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Research on the Operational Resilience of AOV Networks in Flight Support and Control Strategies—— From the Perspective of Cascading FailuresPaper Title

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Abstract: *China's air transport volume has steadily ranked second globally and continues to grow rapidly. However, there is a significant gap in civil aviation infrastructure, and airports are reaching saturation. Developing strategies based on resilience theory has become an industry consensus. Aiming at the flight support operations in the airport movement area, we construct a complex network analysis model. In this model, we abstract nodes into an Activity On Vertex network (AOV net). We then employ the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) model to identify key nodes, providing data support for the cascading failure model. Focusing on the stability and recovery mechanisms of the flight support system, we establish a resilience evaluation system that incorporates metrics such as network efficiency, the relative scale of the largest connected component, etc., and conduct an empirical application of complex network theory. The conclusions drawn from this study guide the formulation of control strategies.*

Keywords: *a-cdm,Complex networks, cascading failures, key nodes, control strategies.*

1. Introduction

In recent years, China's air transport industry has continued to flourish. This trend has placed enormous pressure on airport infrastructure, and issues related to the operational control and management of airlines and airports during flight operation anomalies have become increasingly prominent. Currently, the scheduling of airport support vehicles mainly relies on human experience, while the Airport Collaborative Decision Making (A-CDM) system is of great significance for enhancing airport operational efficiency. It contributes to the improvement of the aviation network and the innovation of operational models. Therefore, research on the failure mechanism of the support network based on the A-CDM system holds important practical significance.

Domestic research on the A-CDM mechanism in airports exhibits a diversified landscape. Han Luya constructed a framework linking collaborative decision-making with flight delay warnings[1], but it lacked analysis of dynamic responses. Zhu Hui optimized the prediction of flight departure times[2]. Ren Yan proposed a multi-entity collaborative operational framework based on Baiyun Airport[3]. Wang Bo and his team explored the coupling of models and platforms and presented an optimization algorithm for the tow truck operation path[4].

In the field of identifying key nodes in networks, there have been abundant research achievements in recent years. In 2020, Wu Minggong's research group constructed a dynamic flight state network model capable of accurately identifying aircraft in airspace conflicts[5]. Ding Jianli et al. designed a weighted aviation network structure to evaluate nodes[6]. In 2021, You Qianjing and Zheng Wei introduced a coverage algorithm and a verification mechanism to improve evaluation accuracy[7], while Yu Senbin established a dynamic analysis model[8]. In 2022, Yin Mengmeng and Wang Lei pointed out the limitations of the multi-indicator fusion assessment method[9]. Li Qiuhui and Han Hua focused on higher-order topological structures[10], constructed a new assessment framework, and validated it.

Significant progress has also been made in the study of network cascading failures. In 2021, Wang

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Xinglong et al. constructed a composite model, revealing the role of parameter optimization in suppressing cascading propagation paths[11]. Xie Benkai et al. established a load-capacity model with node state correlations in their research on the Central and Southern China civil aviation network[12]. In 2022, Huo Feizhou et al. proposed an optimization method that integrates the road congestion index[13], using it as a key variable in load allocation decisions. This effectively enhanced the practical value of cascading failure prevention and control strategies, providing new insights for research on the invulnerability of complex networks.

In response to previous shortcomings in the study of flight support systems, such as inadequate portrayal of dynamic interactions and a lack of spatiotemporal dimensions in resilience evaluation, this paper conducts research based on the theory of cascading failures in complex networks.

2. Model construction

2.1. A-CDM (Airport Collaborative Decision Making) flight support process

The Airport Collaborative Decision Making (A-CDM) technology is constructed based on a systematic thinking framework. Its core logic is to regard the flight plan as a holistic operational system and identify the key nodes of flight support as "milestone events". Based on this concept, the Civil Aviation Administration of China (CAAC) has organized airport operators, airlines, and air traffic management departments to jointly review and determine 43 key milestone nodes for data collection and configuration[14]. These nodes cover various stages of flight operations, establishing a standardized information interaction system. They provide a solid data foundation and operational framework for achieving efficient multi-entity collaboration and enhancing airport operational efficiency. For the specific distribution of these nodes, please refer to the figure.

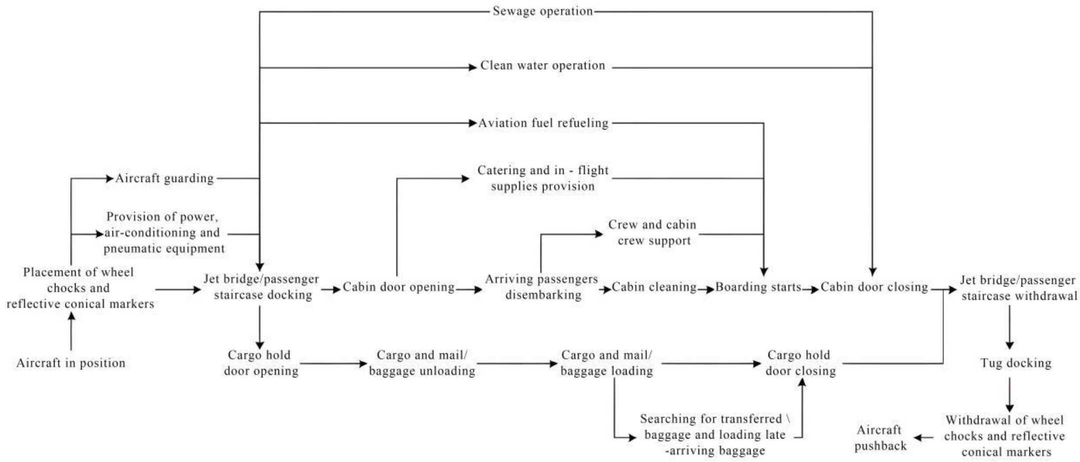

Figure 1: Aircraft departure support flow chart.

2.2. Construction of the AOV Network Model for Flight Support

As the core carrier of flight operations, any link in the ground support process of an aircraft has a significant impact on the on-time departure of flights. Therefore, during the model construction process, it is necessary to consider all support processes as activity units and incorporate them into the analysis to construct a support process model based on an Activity On Vertex network (AOV net).

2.2.1. Network model

This model constructs an AOV (Activity On Vertex) network $G4=<N4,T4;E4>$ for aircraft support, taking the aircraft support processes as the fundamental activity units and utilizing the logical relationships between each process as the connecting links. Here, N represents the set of activity units, which is comprised of n support process nodes, denoted as $N_4 = \{N_4(a_1), N_4(a_2), \dots, N_4(a_{n4})\}$; T is the set of process judgment functions, employed to define the execution conditions and constraints for each process; and E denotes the set of associated relationships between the support processes.

In the aircraft support process model constructed based on an improved AOV (Activity On Vertex)

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network, since the research object specifically targets aircraft, the activity object attribute in the model parameters is uniformly set as "Aircraft". Finally, by systematically depicting the temporal logic and constraint relationships among various support processes, this model provides theoretical support for optimizing flight support processes and enhancing operational efficiency.

The detailed architecture of the AOV network for the aircraft support process during flight operations is illustrated in Figure .

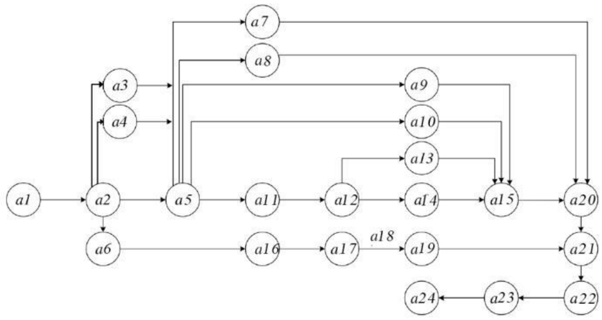

Figure 2: Schematic diagram of the AOV network of the aircraft support process.

According to A-CDM data from a certain airport in East China and the "Flight Safety Operation Support Standards 2020", the service durations for milestone events in aircraft ground support operations vary.

Table 1: Flight Support Network Adjacency Table.

Start node	End node	Weight	Start node	End node	Weight
1	2	4	9	14	30
1	3	4	10	9	2
1	4	4	10	11	2
2	6	10	11	12	20
2	7	10	11	13	20
2	8	10	12	14	30
2	4	10	13	14	30
3	6	10	14	19	20
3	7	10	15	16	30
3	8	10	16	17	30
3	4	10	16	18	30
4	5	4	17	18	15
4	10	4	18	20	2
5	15	2	19	20	2
6	19	30	20	21	4
7	19	30	21	22	3
8	14	80			

2.2.2. Feature analysis of the network model

Based on the established AOV (Activity On Vertex) network model for airport movement area operations, in-depth calculations and analyses were conducted using Matlab software to derive importance evaluation indicators for key milestone nodes within the airport movement area.

In the structural analysis of the AOV network for airport movement area operations, degree centrality and betweenness centrality are core metrics for measuring node importance. Degree centrality reflects the connection strength of a node by quantifying the number of direct connections (in-degree + out-degree) it has with other nodes, thereby indicating the level of active interaction the node has within the network. Nodes with high node degrees and rankings in degree centrality, such as "Jet Bridge Docking" and "Cargo and Mail Loading," require coordination with upstream and downstream nodes and are highly dependent on airport resources. The level of their degree centrality directly reflects the intensity of resource flow within the network.

Betweenness centrality measures a node's control over critical paths by calculating the frequency with which the node acts as an intermediary in the shortest paths between all pairs of nodes. This assesses the node's dominating role in the flow of information or resources within the network. Nodes such as "Provision of Power, Air Conditioning, and Pneumatic Sources" and "Opening and Closing of Cabin Doors" are situated on critical paths within the process network. Their operational efficiency

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affects the system's connectivity, and any disruption can lead to stagnation in subsequent processes.

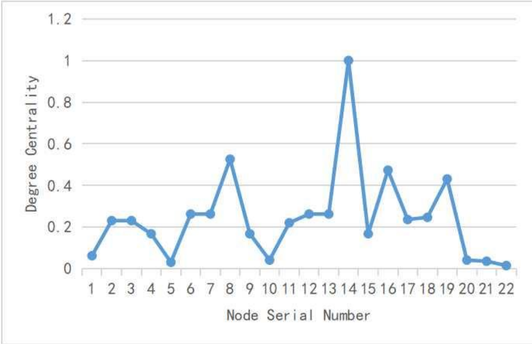

Figure 3: Degree centrality indicator.

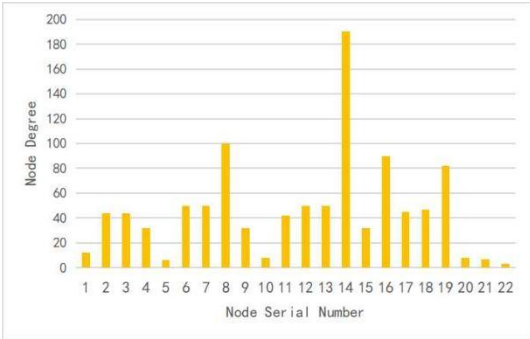

Figure 4: Nodal degree metrics.

Degree centrality and betweenness centrality evaluate nodes from different dimensions, making it difficult for a single indicator to comprehensively depict a node's importance. By employing multi-dimensional centrality indicators, we can both identify resource-intensive nodes to optimize scheduling processes and locate key hub nodes to enhance reliability assurance. This provides a scientific basis for refined management of airport operations, avoids evaluation biases, and achieves systemic optimization.

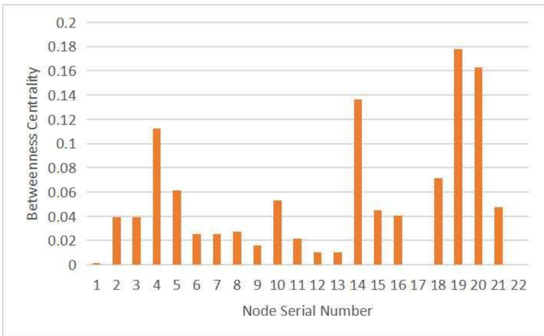

Figure 5: Betweenness Centrality Index.

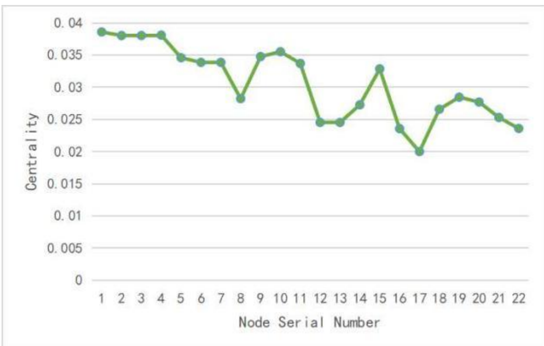

Figure 6: Centrality Indicators.

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In the comprehensive evaluation of complex systems, the comprehensive evaluation method serves as a systematic analytical tool that thoroughly dissects the target object using a multi-dimensional indicator system. The TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method, through constructing matrices and calculating closeness degrees, can objectively reflect a node's comprehensive performance, avoid subjective weighting biases, reveal hierarchical differences among nodes, and align with the characteristics of the flight area's flight support network.

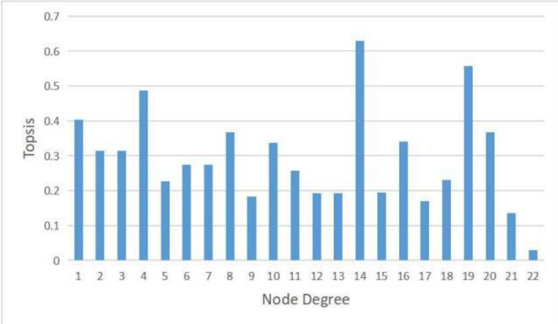

Figure 7:Node Comprehensive Importance Analysis.

Table 2: Node Comprehensive Importance Analysis Table.

Node number	Distance to the positive ideal solution	Distance to the negative ideal solution	TOPSIS score	Ranking
1	0.204737788	0.137865851	0.402406266	4
2	0.193317878	0.088191079	0.313279832	9
3	0.193317878	0.088191079	0.313279832	9
4	0.17965561	0.170112315	0.486357675	3
5	0.232836046	0.068582129	0.227531498	15
6	0.199065436	0.075290471	0.27442628	11
7	0.199065436	0.075290471	0.27442628	11
8	0.192849293	0.111857613	0.36709904	6
9	0.229014734	0.051063608	0.182319017	19
10	0.215071207	0.10956418	0.337499189	8
11	0.204871161	0.070685038	0.256517683	13
12	0.229178022	0.054419447	0.191889747	17
13	0.229178022	0.054419447	0.191889747	17
14	0.128009972	0.21634002	0.628256208	1
15	0.222639716	0.053778267	0.194554153	16
16	0.193385282	0.099667774	0.340101465	7
17	0.234788731	0.04775564	0.169019967	20
18	0.208245509	0.062594381	0.231112118	14
19	0.128275398	0.16136704	0.557124989	2
20	0.21221131	0.123149543	0.367215023	5
21	0.244811275	0.038553681	0.136056629	21
22	0.269318593	0.008149628	0.029371392	22

Under the setting of average weights, Node 4 (Cabin Door Opening) ranks first with a score of 0.628, as it serves as a pivotal hub in the process network, connecting multiple stages and influencing flight turnaround. Node 19 (Cargo Hold Door Closing) ranks second, controlling the cargo transportation link, with its operational progress determining the taxiing of the flight. Node 4 (Provision of Power and Other Equipment, note: there might be a numbering inconsistency here; assuming it's a separate node despite the same number as the first-ranked one, or it could be a correction to refer to another relevant node in context) ranks third, offering standardized services but with a broad coverage. Node 20 (Cabin Door Closing) ranks fifth and is significantly influenced by manual operations. While average weights simplify the calculation process, they may dilute the impact of core indicators. Most nodes still have room for improvement in terms of approaching the ideal

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solution.

2.2.3. Cascading failure model

Given the complexity of the traffic system in airport movement areas, this study has improved the traditional capacity-load model and constructed a road traffic network cascading failure analysis model suitable for this scenario. In the airport movement area, when some nodes exhibit abnormalities, air traffic controllers will adjust the task planning of auxiliary vehicles. This may lead to an overload of traffic at normal nodes, subsequently causing network paralysis and affecting the operational efficiency and safety of the airport.

In the context of the flight support network in the airport movement area, the operational efficiency of intersection nodes not only dynamically correlates with real-time traffic flow and network efficiency but also deeply relies on the traffic coordination between adjacent nodes. Therefore, when node i is in a stable state without being disturbed or experiencing load overflow, its initial load is denoted as :

$$L_i\left(0\right)=\alpha\times d_i+\beta\times FDBC_i \tag{1}$$

Based on the traffic efficiency constraints at the intersections in the airport movement area, each node has a maximum carrying threshold. When the load on a node exceeds its capacity limit, the node may transition into a suspended state or a failed state. Considering that the load-bearing capacity of a node is related to its initial load, the capacity of node i is defined as follows:

$$C_i=\left(1+theat\right)\times L_i\left(0\right) \tag{2}$$

In the road network cascading failure model for airport movement areas, the adjustment parameter for a node's overload capacity is ≥ 1, with a higher value indicating stronger resistance to failure. The state of a node is determined by comparing its real-time load with its capacity threshold: it operates normally when the load is below the rated capacity; it undergoes traffic throttling and diversion when the load exceeds the rated capacity but remains within the maximum adjustable capacity; and it fails permanently when the load surpasses the upper limit, with the load being shared by adjacent nodes. This three-tier threshold mechanism reflects the elastic response of nodes.

$$L_j(t+1)=L_j(t)+\Delta L_j(t) \tag{3}$$

3. Cascading failure evaluation indicators

In this study, focusing on the propagation effects of node failures in the road system of airport movement areas under cascading failure scenarios, network efficiency is selected as a key evaluation indicator to achieve quantitative analysis of the impact. This indicator effectively characterizes the transportation efficiency level of the traffic network by calculating the weighted average of the reciprocals of the shortest travel distances between each pair of nodes. Its value ranges from 0 to 1. When the network efficiency significantly decreases after removing a specific node, it indicates that the node holds a high pivotal value within the overall structure. In comparative analyses of different road network models, when the same number of nodes are removed, systems that maintain higher network efficiency demonstrate relatively more prominent functional stability and resilience. Specifically, for the calculation of network efficiency related to a single node:

$$CH_i=\frac{\sum_{i\neq j}1/d_{ij}}{N-1} \tag{4}$$

The global network efficiency is defined as the arithmetic mean of the efficiency values of all nodes within the network, and this indicator reflects the overall transmission performance of the system:

$$E=\frac{\sum_i CH_i}{N} \tag{5}$$

4. Simulation analysis

The cascading failure analysis process for the road traffic network in the airport movement area consists of eight core steps:

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Step 1: Set the initial load L(0) and capacity C parameters for each node to achieve data initialization.

Step 2: Define the attack strategy and select the target nodes, providing prerequisites for subsequent simulations.

Step 3: After removing the failed nodes, the system implements an average load redistribution mechanism to dynamically refresh the load data of all nodes in the network.

Step 4: By solving for the set of failed nodes and the set of dormant nodes at time t, accurately determine the operational status of the equipment.

Step 5: This is a critical decision-making step. By detecting whether there are new members in the set of failed nodes, assess whether the system has entered the cascading failure phase.

If no new failed nodes emerge in the system, proceed directly to Step 7, output the network efficiency, and terminate the process. If there are new failed nodes, proceed to Step 6, where load redistribution is implemented for the failed and suspended nodes. After updating the node loads, return to Step 4 to continue the loop.

This iterative process continues until the cascading failure process terminates, completing the entire analysis workflow.

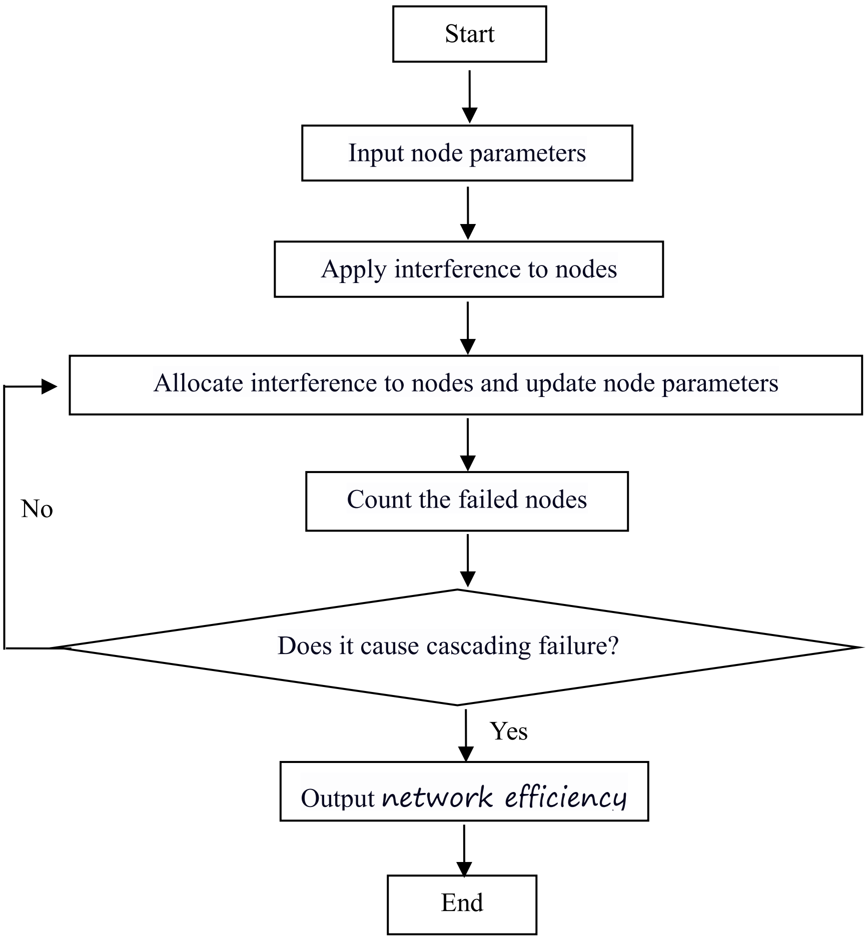

Figure 8:Cascade Failure Flow Chart.

In the study of the flight support network in the airport movement area, different risk-based attack strategies result in varying sequences of node attacks and have distinct impacts on the network. This study utilizes Matlab software for algorithm programming and simulation experiments. During the experiments, parameters are reasonably set and adjusted, with beta set to 0.5 and theat set to 1. Here, beta = 0.5 indicates that when the network is under attack, the ports (or nodes, depending on context; 'port' could be a metaphorical term here for nodes involved in load redistribution) bear 50% of the load

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redistribution.

Subsequently, the network's resilience under different attack strategies is analyzed. Through simulations, the changes in the relative size of the largest connected component and network efficiency are obtained. These changes visually demonstrate the impact of different attack strategies on the network's resilience, as illustrated in Figures 4-2 and 4-3.

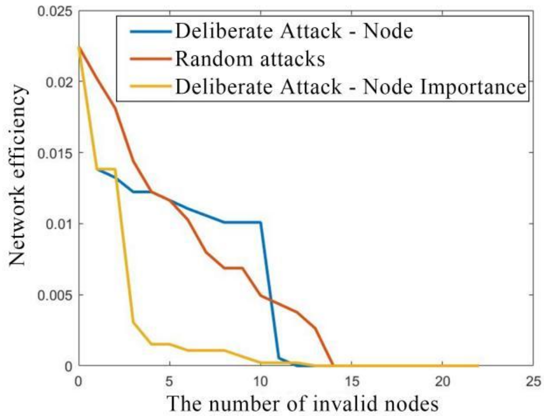

Figure 9:Analysis of the Efficiency of Cascading Failure Networks.

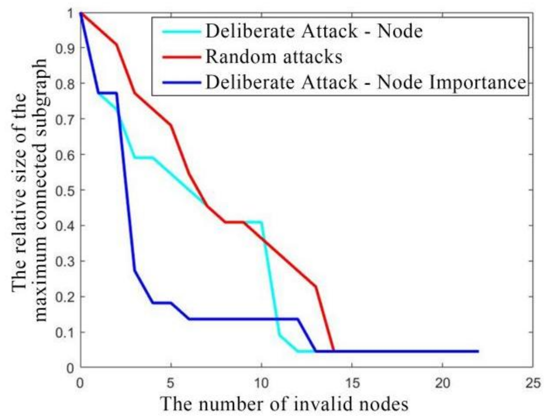

Figure 10:Relative size of the largest connected subgraph in cascading failure.

In this study, three different attack strategies—degree attack, random attack, and TOPSIS attack—were employed to analyze the trends in network efficiency and the relative size of the largest connected component as the number of failed nodes increased. From the perspective of the impact of attack strategies, degree attacks target nodes with high degrees, while TOPSIS attacks are based on node importance. Both strategies can rapidly decrease network efficiency in the early stages of the attack by quickly disabling key network nodes, thereby significantly affecting network performance. Although random attacks do not target specific nodes, their cumulative effect also leads to a gradual decline in network efficiency. Regarding key nodes, the failure of critical operational links such as Node 1 (chock and reflective cone placement), Node 4 (jet bridge/passenger staircase docking), and Node 20 (jet bridge/passenger staircase evacuation) has a notable impact on network efficiency. These nodes are likely to fail early under degree and TOPSIS attacks, leading to a rapid decline in network efficiency and highlighting the importance of their stability and reliability in the actual system. In terms of the trend in network efficiency, as the number of failed nodes increases, network efficiency generally shows a downward trend, with varying degrees and speeds of destruction across different attack strategies. A large number of failed nodes can severely disrupt network connectivity, reducing the size of the largest connected component. In practical applications, such as airport ground service systems, it is crucial to focus on and protect key nodes by enhancing redundancy, strengthening monitoring and maintenance, and other measures to improve their reliability and resilience against attacks. Simultaneously, corresponding countermeasures should be formulated for different attack strategies, such as preemptively protecting key nodes to counter degree and TOPSIS attacks and strengthening the overall system's resilience to withstand random attacks.

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5. Control strategy

In the operation and management of the traffic network within airport movement areas, scientific and reasonable recovery strategies are crucial for ensuring efficient and stable operations. Regarding fault detection, it is necessary to establish a regular and comprehensive mechanism for inspecting production resources. Given that airport traffic networks involve numerous complex facilities and equipment, any minor fault can trigger a chain reaction. Therefore, professional detection equipment and technical methods should be employed to conduct in-depth checks on hardware facilities, software systems, etc., within the network to accurately locate potential fault hazards. Once potential issues are identified, professional maintenance personnel should be promptly arranged to respond and repair them immediately, nipping fault risks in the bud and ensuring that the network remains in a safe and stable operational state, thereby providing solid support for subsequent flight support operations.

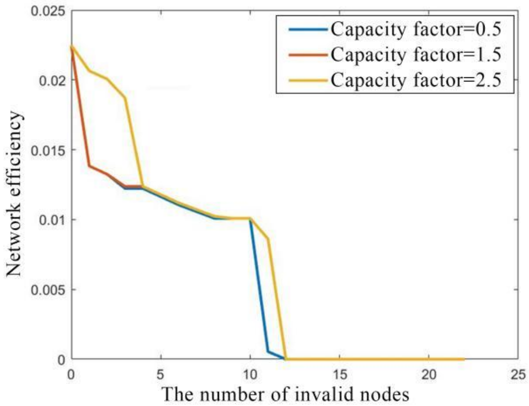

Figure 11:Relative size of the largest connected subgraph in cascading failure.

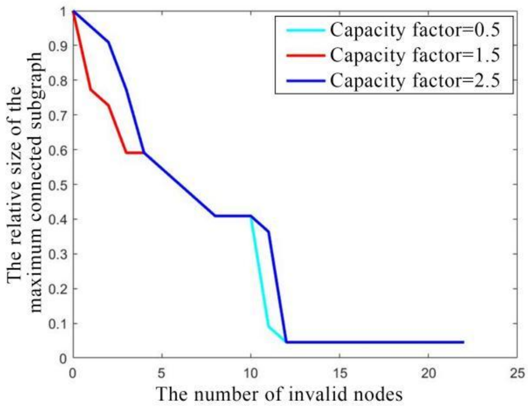

Figure 12:Analysis of the Relative Size of the Maximum Connected Subgraph with Capacity Differences.

The capacity coefficient, as an efficiency indicator, reflects the actual utilization efficiency of equipment or systems, helping managers accurately grasp the operational status of the system and plan resources reasonably. By using capacity parameters to simulate the maintenance level of the system, it can be observed that the higher the capacity parameter, the slower the curve declines.

The node backup strategy is an important defense line for ensuring network continuity. Given the extremely high requirements for real-time performance and reliability in airport traffic networks, it is essential to construct a backup node system. When the primary node fails due to sudden malfunctions, malicious attacks, or other reasons, the backup node can swiftly and seamlessly take over all functions of the primary node, ensuring the continuity of network services and avoiding problems such as flight support delays and traffic congestion caused by node failures, thereby minimizing the impact of faults on the overall airport operations. Capacity parameters and capacity coefficients are also indispensable elements in recovery strategies. As specific numerical values describing the physical quantities of a system, capacity parameters intuitively reflect the maximum capacity that the system can bear, providing an important basis for network planning and resource allocation. By using capacity

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parameters to simulate the backup of auxiliary vehicles, it can be observed that the higher the capacity parameter, the slower the curve declines.

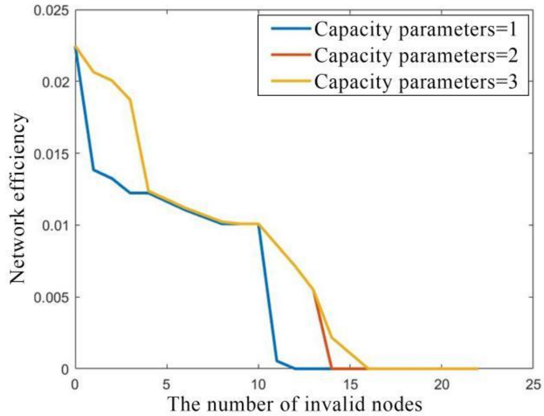

Figure 13:Analysis of Network Efficiency Based on Capacity Parameter Differences.

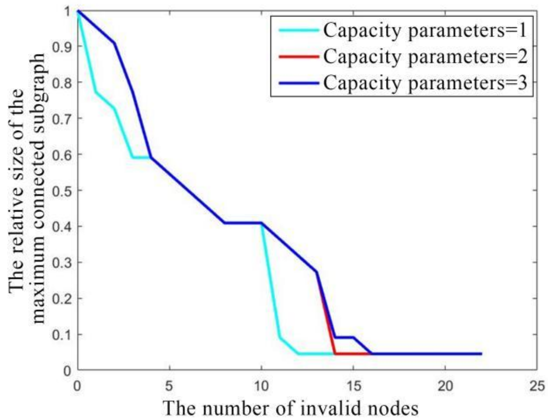

Figure 14:Analysis of Relative Size of Maximal Connected Subgraphs with Differences in Capacity Coefficients.

Through comparison, it can be found that increasing capacity parameters results in a slower curve decline compared to increasing capacity coefficients. The node backup strategy can more effectively enhance the overall efficiency of the system and strengthen the risk resistance capability of the flight support network.

6. Conclusions

This study focuses on the resilience of the AOV (Activity on Vertex) network in airport movement area operations, constructing a cascading failure model for the airport flight support network. By adapting the traditional capacity-load model, we quantify node loads and capacities, introduce a load redistribution mechanism, and establish a three-level threshold state classification, thereby creating an analytical framework that aligns with the dynamic operational characteristics of airports. Matlab simulations reveal that different attack strategies have varying impacts on network invulnerability, with the failure of key nodes having a particularly significant effect. Based on the model, we propose two resilience optimization strategies: a key node protection strategy that incorporates multi-source data for real-time monitoring, and a node backup strategy that constructs a redundant system to ensure operational continuity. The study also finds that capacity parameters play a crucial role in enhancing network resilience. Finally, we propose guidelines for resilience optimization, providing theoretical support for improving the resilience of airport networks.

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