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Research on the Robustness of Air Transportation System Based on Complex Network

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Abstract: Air transportation has the characteristics of fast transportation, high transportation efficiency and independent of ground conditions, so the economic benefits brought by air transportation greatly exceed those of other transportation modes. However, the safety of the air transportation system is constantly challenged. In recent years, the natural environment has changed due to rapid economic development, and meteorological disasters have occurred from time to time. In addition, flight cancellations due to airline aircraft turnarounds, technical aircraft failures, and traffic jams at airport terminals have become commonplace. To address the problem of insufficient stability of China's air transportation system, cities and flights with civil airports existing by the third quarter of 2022 are taken as the research objects, and the network model of China's air transportation system is constructed by using Ucinet software with the cities where airports are located as nodes and regular routes between airports as connecting edges. Then, robustness simulation experiments are conducted by random and intentional disruptions to analyze the extent to which the network can maintain its normal operation after the nodes in the network are down. The conclusions show that the robustness of the Chinese air transport network is better than that of the intentional disturbance in the case of random disturbance. Finally, suggestions for countermeasures that can improve the stability of the air transportation system are given.

1. Introduction

Air transportation is a long-distance transportation mode using aircraft to transport passengers, cargo and mail, which has the characteristics of fast and convenient, and is widely used in international trade to transport valuables, fresh cargo and precision instruments and other items that need to be delivered quickly[1]. According to the "Statistical Bulletin of Transport Industry Development in 2021" released in May 2022, the annual air transportation transported a total of 441 million passengers, an increase of 5.5% year-on-year, and the annual cargo and mail transported 7,318,400 tons, an increase of 8.2% year-on-year, comparing with previous years, we can see that the volume of air transportation and demand are increasing year by year[2]. Air transportation occupies a unique position due to the irreplaceability of international cargo transportation; irreplaceability of long-distance cargo transportation; and irreplaceability of high-value cargo transportation in the air transportation system. In addition, air transportation is also an important channel to achieve rapid integration of regional economy into the global economy. As a basic and pioneering industry, air transportation helps to promote the structural adjustment and industrial upgrading of the regional economy[3]. However, air transportation is also the mode of transportation most susceptible to interference from external factors and most affected by disturbances. In recent years, there have been many instances of flight delays and cancellations due to human activities that have changed the natural landscape and frequent meteorological disasters, and since 2020, flights to areas with high epidemic rates, such as Beijing and Shanghai, have been cancelled several times due to the impact of the new coronavirus. In addition airline aircraft turnaround, technical aircraft failures, fewer passengers and less cargo are also important reasons for the lack of air transport stability[4].

In summary, this paper addresses the problem of insufficient stability of China's air transportation network by first constructing a network model of the air transportation system from the perspective of complex networks[5]. Then studying the problems related to the stability of the air transportation system itself by means of robust simulation experiments, and putting forward targeted suggestions[6].

2. Literature Review

The existing literature focuses on the stability of air transport systems using two tools: complex network theory and robustness analysis.

2.1. Related Studies on Complex Network Theory

Complex network (CN) is a way to describe complex systems in an abstract way. As long as the constituent units are abstracted as nodes and node interrelationships are abstracted as edges, complex systems can be studied from the perspective and approach of complex networks. Understanding the interactions between elements is the basis for understanding the properties and functions of complex systems, so the topology of the network is the focus of complex networks.

The earliest research related to complex networks began with the paper "Collective Dynamics of Small-World Networks," published in Nature in June 1998 by Watts, a PhD student at Cornell University, and his advisor, which focused on the small-world characteristics of complex networks[7]. The following October, Professor Barabāsi of the University of Notre Dame published "The Emergence of Scaling in Stochastic Networks", explaining the scale-free character of complex networks.

Recently, a large number of scholars have applied complex network theory to the field of transportation and have achieved some results. Timothy Donnet et al. summarize the pros and cons of different governance models and management approaches of aviation networks around the world from international aviation networks in Florida, California, and Brazil to assist in developing aviation strategies[8]. Bauranov Aleksandar analyzed the impact of the COVID-19 pandemic on the U.S. air transportation network for the period March to August 2020[9]. Bogdanov I. P. studied the problem of optimal passenger planning in regional airline networks[10]. Xu Kaijun et al. used complex network theory to build a Chinese urban airline directional weighted network to rank nodes by degree centrality, meso-centrality and other indicators, and finally screened out important airport nodes in China[11].

2.2. Related Studies on Network Robustness

The robustness of a network is the ability of the network to remain stable when subjected to external disturbances. Current research related to transport networks and robustness is an emerging hot topic among academic forums.

Supun Perera et al. reviewed various approaches in the literature and research reports to model the topology and robustness of GSCNs and mimicked the GSCN topology demonstrated in the literature through an adaptive-based generative network model[12] . Łukasz Wolniewicz discusses the basic metrics for modeling and schedule and robustness assessment of rail transit systems, taking into account the analysis methods used and the many variables that occur in rail transit[13].Liu Xinmeng argues that the robust optimization model for express rail cargo transportation is highly adaptive, with total costs decreasing as demand changes and transportation duration increases[14].

In summary, current scholars have studied complex networks and network robustness analysis from shallow to deep, but relatively few studies have been conducted specifically for air transportation.

3. Research Methods and Data Sources

3.1. Research Methodology

In this paper, complex network analysis and robustness analysis are used in the study.

3.1.1. Complex Network Analysis Method

Complex network is a method to study complex systems, which focuses on the interrelationship and structure between individuals in the system to reveal the nature and function of complex systems, which is the basis of exploration of complex systems. In this paper, we abstractly construct an air transportation network model based on complex network analysis method by taking cities dependent on airports as nodes and regular routes between city airports as connected edges.

3.1.2. Robustness Analysis Method

The robustness of a network refers to the ability of the network to maintain certain performance characteristics under certain structural and scale parameter perturbations. Most of the robustness analysis methods start from the topology of the network by removing nodes or edges from the network to simulate the damage to the network, and evaluate the robustness of the network based on the topological changes of the network.

3.2. Data Source

According to the statistics from the Civil Aviation Administration of China and the flight data from the website of VariFlight Map, this paper counts 226 cities and regions of general aviation airports such as Beijing, Shanghai, Ningbo, etc., including all 3006 non-directional scheduled routes in China in the third quarter of 2022, so as to build the air transportation network in China.

4. China Air Transport System Modeling

4.1. Software Modeling

Firstly, the data composed from the Chinese route map (shown in Figure 1) provided by VariFlight Map website was binarized. Then the complex network map is drawn by importing the data through Visualize command in the main menu of Ucinet software, and the network layout such as the position of nodes and edges is changed by adjusting the visual effect of the pattern through the actual demand, as the edges and city nodes of the system modeling, which together form the

Chinese air transportation network system model.

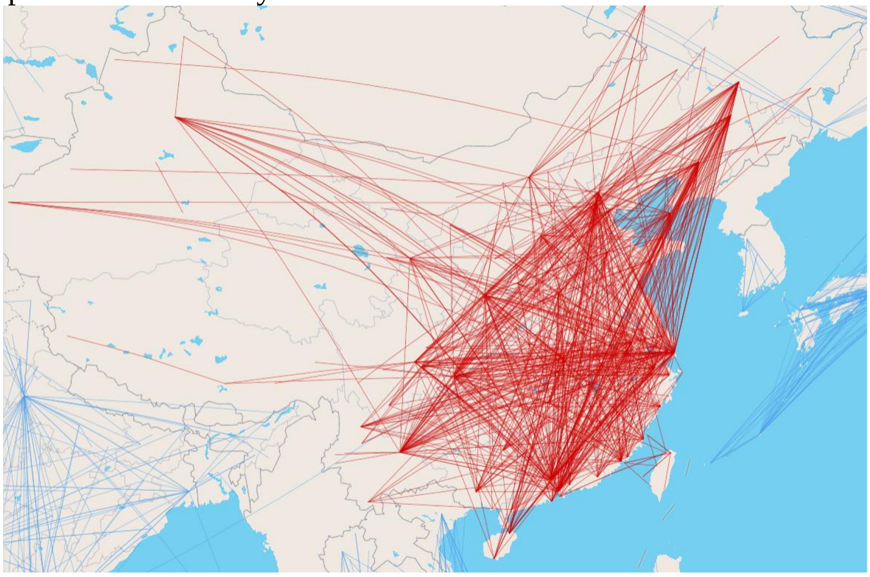

Figure 1: Domestic route map

4.2. Analysis of Statistical Indicators of China's Air Transport Network

Select Network/Centrality/Degree in the Ucinet software tab to obtain specific data on the model degree distribution of China's air transportation network; select Network/Cohesion/Multiple cohesion measure to obtain several holistic indicators of China's air transportation network including average shortest path, network relatedness, network efficiency, etc. Finally, the statistical processing of the results of the runs is obtained in Table 1:

Table 1: Statistical table of characteristic parameters of China's air transport network

Statistical characteristic quantity	Number of nodes	Average shortest pat	Clustering coefficient	Average degree	Network relevance	Network Efficiency
China Air Transport System	226	2.003	0.658	26.602	0.974	0.980

The clustering coefficient and characteristic path length of the random network with the same number of nodes and average degree can be calculated from the characteristic parameters in the above table as:

$$\begin{cases} C_{random} \approx \frac{k}{n} = 0.118 \\ L_{random} \approx \frac{\ln n}{\ln k} = 1.652 \end{cases} \tag{1}$$

$C \geq C_{random}$, $L \geq L_{random}$.It can be seen that this network model meets the criterion of small-world property because its clustering coefficient and average path length are higher than those of a random network with equal nodes and equal degrees. At the same time, most nodes have low degree, and only a few nodes have high degree, demonstrating the typical scale-free property. Therefore, the Chinese air transportation network has both small-world characteristics and belongs to the scale-free network model at the same time.

5. Robustness Analysis of China's Air Transport Network

5.1. Robust Interference Method

In order to determine the robust interference strategy, the stability of the network can be tested by introducing a sudden condition and thus changing the state of the nodes, and the faulty nodes are reflected in the network structure diagram as shown in Figure 2:

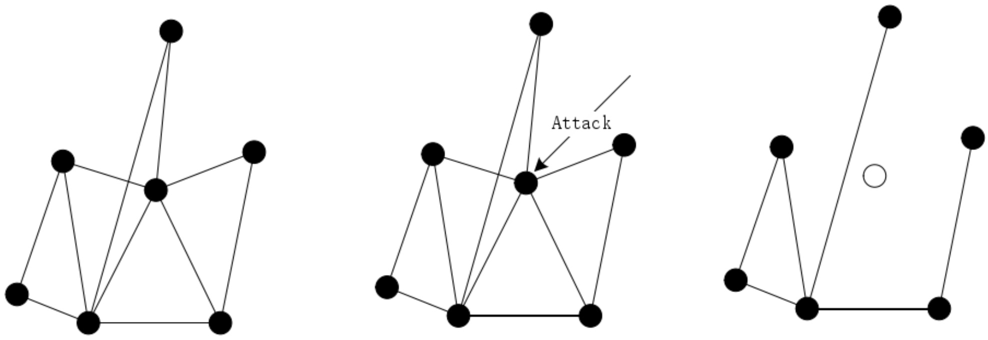

Figure 2: Structure of the network node before and after the attack

Usually such faults may occur randomly or they may be caused intentionally with some subjective and destructive nature. Based on these two fault occurrence scenarios, the strategy for robust interference favors the introduction of intentional interference to observe the maximum ability of the system to maintain its own state by compulsively interfering with the core nodes in the system.

Random interference with network nodes: the number of nodes in the network model randomly selected part of the same proportion of the number of nodes to attack, the number of attack nodes gradually increased.

Deliberate interference with network nodes: the number of attacking nodes is gradually increased by the mandatory removal of those nodes with higher intermediary centrality in the same proportion of the system in the network model.

Let X be the number of nodes removed, and the number of nodes removed each time is 6%, 12% and 18% of the total number of nodes. If the ratio of nodes is not calculated as an integer, rounding can be used to determine the final value. In each round of fetching, five removals of the same number of nodes are required, and then the average of the five removal parameters is taken for analysis.

5.2. Establishing Robustness Evaluation Metrics

According to the characteristics of this network model, the robustness evaluation indexes selected in this paper are the clustering coefficient and the average path length.

5.2.1. Clustering Coefficient

In the air transportation system, the clustering coefficient of node i is given by the following equation:

$$C_i = \frac{E_i}{K_i(K_i-1)/2} \tag{2}$$

E_i represents the number of actually existing connected edges and K_i is the number of nodes. In the air transportation system of this paper, each node represents a city connected to an airport, and the clustering coefficient of the nodes shows the air access of these cities.

5.2.2. Average Path Length

The average path length L of the network is the average of the distance between any two nodes, and the average path can be used to characterize the distance of the whole transportation system. That is, the formula:

$$L = \frac{2}{N(N-1)} \sum_{i \geq j} d_{ij} \tag{3}$$

N is the total number of all nodes in the network graph; d_{ij} denotes the distance between node i and node j in this network graph.

5.3. Air Transport Network Robustness Simulation Experiment

5.3.1. Random Interference

226×6%≈14、226×12%≈27、226×18%≈41.In turn, 14, 27, and 41 nodes in the network are removed randomly and established, and each experiment is removed five times for fault simulation. The statistical average results are shown in Table 2:

Table 2: Statistics of system characteristic parameters after random attack

Number of removed nodes	Percentage of nodes removed	Clustering coefficient	Average path length
0	0	0.658	2.003
14	6%	0.698	2.010
27	12%	0.697	2.010
41	18%	0.681	2.017

5.3.2. Deliberate Interference

$226 \times 6\% \approx 14, 226 \times 12\% \approx 27, 226 \times 18\% \approx 41$. In this study, 14, 27, and 41 nodes in the network were deleted for fault simulation. First, the 30% of node cities with the highest meso-centricity are measured, and 14, 27, and 41 node cities are removed from the 68 cities with the highest centrality to achieve the purpose of deliberately interfering with the network nodes. The statistical average results are shown in Table 3:

Table 3: Statistics of system characteristic parameters after deliberate attack

Number of removed nodes	Percentage of nodes removed	Clustering coefficient	Average path length
0	0	0.658	2.003
14	6%	0.681	2.11
27	12%	0.600	2.324
41	18%	0.628	2.298

The resulting straight lines for the variation of each characteristic parameter of the domestic air transport network model are plotted in Figure 3 and Figure 4:

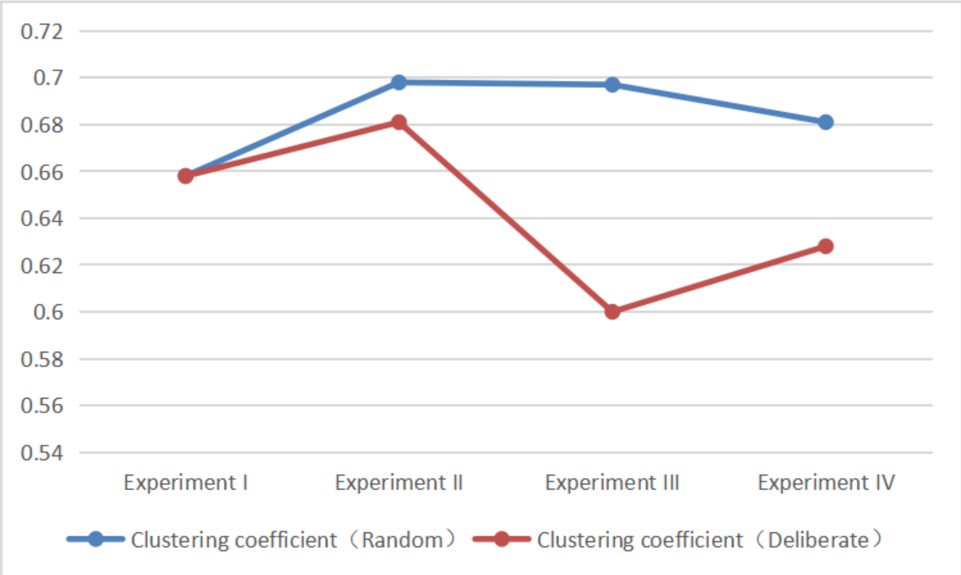

Figure 3: Change of clustering coefficients of China's air transportation network model

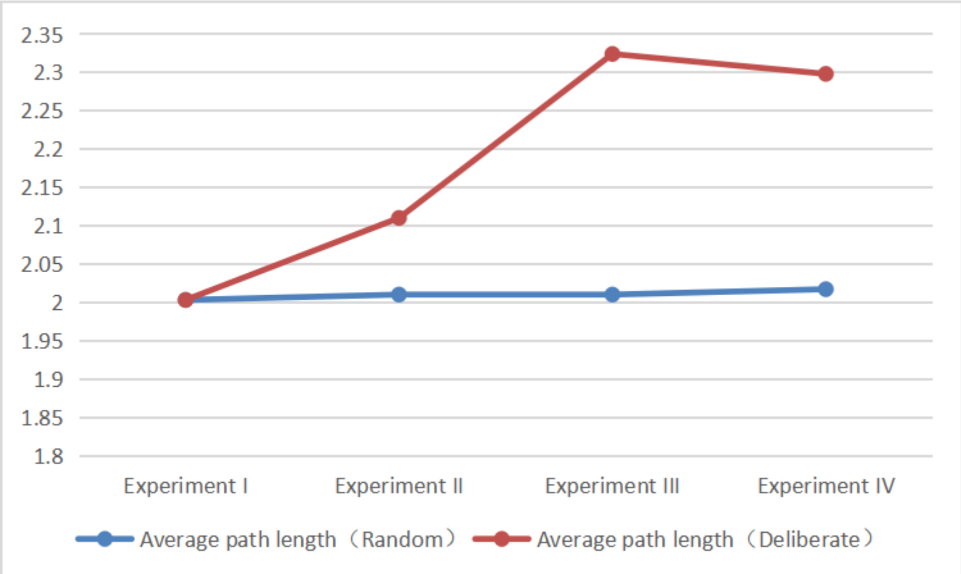

Figure 4: Variation of average path length of air transportation network model in China

5.4. Analysis of results

5.4.1. Clustering coefficient

The degree of aggregation of a network can be described by the clustering coefficient. When the aggregation coefficient is larger, the closer the correlation between the nodes, the better the performance of the overall network transportation.

The variance value of the clustering coefficient data set in the simulation experiment results of the Chinese air transportation network system is 0.00026 under random disturbance and 0.00093 under deliberate disturbance. It can be seen that the variance of the clustering coefficient of the system is more drastic in the case of deliberate disturbance than random disturbance.

In the case of random removal of nodes, the clustering coefficient of the network remains similar to the initial state. In the case of deliberate disturbance, the fluctuation of the change in the clustering coefficient of the network is more pronounced. This is because nodes with higher degree in the network play an important role, and after they are disturbed, the connections between many nodes break, leading to a decrease in the degree of aggregation, which reduces the robustness of the network.

5.4.2. Average Path Length

The average path length reflects the degree of dispersion between nodes, which is an important indicator of global characteristics. The stronger the connection between nodes, the shorter the distance between them; if the average path is longer, it indicates that they need to go through more intermediate nodes. In air transport systems, this can lead to energy and impact losses, such as worse timeliness and reduced turnaround.

The average path length of the domestic air transport system is significantly higher than that of the random disturbance in case of intentional disturbance, respectively. Moreover, the system's curve decreases faster in the case of deliberate disturbance. After random node removal, the average path length of the network does not change much compared to the initial state.

This shows that when the nodes with high node centrality are removed from the network, the average path length will increase, resulting in a more fragile system, and once the system is disturbed again the fault propagation in the network will be fast, making the network less robust; while in the random interference mode, the average path length of the network does not change much for those systems with a low overall node degree. And as more low node numbers are removed, the average path length of their networks gradually decreases.

6. Conclusions and Countermeasure Suggestions

In summary, the Chinese air transport network can guarantee its functional properties better and has better robustness in the case of random disturbances, while it cannot guarantee its normal operation better in the case of deliberate disturbances, and its performance decreases significantly and has poor robustness.

In response to the above results, several countermeasures are proposed that can improve the robustness of air transportation network. Firstly, at the overall level, the scale of the air transportation system should be continuously increased so as to create economies of scale. This will help promote the integrity of the chain, optimize the allocation of resources and improve the efficiency of cargo transportation. Not only should the influence of existing large hub airports be strengthened, but also the construction and development of small and medium-sized airports should be emphasized to better reflect the network hub function of small airports. Secondly, from the airport level, the infrastructure of large hub airports including terminals and runways should be improved. Expansion of the terminal building, on the one hand, to meet the growing demand for passenger and cargo traffic, and on the other hand, to more effectively enhance the stability of the aviation network. New runways will ensure the normal operation of multiple routes and prevent runway congestion, thus improving the robustness of the airport's aviation network. Finally, from the enterprise level, it is necessary to improve the risk management awareness of the shipping enterprises, to prepare in advance for certain unexpected situations such as technical aircraft failure, to reduce the possibility of this risk as much as possible, and to develop countermeasures in advance to reduce the adverse effects if the node failure is caused by natural disasters and other factors, so as to improve the stability of the hub airport itself.

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