation of control cost to realize residual risk loss and control cost minimization.

3.1. Minimize Residual Risk Loss

The minimum residual risk loss is the limiting condition to minimize the control cost, assuming that it is expressed in \( \mu \), then

\[
\mu = \min f = \min \left[ \sum_{n=1}^{N} \sum_{k=1}^{K} V_n^2 \phi_k \omega_k (1 - \frac{\theta_{sk}}{\max \theta_{nk}})^{\omega_k} \right]
\]

\[
\text{s.t.} \quad \omega_k \in [0,1]
\]

\[
\sum_{n,k} \theta_{nk} \leq M
\]

Under the constraints of (9-10), the deployment scheme which minimizes the residual risk loss and the corresponding residual risk loss \( \mu \) can be obtained after many cyclic planning operations.

3.2. Minimization of Control Costs

The cost of risk control is determined by the location of nodes, different node deployment costs are
different, and the implementation effect may be different. Therefore, it is necessary to determine the deployment scheme of risk measures with minimum control cost under the limit of minimum residual risk loss. Define objective functions:

\[
\min \sum_{n \in N} \sum_{c \in C} \theta_{nc}
\]  

(11)

According to the risk quantification process and previous analysis, there is still the limitation of formula (11) in the process of controlling cost minimization. At the same time, the residual risk loss should not exceed the minimum residual risk loss \( \mu \), so there are constraints:

\[
\sum_{n \in N} \sum_{c \in C} \nu_{a} \phi \omega (1 - \frac{\theta_{nk}}{\max \theta_{nk}})^{\gamma_{n}} \leq \mu
\]

(12)

Under the above constraints, the optimal deployment scheme can be obtained after many cyclic programming operations.

4. Experimental Analysis

4.1. Experimental Programme
In order to verify the effectiveness of this method, the experimental scheme is designed as follows:

1) Refer to the aviation network system, use the MATLAB to set the network topology and network parameters, and build the virtual aviation network as shown in figure 1.

[Diagram of an aviation network]

Fig 1. Aviation network diagram

Among them, the letters in the node represent the name of the airport, the numbers on the line represent the route flow, the sum of all route traffic connected to the node represents airport throughput.

2) In order to simplify the process, it is assumed that the system faces only one risk, that is, only one risk control measure (personnel, \( a_{1} = 2.1 \)) needs to be deployed, the total cost is 5000, and the maximum deployment cost of the node to the risk control measure is shown in Table I.

3) The risk control measure deployment scheme in ALTRCM method is realized by LINGO software.

4) The simulation attack scheme is used to attack the ALTRCM, ARCM (average risk control method) and HRCM (heuristic risk control method) methods to verify the control effect of the ALTRCM method

4.2. ARCM and HRCM
ARCM method ignores the difference of nodes in the deployment of risk control measures and distributes the risk control measures equally under the overall cost constraint. This method is an easy method to implement. HRCM method is to iteratively select the deployment location. When deploying a risk control measure beyond the cost limit, try another risk control until all measures are tried.

4.3. Comparison of Risk Control Effects

The optimization results of risk control measures deployment of each node are shown in Table I. As can be seen from Table I, nodes c, f, g, i are the main key nodes, and they assign relatively more control measures; nodes h, j with the same kernel centrality, node h with higher throughput obtain more risk control measures; nodes b, d with the same throughput, node d with greater kernel centrality deploy more control measures.

In order to compare the effect of the three methods in safety risk control, the influence degree of the risk is $\varphi = 100$. First, the residual risk loss $f$ after the deployment of the risk control measure is calculated, the larger the value reflects the worse the risk control effect, and then the control cost $\theta$ is calculated when the same residual risk loss is calculated, the larger the value means the worse the cost control under the same residual risk tolerance.

To facilitate the observation of the performance of the three methods, the residual risk loss $f$ and cost $\theta$ calculated by the ALTRCM method are set as reference value 1 respectively. If the value of $f$ after calculation is greater than 1, it means that the risk control effect is worse than the ALTRCM method; if the value of $\theta$ after calculation is greater than 1, it means that the cost control is worse than the ALTRCM method. The experimental results are shown in Table II.

| $n$ | max $\theta_n$ | $v_n$ | $V_n$ | $\theta_n$ |
|-----|----------------|-------|-------|------------|
| a   | 2              | 0.417 | 0.004 | 0.37       |
| b   | 144            | 3.75  | 0.038 | 48.7       |
| c   | 3063           | 17.125| 0.175 | 1030.41    |
| d   | 706            | 8.25  | 0.084 | 237.33     |
| e   | 144            | 3.75  | 0.038 | 48.7       |
| f   | 3960           | 19.5  | 0.199 | 1332.6     |
| g   | 3497           | 18.375| 0.187 | 1176.7     |
| h   | 980            | 9.75  | 0.099 | 329.83     |
| i   | 2310           | 14.875| 0.152 | 777.57     |
| j   | 53             | 2.25  | 0.023 | 17.77      |

| methodology | $f$ | $\theta$ |
|-------------|-----|----------|
| ALTRCM      | 1   | 1        |
| ARCM        | 1.268 | 1.56    |
| HRCM        | 1.034 | 2.058    |

Experimental results show that ALTRCM have obvious advantages in both risk control effect and cost control. Because ARCM ignores the different importance of nodes and the different probability of risk occurrence, it causes the waste of control cost, which makes the control effect and control cost not ideal. HRCM ignores cost control while paying attention to control effect. Once the deployment implementation process exceeds the upper limit of control cost, it will become difficult to determine effective risk control measures. Therefore, although the control effect can be close to or even exceed
ALTRCM in some cases, the overall performance is not as good as ALTRCM because of its instability, and very poor performance in cost control.

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