Research on the Robustness of Domestic Airline Route Network under Perspective of Complex Network

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Abstract. In order to comprehensively improve the operation and management level of domestic routes of air transport enterprises, this paper studies the domestic routes of air transport enterprises from the perspective of complex networks. Firstly, the domestic route network model of the air transport enterprises is constructed based on the national flight running time. Secondly, the complexity of the airline route network is tested according to the statistical analysis of the small world network model. Thirdly, the robustness of the complex network is studied from the perspectives of random attack and deliberate attack. Finally, based on the research results, the methods and strategies for optimizing the domestic airline route network are proposed.

1. Introduction

With the rapid development of China's economy, China's air transport industry is facing a good opportunities for development. As one of the direct participants in air transport, air transport enterprises will embrace huge development opportunities. The route is an important resource for air transport enterprises to carry out operations and production. By 2019, the number of domestic routes in China has reached more than 4,000, becoming an important source for air transport enterprises to improve market competitiveness. Especially in recent years, the number of domestic flights has been increasing and second-line and even some third-tier cities have experienced frequent shortages of routes due to limited airspace resources. The continuous expansion of the transportation scale of the aviation industry will inevitably make the route network more and denser and complex, and the impact on the air transportation will also increase. The construction and management of the airline route network has become an important part of China's realization of a major civil aviation country to the civil aviation power.

Therefore, studying the robustness of the domestic airline route network structure is of great theoretical and practical significance for comprehensively improving the operational management level of airline routes, reducing the impact of typhoons, military exercises and other events on the airline route network, and improving the operational efficiency of the airline route network. By consulting the literature, most scholars at home and abroad have analyzed and studied the airline route network from the perspective of route points. From the perspective of air transport enterprises, there is not much research on the robustness of domestic route networks. This paper will carry out systematic research from the perspective of the robustness of the air transport enterprise airline route network.
2. Construction and characteristics analysis of airline route network model for domestic air transport enterprises

2.1. Construction of the airline route network model

The construction of the airline route network model can be considered from different perspectives, for example, it can be considered from the layout of the regulatory unit and can be considered from the layout of the airport. This paper takes the city where the airline is navigating as the network node, abstracts the relationship between the two cities as the connecting edge, and uses the Interpretive Structural Model Method (ISM) to establish the domestic air transport enterprise airline route network model diagram \( G = (S, P) \), where \( S \) represents the domestic navigable city set \( S = \{ S_1, S_2, \ldots, S_n \} \), and \( P \) represents the relationship between the city pairs as a set of network diagram edges. The element \( a_{ij} \) of the adjacency matrix \( A \) is:

\[
a_{ij} = \begin{cases} 1, & \text{If there is navigation between two nodes} \\ 0, & \text{No navigation between two nodes} \end{cases}
\]

If the navigation between the two cities is set to the edge, the airline route network structure can be divided into a directed graph and an undirected graph. In order to simplify the research process, when there are round-trip flights between the two cities, an undirected graph is adopted, which is also applies to the complete airline route network structure research. According to the above rules, the model of domestic air transport enterprise airline route network is constructed, as shown in Figure 1. The airline route network model graph is similar to the developed degree of China's air transport, showing the characteristics of dense airline route network in the central and eastern and sparse airline route network in the west.

![Figure 1. Model diagram of domestic air transport enterprise airline route network](image)

2.2. Analysis of airline network model characteristics

The airline route network model is an abstract description of a complex system, a network with characteristics such as self-organization, self-similarity, and small world [1]. The domestic air transport enterprise airline route network model is established by abstracting the city of each airport connecting the route into a network node. The domestic air transport enterprise airline route network has the typical characteristics of a complex network, but whether it can be identified as a complex network needs to be further confirmed. The following paper uses the commonly used function distribution test method of complex network test to further verify.

According to the statistical analysis of the small world network model, the clustering coefficients of the WS small world network and the clustering coefficients of the NW small world network are shown in Equations 1 and 2, respectively. The formula for the average path length \( L(p) \) of the WS small world model is 3. When the network clustering coefficient \( C(p)>0.1 \) and the average path length \( L(p)<10 \), it is possible to determine that the network is a small world network.
\[ C(p) = \frac{3(k-2)}{4(k-1)} (1-p)^3 \tag{1} \]

\[ C(p) = \frac{3(k-2)}{4(k-1)+4kp(p+2)} \tag{2} \]

Where

\[ L(p) = \frac{2N}{K} f \left( \frac{Nkp}{2} \right) \]

\[ f(u) = \begin{cases} \text{constant, } u \ll 1 \\ (nu)/u, \ u \gg 1 \end{cases} \]

By calculation, the domestic air transport enterprise airline route network \( L(p)=2.813, C(p)=0.518 \), so it can be considered that the domestic air transport enterprise airline route network has a small world feature, which is a typical small world network.

3. Robustness analysis of the airline route network of domestic air transport enterprises

3.1. The airline network robustness measurement index

When the node on the airline route network (the city where the airport is located) or the edge is attacked (typhoon and other extreme bad weather, navigation equipment failure, etc.), the entire airline route network structure will change, affecting the normal operation of other nodes, and thus leading to the operation capacity of the entire airline route network. The robustness of the airline route network refers to the ability level of the airline route network to maintain normal operation or restore the original state when a typhoon or the like affects the normal operation of the flight. Referring to domestic and foreign research, this paper adopts network efficiency as the index to measure the robustness of the network. Network efficiency can measure the impact of changes in airline route network structure on the shortest path length between any two nodes [2], which can reflect the effective degree of network traffic, and its changes can also reflect the abilities in resistance against strike of the network, denoted by:

\[ E = \frac{1}{N(N-1)} \sum dij, \ dij = \begin{cases} 0 & (i \neq j) \\ 1 & \end{cases} \tag{3} \]

Where, when \( dij=1 \), it means that there is a airline route connection between node i and node j; when \( dij=0 \), it means that there is no airline route connection between node i and node j, and N is the total number of nodes. When \( E=1 \), it means that there are airline routes connecting any two nodes in the airline route network. When \( E=0 \), all nodes in the airline route network are isolated nodes.

3.2. Calculation method

Random attack: Each attack randomly removes a certain number of network nodes, and each attack will form a new network. The invulnerability measure is used to measure the network invulnerability after the attack. After multiple consecutive attacks, the number of de-point and the value of the invulnerability measure are mapped one by one, and the graph of the change of the measured index with the number of points to be removed is generated to observe the changing rule of the invulnerability of airline route network under random attack conditions.

Deliberate attack: Sorting according to the degree value or point weight size of network nodes, priority attack the node with large degree value or point weight, after each attack will form a new network, and calculates the invulnerability measure index of the newly formed network. After multiple consecutive attacks, the number of de-point and the value of the invulnerability measure are mapped one by one, and the graph of the change of the measured index with the number of points to be removed is generated to observe the changing rule of the invulnerability of airline route network under deliberate attack condition.
3.3. Analysis of calculation results

Compare the impact of three different attack modes on the invulnerability of airline route networks, and network efficiency is used as a measure index [3].

As shown in Figure 2, in order to simulate the impact of military activities or weather conditions on network connectivity performance, through three means of attack (based degree-priority de-point attacks, based node-traffic de-point attacks, and random de-point attacks) to test of air transport enterprises domestic airline route network and use network efficiency as a measure of damage resistance. As can be seen from the figure, no matter which attack method makes the network efficiency show a downward trend. Among them, the random de-point attack has a relatively small impact on network efficiency, and the overall decline trend is relatively flat. When the number of removed nodes reaches a certain number, the network efficiency drops to zero and the network is in a state of paralysis. The attack method based on the degree value priority and the attack method based on the point-weighted priority has a great impact on the network. Both of them make the network efficiency decline trend and the decline trend shows obvious consistency. When the number of removed nodes reaches 200 or so, both attacks cause the network to be in a state of paralysis.

![Figure 2. Efficiency changes of the airline route network under different attack conditions](image)

The pursuit of high-profit economic benefits is the driving force for the development of air transport enterprises, and to achieve this goal, air transport enterprises must build an airline route network with strong invulnerability, so as to improve their operational efficiency under special operating conditions. The two major factors affecting the economic benefits of air transport enterprises are flight volume and flight normality [4]. Based on these two factors, according to the results of the above calculations, the overall difference of the impact of the attack mode based on degree value priority and point weight priority on invulnerability of air transport enterprise airline route network is small.

Therefore, in the case of limited transportation resources such as air transport enterprise aircraft, priority is given to ensuring that nodes with large flight flows can reduce the economic losses caused by airline route network attacks, and continue to pay attention to weather conditions or military activities at the airport of the city. If the flight has an impact, it is necessary to change the flight time in advance to ensure that the normal rate is a necessary means to ensure the normal operation of the airline route network.

References

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