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Repair Strategy of Airport Network Reliability under the Disturbance of Large Area Flight Delays

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Abstract: The frequent occurrence of flight delays has a disturbing effect on the stability and the reliability of airport network. It is the key to design and screen effective repair strategies for solving the practical problem of airport network reliability damaged by flight delay. In this paper, the complex airport network was established in P-space, and the reliability repair model of the airport network under the disturbance of flight delays was constructed. Two repair strategies were designed for the airport network under the disturbance of large-scale flight delays: the random repair strategy and the priority repair strategy. Then, taking the airport network of China Eastern Airlines as an example, the failure and repair rules of airport nodes under the disturbance of flight delays were established. And the repair effects of different repair strategies were compared and analyzed. The results showed that the effect of priority repair strategy was better than that of random repair strategy. Under the disturbance of large area flight delays, the reliability of airport network could be improved faster to repair the important hubs and key nodes of airport network than to repair the normal nodes. The above conclusions could provide a reference for airlines to deal with the disturbance of flight delays and to ensure the reliable operation of airport network.

1. Introduction

Civil aviation transportation system is an important part of fast transportation system in China. The reliable operation of airport network is conducive to the smooth implementation of transportation power strategy in China. Many airlines constantly expand the airport business and air transport business, and the networking operation characteristics of airports are obvious. However, in the daily operation of the airport network, various kinds of flight delays occurred frequently, which were caused by bad weather, natural disasters, sudden failures and even deliberate attacks, affecting the normal functions of the airport network. In particular, the large area of flight delay was easy to cause the failure of airport network nodes, resulting in the loss of network reliability. Therefore, it is of great practical significance to study the reliability repair strategy of airport network under the disturbance of large area flight delays.

In the research on network reliability, scholars usually adopt different attack modes for specific networks, move the failure point edge out of the network, and then measure the reliability indexes of the network. Reliability measurement indexes include global efficiency and local efficiency of the network [1], relative size of maximum connected subgraph and network dispersion [2], overall connectivity and efficient connectivity [3], proportion of passengers traveling reliably [4], capacity and relative circulation degree [5], etc. As for the problem of network repair, research on the repair strategies of transport networks has emerged increasingly in recent years. And the research objects mainly included urban road network [6-7], air transport network [8], urban agglomeration passenger transport network [9], urban rail transit network [10-11], etc. Researchers generally designed repair strategies to improve network reliability based on the failure situation after the network was disturbed or attacked.

The above studies provided useful inspiration and reference for this study. However, existing literatures seldom pay attention to the airport network, and the repair strategy of airport network under the background of large-scale flight delays has not been reported. In addition, different airlines enter and be stationed in in airports in different cities, and each airline has the different layout of airport network. There are few studies on how to ensure the reliable operation of its airport network under disturbance events based on the perspective of airlines. Therefore, the airport network of China Eastern Airlines was taken as the research object in this paper. The process of network reliability damage and recovery was analyzed, which caused by the failure of the network nodes of China Eastern Airlines under the disturbance of a large area of flight delay. And the repair effects of different repair strategies on the airport network reliability were compared and analyzed. It was hoped to provide decision-making reference for airlines to deal with various disturbance events caused by flight delays and to ensure the reliable operation of airport networks.

2. Construction of Airport Network

According to the complex network theory, the network can be constructed in P, R and L three spaces [12]. Take the airport network as an example. In space P, the node is the airport, if at least one flight stops at two airports, an edge is connected between these two airport nodes. In space R, the node is flight, if two flights stop at least the same one airport, an edge is connected between these two flight nodes. In space L, the node is still an airport, and an edge is connected between two airport nodes if they are adjacent nodes in at least one flight. In this paper, the complex airport network was constructed in space P.

For the convenience of research, the construction instructions and assumptions of airport network were as follows:

(1) Airport network is constructed in space P. The airports are taken as the nodes. As long as one flight can reach two airports, there is a connection between the two airport nodes.

(2) Nodes merger rules. If two or more airports are located in the same city, multiple airport nodes in the same city are merged into one node.

(3) Edges and edge weights. If there is direct flight between airport A and airport B, the connection between node A and node B is an edge, and the frequency of direct flight between airport A and Airport B within 24 hours is the edge weight.

(4) Undirected network. In general, if we can take a flight from airport A to airport B, we can also from airport B to airport A through the same route. Therefore, the airport network can be abstracted as undirected network.

According to the above assumptions, the airport network was abstracted as a graph $G=(V,E)$ composed of nodes set $V(G)$ and edge set $E(G)$. Each edge e has a pair of nodes (i,j) corresponding to it. And the pair of nodes (i,j) and (j,i) corresponded to the same edge. The adjacency matrix was used to represent the weighted airport network. If there are m flights between the airport node

i and the airport node j within 24 hours, the corresponding elements in the matrix was $a_{ij} = m$; The diagonal elements of the matrix was $a_{ii} = 0$.

3. Repair Model of Airport Network under the Disturbance of Flight Delays

3.1. Disturbance Scenarios of Flight Delay

In the daily operation of the airport network, the disturbance attack modes to the airport network caused by flight delays with different reasons may be different. The disturbance degree to the airport network caused by flight delays with different scale and duration were different, and the nodes' failure situations were also different. According to the randomness and intentionality of flight delays, the disturbance attack mode of flight delay on airport network can be divided into random attack and deliberate attack, and the nodes' failure can be divided into random failure and selective failure. According to the different delay scale and delay duration, flight delay scenarios can be divided into four types: single node short time delay, single node long time delay, multiple nodes short time delay and multiple nodes long time delay. Assuming that only long delays can make the airport nodes fail, then the airport network's failure can be divided into single node failure and multi-node failure under different flight delay disturbance scenarios. The multiple-node long delay is large-scale flight delays in this paper.

3.2. Reliability of Airport Network under the Disturbance of Flight Delays

Once large-scale flight delays occur, the connectivity of the airport network will be seriously damaged and the reliability of the network will be reduced. Therefore, the nodes' ratio of maximum connected subgraph, which reflecting the connectivity of network, was selected as the reliability index of airport network in this paper. The formula is:

$$Z(t) = \frac{S'(t)}{S} \qquad (1)$$

In formula (1), [illegible] is the nodes' ratio of maximum connected subgraph of the airport network at time [illegible]; [illegible] is the nodes' number of maximum connected subgraph before the airport network was disturbed by flight delays; [illegible] is the nodes' number of maximum connected subgraph after suffering the disturbance of flight delays at time [illegible]. Obviously [illegible], the larger the value of [illegible], the better the connectivity and reliability of the airport network.

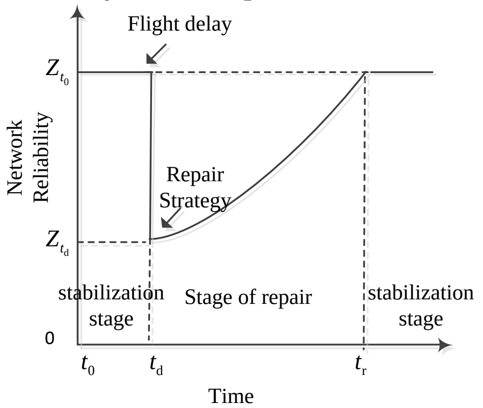

Figure 1: Schematic diagram of reliability of airport network under the disturbance of flight delays

As shown in Figure 1. When $t \in [0, t_d)$, the airport network has not been disturbed by flight delays, and the network is in the stabilization stage of reliability. When $t = t_d$, the disturbance of flight delays occur, and the reliability of airport network decreases from Z_{t_0} to Z_{t_d} . It is assumed that the airport or the airline company can immediately adopt the repair strategy after the flight delays occur, but the repair strategy needs a certain time from implementation to completion, so when $t \in [t_d, t_r)$, the airport network is in the stage of reliability repair. When $t = t_r$, the failure nodes of the airport network are all repaired. The reliability of airport network is restored to the initial level, and the network is in the stabilization stage of reliability again.

3.3. Repair Strategy

The repair strategies were designed for the airport network under the disturbance of flight delays, as shown in Table 1. Since there was no airport node failure in single node short time delay scenario and multiple nodes short time delay scenario, so no airport node was failure. In addition, because the single node long time delay only leads to the failure of one single node, the repair sequence of the failed node need not to be considered. Therefore, the damage and repair of airport network reliability under the scenario of multiple nodes long time delay, which was large-scale flight delays in fact, was studied in this paper. On the basis of comprehensive reference to the existing literature, the repair strategies to airport network under the disturbance of large-scale flight delays were divided into two types: random repair strategy and priority repair strategy. Random repair strategy referred to randomly select a failed node to repair. Priority repair strategy referred to preferentially select important nodes to repair, and the importance of nodes could be ranked according to their degree centrality value.

Table 1: Repair strategy of airport network under different flight delay scenarios

Scenarios	Node failure	Repair strategy
Single node short time delay	No node failure	Recessive disturbance , need not to repair
Single node long time delay	Single node failure	Single node repair (regardless of the repair order)
Multiple nodes short time delay	No node failure	Recessive disturbance , need not to repair
Multiple nodes long tome delay (large-scale flight delays)	Multiple nodes failure	Random repair strategy :randomly select a failed node to repair
		Priority repair strategy: preferentially select important nodes to repair

4. Example Analysis

The airport network data of China Eastern Airlines was selected for example analysis in This paper. As of August 1, 2021, the airport network of China Eastern Airlines in Chinese consisted of 113 airport nodes and 1,032 airport links, and the edge weights were direct flights between airport nodes within 24 hours. The Data were mainly obtained from the official websites of China Eastern Airlines (http://www.ceair.com) and Ctrip (https://hotels.ctrip.com). According to the statistical data, the adjacency matrix of the airport network of China Eastern Airlines was made as $A_{113\times113}$. And the adjacency matrix could be imported into Pajek to process data, such as the degree centrality of nodes and the number of nodes in the maximum connected subgraph.

4.1. Repair Rules of Airport Network

The rules of flight delay disturbance and network repair were set as follows: (1) It was assumed that large area of flight delay occurred at a certain time, and the disturbance of flight delays caused the failure of 15 nodes, which were numbered 1-15 in the airport network of China Eastern Airlines. (2) There were two kinds of repair strategies: random repair and priority repair. The repair order of priority repair was ranked according to the degree centrality value. If two different nodes had the same ranking, the node with the first numbered order was repaired firstly. (3) Repair one node at a time. The importance rank and preferentially repair order of nodes numbered 1-15 were listed in Table 2.

Table 2: Importance rank and preferentially repair order of nodes numbered 1-15

Number	Airport Node Name	Degree centrality value	Rank of importance	Preferentially repair order
1	Beijing	100	2	2
2	Shanghai	174	1	1
3	Changchun	29	4	4
4	Mudanjiang	10	8	8
5	Haerbin	23	5	5
6	Qiqiha’er	10	8	9
7	Jiamusi	5	12	12
8	Yichun	5	12	13
9	Yanji	10	8	10
10	Lasa	13	7	7
11	Tonghua	3	15	15
12	Jinzhou	4	14	14
13	Dalian	39	3	3
14	Huhehaote	17	6	6
15	Tianjin	7	11	11

As shown in Table 2, the degree centrality value of Shanghai was 174, which was the highest among the 15 nodes. So the node of Shanghai was the most important node, and it would be recovered first in priority repair strategy. The degree centrality values of Mudanjiang, Qiqiha’er and Yanji were all 10. The importance rank of these three cities were the same 8. However, the first numbered order of these three cities respectively were 4, 6 and 9. So the repair order of them respectively were 8, 9 and 10. In addition, the degree centrality values of Jiamusi and Yichun were both 5. The importance rank of the two cities were the same 12. However, the first numbered order of the two cities respectively were 7 and 8. So the repair order of them respectively were 12 and 13.

4.2. Repair Effects Analysis of Different Strategies

According to the above disturbance and repair rules, when $t=0$, the airport network of China Eastern Airlines has not been attacked by flight delays, and the initial nodes ratio of maximum connected subgraph was 1, which could be understood as the network’ reliability value was 1. When $t=1$, the large area of flight delays caused the failure of 15 nodes of the airport network, and the nodes ratio of maximum connected subgraph decreased to 0.8584. The connectivity and reliability of the network declined sharply. Then, random repair strategy and priority repair strategy were respectively adopted to repair one node in each time step, and Pajek software was used to calculate the nodes ratio of maximum connected subgraph after repairing. The recovery trend chart of network reliability was drawn, as shown in Figure 2.

As shown in Figure 2, with the time went on, the reliability of airport network had been repaired and improved under both kinds of repair strategies. However, the recovery speed of network reliability under priority repair strategy was significantly faster than that under random repair strategy. For example, when $t = 2$, the nodes ratio of maximum connected subgraph under the priority repair strategy recovered to 0.8761, while the nodes ratio of the maximum connected subgraph under the random repair strategy only recovered to 0.8673. When $t = 10$, the nodes ratio of maximum connected subgraph under the priority repair strategy recovered to 0.9469, while the nodes ratio of the maximum connected subgraph under the random repair strategy only recovered to 0.9380. When $t = 15$, all the failed nodes were repaired, and the reliability of the airport network under the two kinds of repair strategies were finally restored to the state before the flight delay occurred. It could be seen that the repair effect of priority repair strategy was significantly better than that of random repair strategy at the same repair time step.

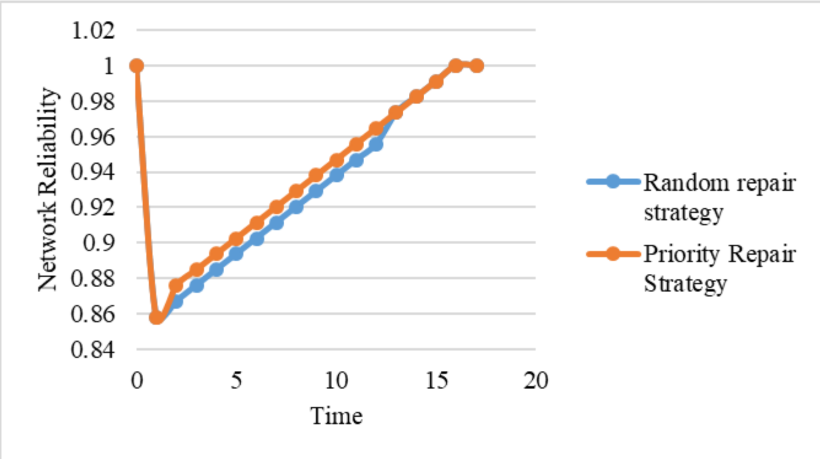

Figure 2: Repair effects of network reliability under different repair strategies

5. Conclusions

Flight delays had the disturbing effect on the reliability of airlines' airport network. In this paper, a complex airport network was established in space P, and a reliability repair model of airport network under the disturbance of flight delays was constructed. The flight delay scenarios were divided into four types: single node short time delay, single node long time delay, multiple nodes short time delay and multiple nodes long time delay. The repair strategies corresponding to each delay scenarios were different. The repair strategies for the airport network disturbed by large-scale flight delays were divided into two kinds: random repair strategy and priority repair strategy. Taking the airport network of China Eastern Airlines as an example, the failure and repair rules of airport nodes under flight delay disturbance were designed, and the repair effects of different repair strategies were compared and analyzed. The results showed that:

(1) The effect of priority repair strategy was better than that of random repair strategy.

(2) Under the disturbance of large area flight delays, the reliability of airport network could be improved faster to repair the important hubs and key nodes of airport network than to repair the normal nodes.

It played an important role in ensuring the reliable operation of airport network to protect important hubs and key nodes in the daily operation of airport network.

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