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Research Article

The Construction of an Aircraft Control Multilayer Network and Its Robustness Analysis

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When aircraft are flying along the routes, their states present diversity and complexity. To clarify the control or monitoring relationship between air sectors and aircraft in the airspace and to promote reliability and efficiency of air traffic control (ATC), in this paper, an aircraft control multilayer network (ACMN) model is built by considering the air sector network (ASCN) and the aircraft state network (ASTN). The characteristics of ACMN are studied based on complex network theory. Simultaneously, according to the multilayer characteristics of ACMN and the relative entropy theory, a robustness analysis method is proposed. Results show that the proposed method is applicable for evaluating the structural stability and robustness of ACMN and is effective in improving the efficiency of ATC. It can also provide a new idea for the robustness research of multilayer networks.

1. Introduction

Air transport is an important part of the traffic system. In recent years, more and more people have chosen air travel, and the aviation industry has ushered in great development. As a result, air traffic busyness and congestion are rising, and the safety, reliability, and smoothness of air traffic are facing challenges. When an aircraft is flying along the route, its distribution is complex and diverse, and the state between aircraft is bound to have relevance. Each aircraft can be regarded as a point, and the correlation between aircraft can be expressed by a line. Thus, an aircraft state network model is formed, and the key points in the model can be effectively evaluated so as to analyze the correlation complexity of aircraft. Therefore, the state of the aircraft can be accurately handled, which can not only improve the smoothness and safety of flight but also improve the accuracy and efficiency of air traffic control (ATC).

In addition, aircraft fly in air sectors, and each sector is monitored by air traffic controllers. Considering the air sector network and aircraft state network, the aircraft control multilayer network (ACMN) model is conducive to clarifying the relationship between air sectors and aircraft, thereby promoting the safety and reliability of ATC. The ACMN model is essentially a complex network, so its characteristic analysis can be based on complex network theory. Simultaneously, according to the multilayer characteristics of ACMN and the relative entropy theory, a network robustness analysis method is proposed in this paper. The results can provide a reference for improving the efficiency of ATC.

This paper is organized as follows: the literature review is in Section 2, and Section 3 analyzes the air-state relationship among aircraft and establishes the ACMN model. Section 4 introduces some basic centrality theories and establishes a robustness analysis model. The results are analyzed in Section 5. Finally, Section 6 concludes this paper and future work.

2. Literature Review

The aircraft control multilayer network (ACMN) is essentially a complex network model, and its node evaluation analysis can be implemented based on complex network theory. With the passage of time, the evaluation model for key nodes in complex networks has developed considerably. Common centrality theories include node degree [1], betweenness [2], closeness [3], clustering coefficient [4], and so on. At the same time, some scholars have made some improvements based on the common centrality theory. Opsahl et al. [5] use both generalizing degree and shortest paths to evaluate the node centrality in weighted networks. The generalized centrality measures are used to identify important nodes in weighted covert networks [6]. A local ranking algorithm named ClusterRank is proposed in [7], which takes into account not only the number of neighbors and the neighbors' influences but also the clustering coefficient. The influence of the global structure and the local structure is considered in [8] to identify influential nodes in complex networks. Fei and Deng [9] apply relative entropy to identify influential nodes. Of course, the corresponding use in the air transportation network is also very common. Zhang et al. [10] investigate the evolution of the Chinese airport network (CAN) via complex network theory, and results show that many dynamic switchings inside the network have changed the relative importance of airports and airlines. The study in [11] shows that the present Chinese domestic airline network is a small-world network with degree distribution obeying a double power law. In [12], two network layers —the air navigation route network and the airport network —are analyzed to study the temporal evolution of the European air transportation system. Hossain and Alam [13] model Australia's civil domestic airport infrastructure as a network and analyze the resulting network structure and its features using complex networks. The air cargo transport network is analyzed by complex network theory in [14]. Besides, an air sector network is built based on the obtained data describing the airspace of the world by Wang et al. [15]. In [16], from the perspective of multilayer network mechanisms, the dynamics of the Chinese air transportation network are extensively investigated.

In addition, as the aviation network continues to expand, its structural properties and robustness have also become the focus of attention. Wen et al. [17] evaluate the importance of nodes in an aviation network based on complex network theory and the node deletion method. The structure of the world airline network is analyzed in [18]. Besides, the characteristics of air traffic networks [19] and air traffic situation networks [20, 21] have also been studied based on complex network theory. From the perspective of network structure, Li et al. [22] analyze the reliability of an air traffic network. Scholars have also studied the European air transport network [23] and the Chinese air route network [24]. Moreover, based on complex network theory, the robustness of the air transport network [25] and aircraft state network [26] are also studied by researchers. Roucolle et al. build comprehensive indicators to measure airline networks [27]. In [28], the authors discover the robustness paradox phenomenon in air traffic networks (ATNs) and propose ways to enhance the robustness of ATNs. Lordan et al. [29, 30] carry out a robustness analysis on the global air transport network (ATN) and airline alliance route networks, respectively, which provided ideas for studying the robustness of the air transport network. Pien et al. [31] conducted topological and operational analyses of the European air traffic network (ATN) in order to derive a more relevant and appropriate indicator of robustness. To analyze the temporal pattern of the Chinese aviation network (CAN), a time series of topological statistics through sliding the temporal CAN with an hourly time window is obtained in [32]. The robustness of the air route network (ARN) is analyzed by the topology potential and relative entropy methods in [33]. In addition, Ren and Li [34] compare the characteristics of air traffic networks between China and the United States. Over the past two years, the robustness of aviation networks has also received attention [35, 36].

Based on the research above, previous papers rarely analyze air traffic networks from the perspective of ATC. In this paper, the aircraft control multilayer network will be established, and then its characteristics and robustness will be analyzed to provide a reference for the robustness analysis of the aviation network. Furthermore, to promote the safety and smoothness of ATC.

3. Aircraft State Network (ASTN)

3.1. Air Route Network. Airspace is the specific space in which aircraft operate in the air. The trajectory of aircraft in the airspace is guided by the air route; that is, the air route is the carrier of aircraft. The utilization efficiency of airspace is deeply affected by the structure of air routes, and the crowding effect of airspace. Route structure and aircraft distribution are of practical significance for ensuring aviation safety and improving airspace utilization efficiency. In this section, the structural characteristics of the route and the correlation of aircraft along the route will be analyzed, and then the aircraft state network (ASTN) model will be established.

The airline network represents the transportation relationship between the initial airport and the destination, which is a logical relationship between OD pairs. It reflects the flight direction, origin, destination, and stop location of the aircraft. However, unlike the airline, the air route represents the physical trajectory of the aircraft. In general, the aircraft does not fly along the optimized and smooth trajectory between airports in the airspace but follows the preset path network in the airspace. The diagram of the air route network (ARN) is shown in Figure 1.

As shown in Figure 1, route sections and waypoints (such as navigation points, route intersections, turning points, and reporting points) are connected to each other to form an ARN model. In general, the ARN has a hub-and-spoke structure. Furthermore, the structure of ARN shows that the most basic ones are linear, cross, convergent, and divergent. The specific structure of ARN is shown in Figure 2.

Air traffic flow is distributed on the ARN, and the distribution of traffic is unbalanced. As air traffic continues to grow, there is an increasing likelihood of flight conflicts, delays, and localized congestion in the air. The structural characteristics of ARN have an important influence on the smooth operation of the aircraft in airspace, and they also

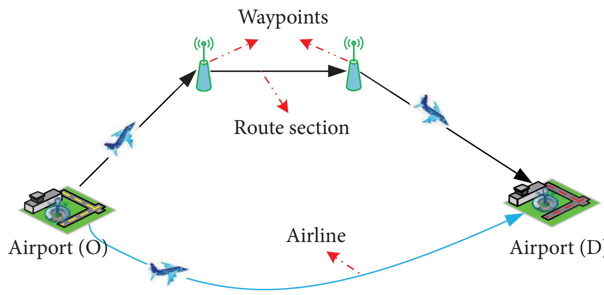


FIGURE 1: Diagram of the air route.

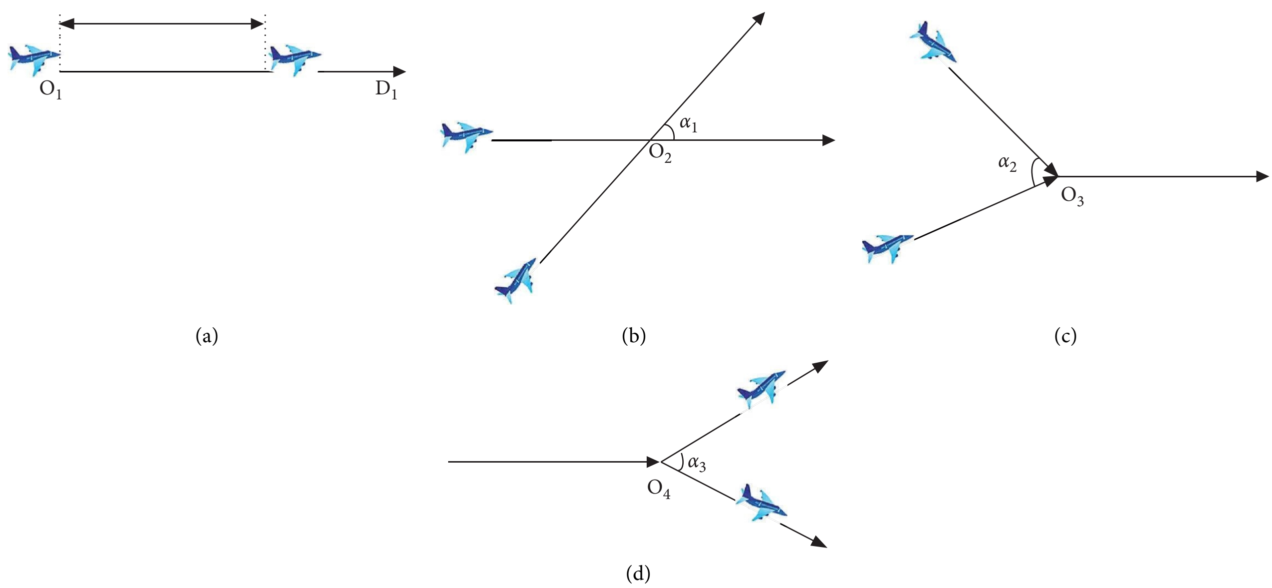


FIGURE 2: The basic structure of air routes. (a) A linear air route. (b) Cross-air routes. (c) Convergent air routes. (d) Divergent air routes.

affect the distribution state of aircraft. The distribution of aircraft along different air routes and the correlation between them play an important role in the efficiency and orderliness of aircraft in the airspace.

3.2. Establishment of ASTN. The air state of the aircraft refers to the distribution and operation trend of the aircraft when it is running in the airspace. There is a situational correlation between two aircraft when there is a direct impact or connection between them, such as a flight conflict, delay, or congestion. Obviously, the state relevance of aircraft is directly affected by flight direction, flight attitude, and route structure. The distribution of aircraft along different air routes is shown in Figure 3.

As shown in Figure 3(a), three aircraft A_1, A_2, and A_3 fly along the air route. A_3 is the front plane, and its flight condition directly affects the rear A_2, while A_2 affects A_1. Therefore, there is a state correlation between A_2 and A_1 or A_3 (represented by red dotted lines), and this correlation has a transmission effect. In Figure 3(b), aircraft B_3 and B_4 intersect at the same point Q_2, and there is a state correlation between the two aircraft. However, B_1 and B_2 are in a divergent state of flight from each other, and there is no correlation. Meanwhile, B_1 and B_2 also pass Q_2, so they are affected by aircraft B_3 and B_4. Similarly, Figures 3(c) and 3(d) can be obtained.

The aircraft can be regarded as nodes, and an edge is added if there is a state correlation between the nodes, thus constructing the ASTN model. The ASTN along different air routes is shown in Figure 4.

Set the ASTN as $G = (V, E)$ where $V = \{v_i | i = 1, 2, 3, \ldots, n\}$ represents the number of nodes; that is, the number of aircraft, $E = \{(v_i, v_j) | i \neq j, v_i, v_j \in V\}$ is the number of edges, which represents the state correlation between aircraft. The state correlation between aircraft can be expressed by $A = (a_{ij})_{n\times n}$, and the elements in the matrix are

$$a_{ij} = \begin{cases} 1, & \text{State correlation between aircraft } i \text{ and } j, \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

For example, in Figure 4(b), its adjacency matrix is expressed as

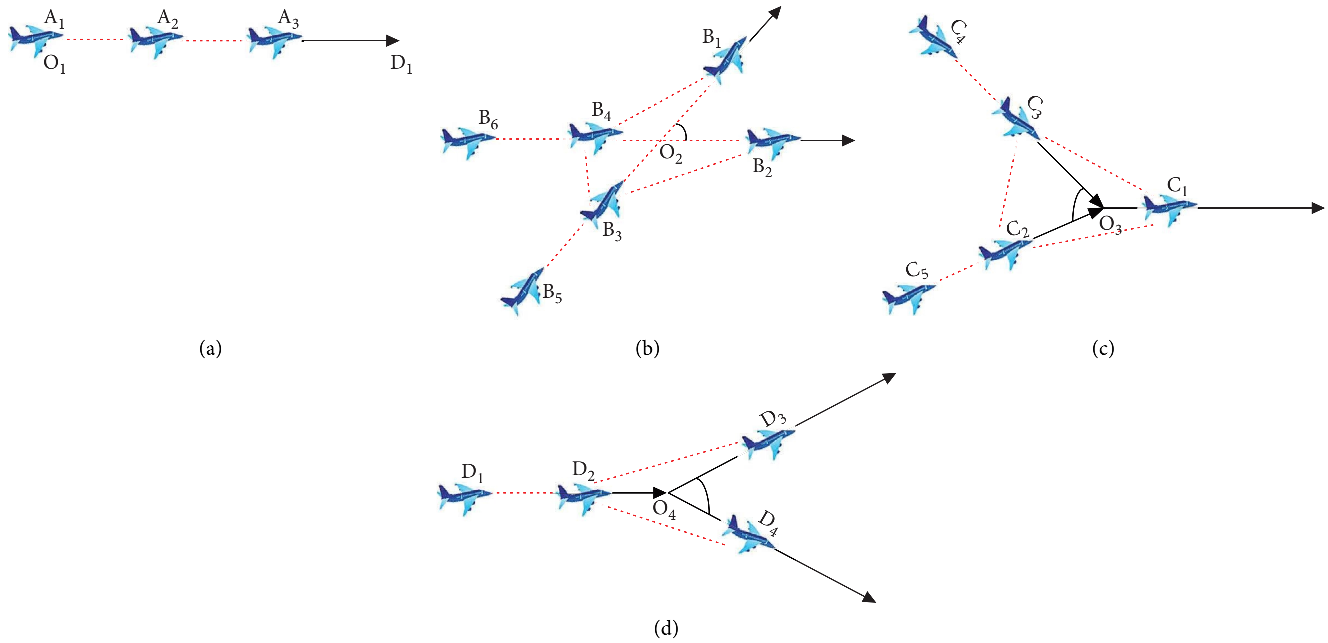


Figure 3: State of aircraft along different air routes. (a) Aircraft state along linear air routes. (b) Aircraft state along cross-air routes. (c) Aircraft state along convergent air routes. (d) Aircraft state along divergent air routes.

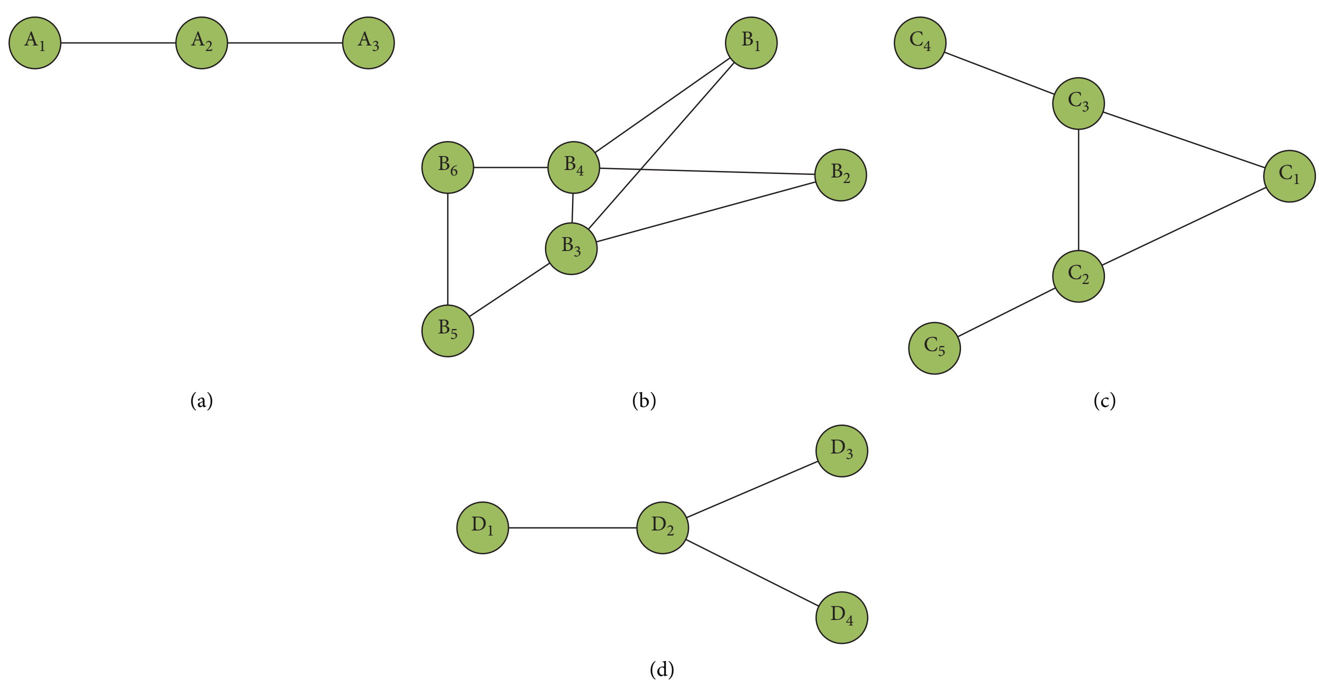


Figure 4: ASTN along different air routes. (a) ASTN along linear air routes. (b) ASTN along cross-air routes. (c) ASTN along convergent air routes. (d) ASTN along divergent air routes.

$$A = \begin{Bmatrix} 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 \end{Bmatrix}. \quad (2)$$

The ASTN reflects the smooth operation of aircraft in airspace, in which the key nodes (aircraft) have an important impact on the safety, efficiency, and stability of flight operation. Accurate and effective identification of key nodes in the model is of great significance for improving airspace utilization and reducing delay. Moreover, the robustness of ASTN can reflect the orderliness of air operations, which is important for air traffic control (ATC).

3.3. Air Sector Network. Airspace is the specific environment for aircraft operation, and it is also the area where aircraft receive air traffic control services. In order to improve the reliability and efficiency of ATC and ensure the safety and order of aircraft operations, the airspace is divided into several areas, each of which is equipped with at least one air traffic controller; this area is called air sector. Each sector is a basic ATC unit. When the aircraft passes through the sector, the controller and the aircraft will have a control connection, and at the same time, there will be communication between adjacent sectors.

Each sector is reduced to a node. If there is communication between two sectors, an edge is added, which constitutes an air sector network (ASCN) model. The ASCN model is shown in Figure 5.

3.4. Aircraft Control Multilayer Network. Air route sections and waypoints are widely distributed in the sector. At the same time, the airways can guide the flight of the aircraft. When aircraft are flying, the controller will always pay attention to them and communicate with them. Within a certain period of time, all aircraft in the sector are controlled by the sector controller. Besides, a sector will communicate with multiple aircraft, so there is a "one-to-many" relationship between the sector and the aircraft. Therefore, the aircraft control multilayer network (ACMN) has the characteristics of a dual-level and multicorresponding relationship.

Assuming that the ACMN is expressed as G, the ASTN is $G1$, and the ASCN is $G2$, then,

$$G = \{G1, G2\}. \quad (3)$$

Based on the abovementioned analysis, the adjacency matrix A of G includes the following parts.

For $G1$ (or $G2$), the element of adjacency matrix $A^{(G1)}$ is

$$a_{ij}^{(G1)} = \begin{cases} 1, & i \text{ is connected to } j,\ i\ j \in G1, \\ 0, & i \text{ and } j \text{ are not connected},\ i\ j \in G1. \end{cases} \quad (4)$$

For the adjacency matrix $A^{(G1G2)}$ between two layers, its elements are represented as

$$a_{ij}^{(G1G2)} = \begin{cases} 1, & i \text{ is connected to } j,\ i \in G1\ j \in G2, \\ 0, & i \text{ and } j \text{ are not connected},\ i \in G1\ j \in G2. \end{cases} \quad (5)$$

Therefore, the adjacency matrix of ACMN is $A = \{A^{(G1)}, A^{(G1G2)}, A^{(G2)}\}$.

The structure of ACMN is shown in Figure 6.

It can be seen from Figure 7 that aircraft $A1$, $A2$, and $A3$ are in sector 1, so they are connected to sector 1, forming a multilayer network relationship. Similarly, other aircraft are also connected to their corresponding sectors. Finally, the multilayer network model of an aircraft is formed.

4. Evaluation Model

4.1. Basic Parameters. The ACMN is a complex network, so the basic parameters of complex network theory can be used. Node centrality reflects the relative importance of each node in the model. In this paper, the node centrality of the ACMN indicates that there are direct connections between the aircraft and their surroundings. The key aircraft directly affects the operation state of others, which also play an important role in the safety and smoothness of airspace.

The main parameters that represent node centrality in complex network theory are degree, betweenness, and closeness centrality.

The degree centrality $C_D(v_i)$ of node v_i can be expressed as

$$C_D(v_i) = \frac{d_i}{(n-1)}, \quad (6)$$

where d_i is the degree of node v_i, $(n-1)$ is the maximum degree. In ASTN, degree centrality represents the tightness of one aircraft with its neighbors, reflecting the operational situation (smoothness, safety, etc.) of the aircraft. Similarly, in ASCN, the degree of centrality represents the connectivity of a sector to its neighboring sectors, reflecting the importance of the sector in the airspace.

The degree centrality C_D of network G can be expressed as

$$C_D = \frac{1}{n-2} \sum_{i=1}^{n} [C_D(v_{\max}) - C_D(v_i)], \quad (7)$$

where $C_D(v_{\max})$ is the maximum degree of nodes in G.

Similarly, the betweenness centrality $C_B(v_i)$ of node v_i is

$$C_B(v_i) = \frac{2B_i}{[(n-1)(n-2)]}, \quad (8)$$

where B_i represents the betweenness of node v_i. In ASTN, the betweenness centrality reflects those changes in the operational situation of one aircraft that have a greater impact on the operation of other ones. Meanwhile, the betweenness centrality of one sector indicates the importance of the sector to the global structure and stability of the

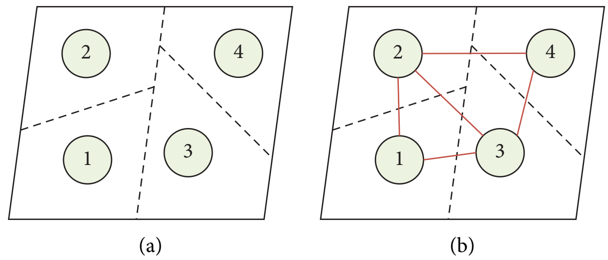


Figure 5: The ASCN model. (a) Diagram of the air sector. (b) Air sector network.

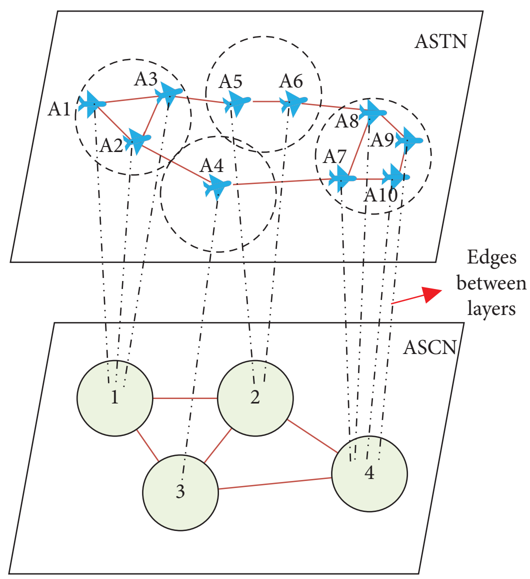


Figure 6: The ACMN model.

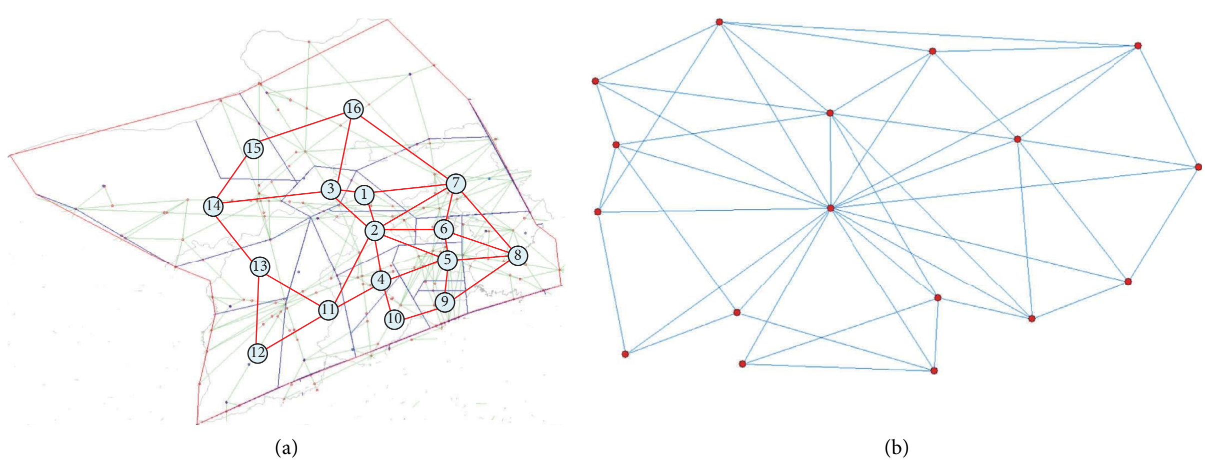


Figure 7: The ASCN model of BCA. (a) Air sectors in the BCA. (b) Air sector network.

airspace. Of course, closeness and centrality have similar meanings.

The betweenness centrality C_B of network G is

$$C_B = \frac{1}{n-1}\sum_{i=1}^{n}\left[C_B\left(v_{\max}\right) - C_B\left(v_i\right)\right], \tag{9}$$

where $C_B(v_{\max})$ is the maximum betweenness of nodes in G.

The closeness centrality $C_C(v_i)$ of node v_i is

$$C_C\left(v_i\right) = \frac{(n-1)}{\sum_{i=1, j\neq i}^{n} l_{ij}}, \tag{10}$$

where l_{ij} represents the distance from node v_i to v_j.

The closeness centrality C_C of G is

$$C_C = \frac{2n-3}{(n-1)(n-2)} \sum_{i=1}^{n} \left[C_C(v_{\max}) - C_C(v_i)\right], \quad (11)$$

where $C_C(v_{\max})$ is the maximum closeness of nodes in G.

4.2. Characteristic Parameters. The cumulative degree is used to represent degree distribution in complex networks, and its expression is

$$P_d = \sum_{i=d}^{\infty} P(i), \quad (12)$$

where P_d denotes the probability distribution of nodes whose degree is not less than d.

In addition, the degree-degree correlation (r) of the network is also an important statistical feature. Generally, it can be expressed by the Pearson correlation coefficient and the relationship between the degree and the average degree of the nearest neighbor.

The degree-degree correlation is

$$r = \frac{M^{-1}\sum_{e_{ij}\in E} d_i d_j - \left[M^{-1}\sum_{e_{ij}\in E}(1/2)\left(d_i + d_j\right)\right]^2}{M^{-1}\sum_{e_{ij}\in E}(1/2)\left(d_i^2 + d_j^2\right) - \left[M^{-1}\sum_{e_{ij}\in E}(1/2)\left(d_i + d_j\right)\right]^2}, \quad (13)$$

where d_i and d_j are the degrees of the two nodes of edge e_{ij}, E is the set of edges, and M is the number of edges. The absolute value $|r| \in [0,1]$, $r > 0$ represent the positive correlation of the network, $r < 0$ represents the negative correlation, and $r = 0$ represents the noncorrelation.

The nearest-neighbor average degree is

$$d_{nn.i} = \frac{\left[\sum_j a_{ij} d_j\right]}{d_i}, \quad (14)$$

where a_{ij} is the element of the adjacency matrix.

Furthermore, the average value of $d_{nn,i}$ is expressed as

$$d_{nn}(d) = \frac{\sum_{i|d_i=d} d_{nn,i}}{[N \cdot P(d)]}, \quad (15)$$

where N is the number of nodes, $P(d)$ is the degree distribution. $d_{nn}(d)$ is an increasing function of d, indicating that the network is assortative. Otherwise, the network is disassortative.

4.3. Evaluation Index. The average path length $L(G)$ of G is expressed as

$$L(G) = \frac{2}{n(n-1)} \sum_{1\le i<j\le n} l_{ij}, \quad (16)$$

where l_{ij} represents the distance between any two nodes.

The average reciprocal of the distance between nodes is network efficiency, expressed by $E(G)$, and then,

$$E(G) = \frac{2}{n(n-1)} \sum_{1\le i<j\le n} \frac{1}{l_{ij}}. \quad (17)$$

Network connectivity can reflect the integrity of a certain function, and the impact of nodes on network connectivity can reflect the relative importance of nodes. In this section, the maximum connected component and connectivity coefficient are used to measure the connectivity of the network.

The ratio $C_R(v_i)$ is expressed as

$$C_R(v_i) = \frac{n_{v_i}}{n}, \quad (18)$$

where n is the number of nodes in the network, and n_{v_i} is the number of nodes in the maximum connected component after removing node v_i.

4.4. Multilayer Network Robustness Model. When a node in a multilayer network is deleted, there are two changes in the single-layer network and cascading failures between networks. Therefore, when analyzing its robustness, the comprehensiveness of the multilayer network should be considered, and the change in the robustness index should be considered as a whole.

Let G be a multilayer network with m layers and the network efficiency is $[E(G1), E(G2), \ldots, E(Gm)]$. When the network G is attacked, the remaining network can be expressed as G'. After a random attack, the efficiency of each layer of G' is $[E(G_r'1), E(G_r'2), \ldots, E(G_r'm)]$, and after a deliberate attack, the efficiency of each layer of G' is $[E(G_d'1), E(G_d'2), \ldots, E(G_d'm)]$. The distribution of the abovementioned network efficiency can be expressed as

$$\begin{bmatrix} E(G1) & E(G2) & \cdots & E(Gm) \\ E(G_r'1) & E(G_r'2) & \cdots & E(G_r'm) \\ E(G_r'1) & E(G_r'2) & \cdots & E(G_r'm) \end{bmatrix}. \quad (19)$$

The abovementioned data can be regarded as a distribution of random variables. The robustness of a multilayer network can be represented by the total relative change in the efficiency of different layers. Therefore, the relative entropy theory can be used to measure the network efficiency change.

Let $P(x)$ and $Q(x)$ be two random distributions, and their relative entropy D can be expressed as

$$D = D_K(P\|Q) = \sum P(x) \ln \frac{P(x)}{Q(x)}. \quad (20)$$

For the network efficiency distribution of multilayer networks, the relative entropy can be expressed as

$$
\begin{aligned}
\Delta E_r &= D_K\left(E(G)||E(G_r')\right),\\
&= E(G1)\ln\frac{E(G1)}{E(G_r'1)} + E(G2)\ln\frac{E(G2)}{E(G_r'2)} + \cdots + E(Gi)\ln\frac{E(Gi)}{E(G_r'i)},\\
&= \sum_{i=1}^{m} E(Gi)\ln\frac{E(Gi)}{E(G_r'i)},\\
\Delta E_d &= D_K\left(E(G)||E(G_d')\right),\\
&= E(G1)\ln\frac{E(G1)}{E(G_d'1)} + E(G2)\ln\frac{E(G2)}{E(G_d'2)} + \cdots + E(Gi)\ln\frac{E(Gi)}{E(G_d'i)},\\
&= \sum_{i=1}^{m} E(Gi)\ln\frac{E(Gi)}{E(G_d'i)}.
\end{aligned}
\tag{21}
$$

Then, the relative entropy ΔE is normalized as follows:

$$\overline{\Delta E} = \frac{\Delta E - \Delta E_{\min}}{\Delta E_{\max} - \Delta E_{\min}}. \tag{22}$$

Furthermore, for multilayer networks, the robustness index based on network efficiency can be expressed as

$$BE = \frac{1}{\exp\left(\overline{\Delta E}\right)}. \tag{23}$$

Similarly, in the multilayer network G, the maximum connected component size of each layer is $[R(G1), R(G2), \ldots, R(Gm)]$. When the network G is attacked, the remaining network can be expressed as G'. After a random attack, the maximum connected component size of each layer of G' is $[R(G_r'1), R(G_r'2), \ldots, R(G_r'm)]$, and after a deliberate attack, the maximum connected component size of each layer of G' is $[R(G_d'1), R(G_d'2), \ldots, R(G_d'm)]$. The maximum connected component size abovementioned can be represented by a matrix as

$$\begin{bmatrix} R(G1) & R(G2) & \cdots & R(Gm)\\ R(G_r'1) & R(G_r'2) & \cdots & R(G_r'm)\\ R(G_d'1) & R(G_d'2) & \cdots & R(G_d'm) \end{bmatrix}. \tag{24}$$

For the distribution of the maximum connected component size of a multilayer network, its relative entropy ΔR can be expressed as

$$
\begin{aligned}
\Delta R_r &= D_K\left(R(G)||R(G_r')\right) = \sum_{i=1}^{m} R(Gi)\ln\frac{R(Gi)}{R(G_r'i)},\\
\Delta R_d &= D_K\left(R(G)||R(G_d')\right) = \sum_{i=1}^{m} R(Gi)\ln\frac{R(Gi)}{R(G_d'i)}.
\end{aligned}
\tag{25}
$$

Similarly, the relative entropy ΔR is normalized as follows:

$$\overline{\Delta R} = \frac{\Delta R - \Delta R_{\min}}{\Delta R_{\max} - \Delta R_{\min}}. \tag{26}$$

Therefore, for multilayer networks, the robustness index based on the maximum connected component size can be expressed as

$$BR = \frac{1}{\exp\left(\overline{\Delta R}\right)}. \tag{27}$$

Finally, for the ACMN, its robustness can be represented by the combination of BE and BR.

5. Results Analysis

5.1. Data Analysis. The Controlled Airspace of Beijing (BCA) is one of the busiest areas of civil aviation in China. Based on the statistics of the Air Traffic Administration, this section takes the BCA as an example for analysis. The spatial distribution of air routes and sectors in the BCA is shown in Figure 8.

In Figure 8, the spatial distribution of air routes and sectors in the BCA is shown. The red solid line represents the boundary of the controlled airspace, and the red dots represent key waypoints. These key waypoints include navigation points, position reporting points, route intersections, etc., and routes are between the waypoints. In addition, the blue solid line represents the boundary of the air sector, and the numbering shows that the number of sectors is 16.

The distribution of 72 aircraft in BCA within a time window is shown in Figure 7. According to the situation correlation analysis in Section 1, the ASTN model can be established as shown in Figure 9.

According to the distribution of aircraft, the control relationship between air sectors and aircraft is analyzed, and an aircraft control multilayer network (ACMN) model is constructed. The results are shown in Figure 10.

5.2. Characteristic Analysis. The ACMN is a typical complex network, so its basic characteristics can be analyzed by complex network theory. The cumulative degree distribution function is used to describe the degree distribution characteristics, and the results are shown in Figure 11.

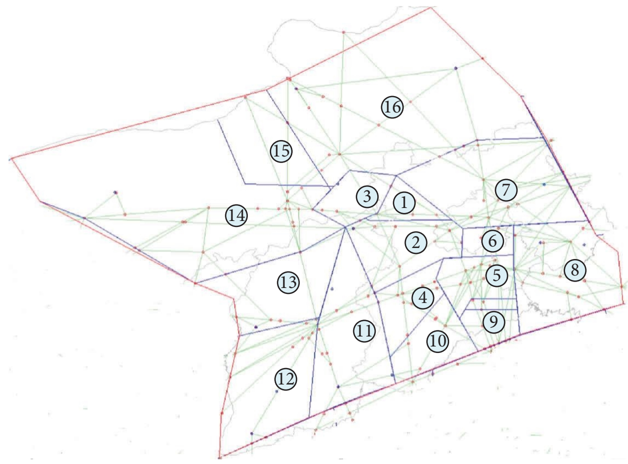
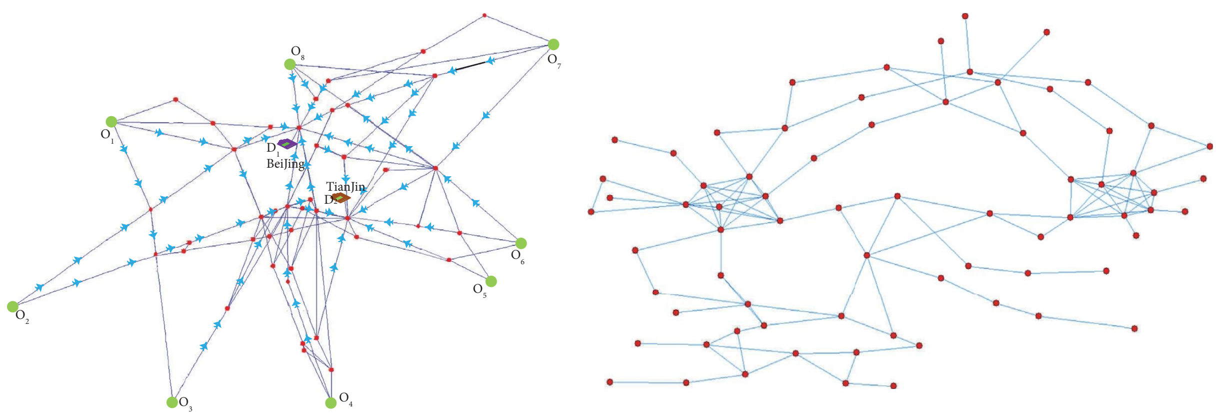


Figure 8: The diagram of BCA.



(a) (b)

Figure 9: The ASTN model of BCA. (a) The distribution of aircraft in the BCA. (b) Aircraft state network.

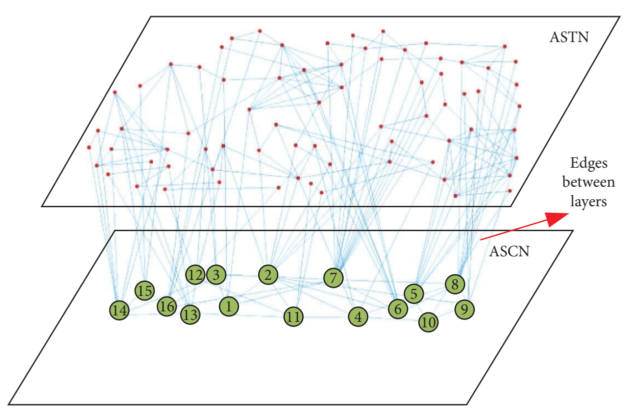


Figure 10: The ACMN model.

Figure 11 shows that the degree distribution of ACMN obeys an exponential distribution and its fitting degree $R^2 > 0.9$. Therefore, the degree of the ACMN decreases rapidly; that is, the degree of a few nodes is large, and the degree of most nodes is relatively small. Furthermore, the degree-degree correlation of the ACMN is analyzed, and the degree correlation coefficient (r) is calculated. The results are shown in Figure 12.

Figure 12 shows the changes of the nearest-neighbor average degree $d_{nn}(d)$ with the degree d. The trend shows that the nearest-neighbor average degree has a positive correlation with the degree; that is, $d_{nn}(d)$ is an increasing function of d. In addition, the degree-degree correlation coefficient $r > 0$ of the ACMN shows that nodes with a large degree tend to connect large-degree ones. Therefore, the ACMN has assortative structure characteristics.

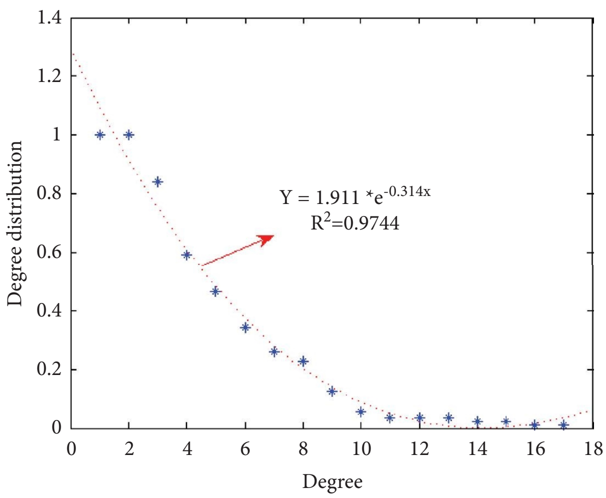


Figure 11: The degree distribution of ACMN.

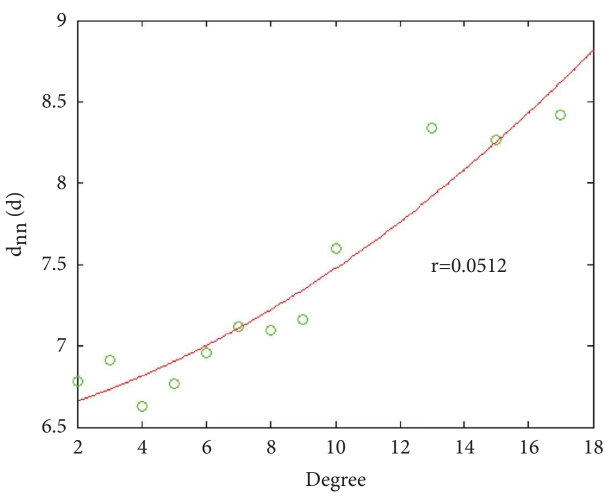


Figure 12: The changes of $d_{nn}(d)$ with d.

Then, the basic characteristics of each subnet in the ACMN model are given, and the results are shown in Table 1.

It can be seen from Table 1 that the number of nodes in ASTN is 72 and the number of edges is 197, so its density is 0.07, which is a relatively low density. The average degree is 3, indicating that on average, the state connection among each of the three aircraft is the closest. From the clustering coefficient and the average shortest path, the ASTN has no obvious small-world characteristics. The density of the ASCN is 0.41, indicating that the network is relatively dense, and its average degree is 3, indicating that each aircraft flies through an average of 3 sectors. At the same time, the ASCN exhibits certain small-world characteristics. Similarly, the ACMN is a low-density network, and every 5 nodes are most closely connected. In addition, the ACMN model does not have obvious small-world characteristics.

5.3. Robustness Analysis Based on Attack Strategy. In a complex network, the centrality of a node expresses the important influence of a node's attributes in the network. In the ASTN, the node is the aircraft, and its centrality has an important relationship with the congestion, delay, and safety of the aircraft in the airspace. Namely, the relationship between the aircraft is that during the flight, the state of each aircraft will be affected by the others (for example, when one aircraft accelerates or climbs, adjacent or even surrounding ones may have to monitor or make avoidance operations). In the ASCN, the centrality of nodes reflects the control relationship between aircraft and the sector. Therefore, different nodes have different effects on the robustness of the ACMN, and attacking different nodes can reflect the robustness of the model.

Next, the attack strategy is implemented on the ACMN. First, the nodes are sorted from high to low according to the results of node centrality, and then the nodes are attacked in turn to obtain the evaluation index value. The robustness of ACMN is analyzed based on complex network theory, and the results are shown in Figure 13.

Figure 13 shows the changes in network efficiency and the maximum connected component under an attack strategy. The trend of the curve is consistent with the common complex network, but it does not reflect the influence of the characteristics of the multilayer network on the robustness. Next, the robustness will be analyzed based on the characteristics of multilayer networks.

5.4. Robustness Analysis Based on Multilayer Networks. For the ACMN, the multilayer network is intentionally attacked based on different centrality strategies, and then the robustness of the network model is analyzed. From the perspective of cascading failure in a multilayer network, when the air sector is closed by interference, the aircraft in it cannot accept the control instructions and cannot pass normally, so the ASTN is also affected, resulting in cascading failure. The robustness is shown in Figure 14. A non-cascading failure means that when the air sector is affected, the aircraft can communicate with each other through airborne navigation or other navigation methods so that the flight can be maintained. At this time, the ASTN can avoid the impact of the air sector. Its robustness is shown in Figure 15.

The results in Figures 14 and 15 show that the integrity of the sector structure has an important impact on the stability of the ACMN, which is consistent with the rule that the normal flight of aircraft is regulated by the sector. Besides, the stability of the sector also has an impact on the reliability and efficiency of the flight.

Next, based on the relative entropy theory in Section 4.4, the influence of the coupling between ASTN and ASCN on the robustness of ACMN is analyzed, and the results are shown in Figure 16.

Figures 16(a) and 16(b) show that with the failure of nodes, the relative entropy of the network efficiency and the relative entropy of the maximum connected component both increase rapidly. That is, the more the network efficiency and the maximum number of connected components are affected, the more obvious the relative entropy changes

Table 1: Basic characteristics of each subnet in the ACMN.

Model	Nodes	Edges	Average degree	Clustering coefficient	Average shortest path
ASTN	72	197	3.3611	0.5328	10.3044
ASCN	16	49	3.6874	0.4053	4.5167
ACMN	88	316	5.0795	0.4700	6.7644

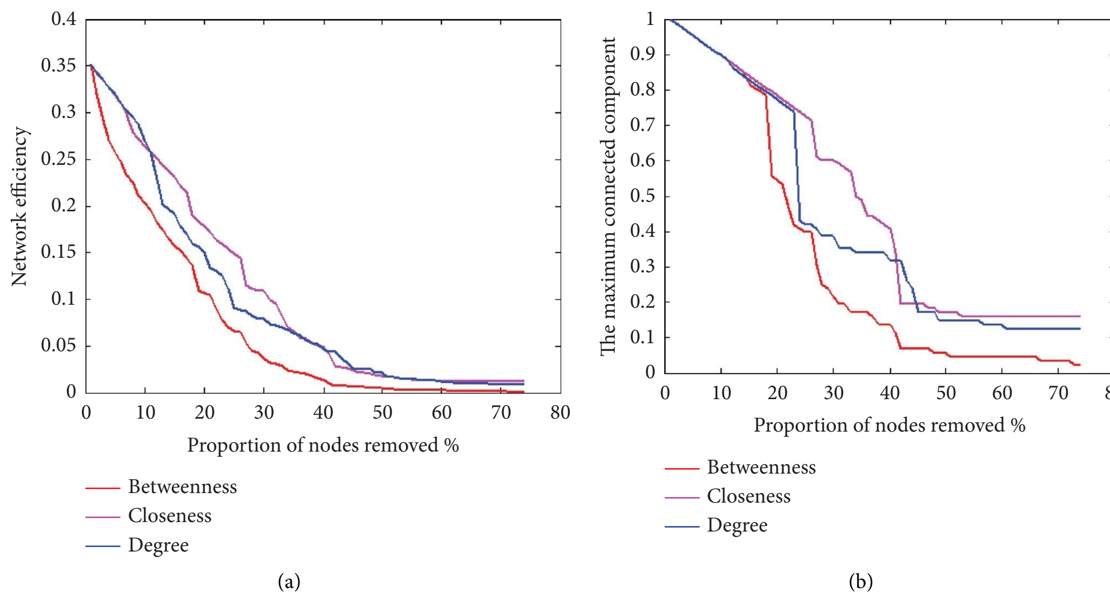


Figure 13: The robustness of ACMN under different attack strategies. (a) Network efficiency. (b) Maximum connected component.

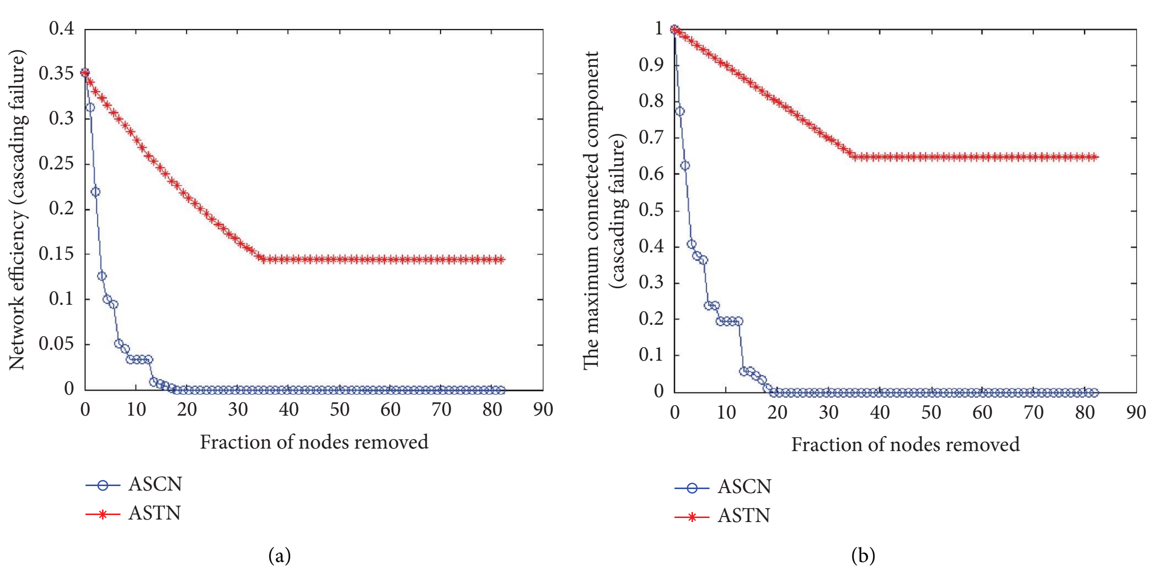


Figure 14: The robustness of ACMN under cascading failure. (a) Network efficiency (cascading). (b) Maximum connected component (cascading).

are, and the weaker the network can maintain stability. The curves in Figures 16(c) and 16(d) show that betweenness and degree have the greatest impact on the robustness of the ACMN. Furthermore, the coupling properties of ASTN and ASCN are also reflected, and the results demonstrate the practicability and effectiveness of the proposed method.

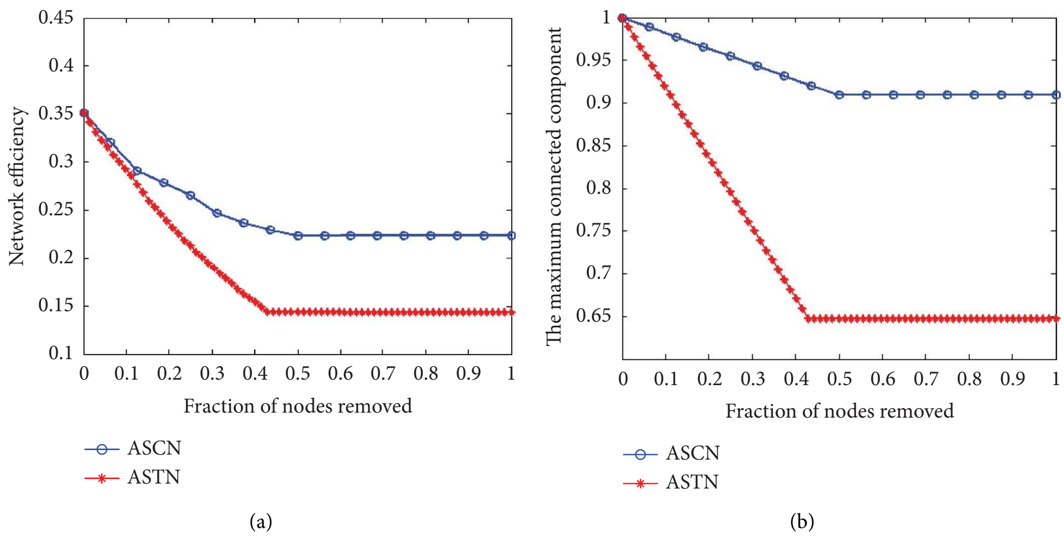


Figure 15: The robustness of ACMN under noncascading failure. (a) Network efficiency (noncascading). (b) Maximum connected component (noncascading).

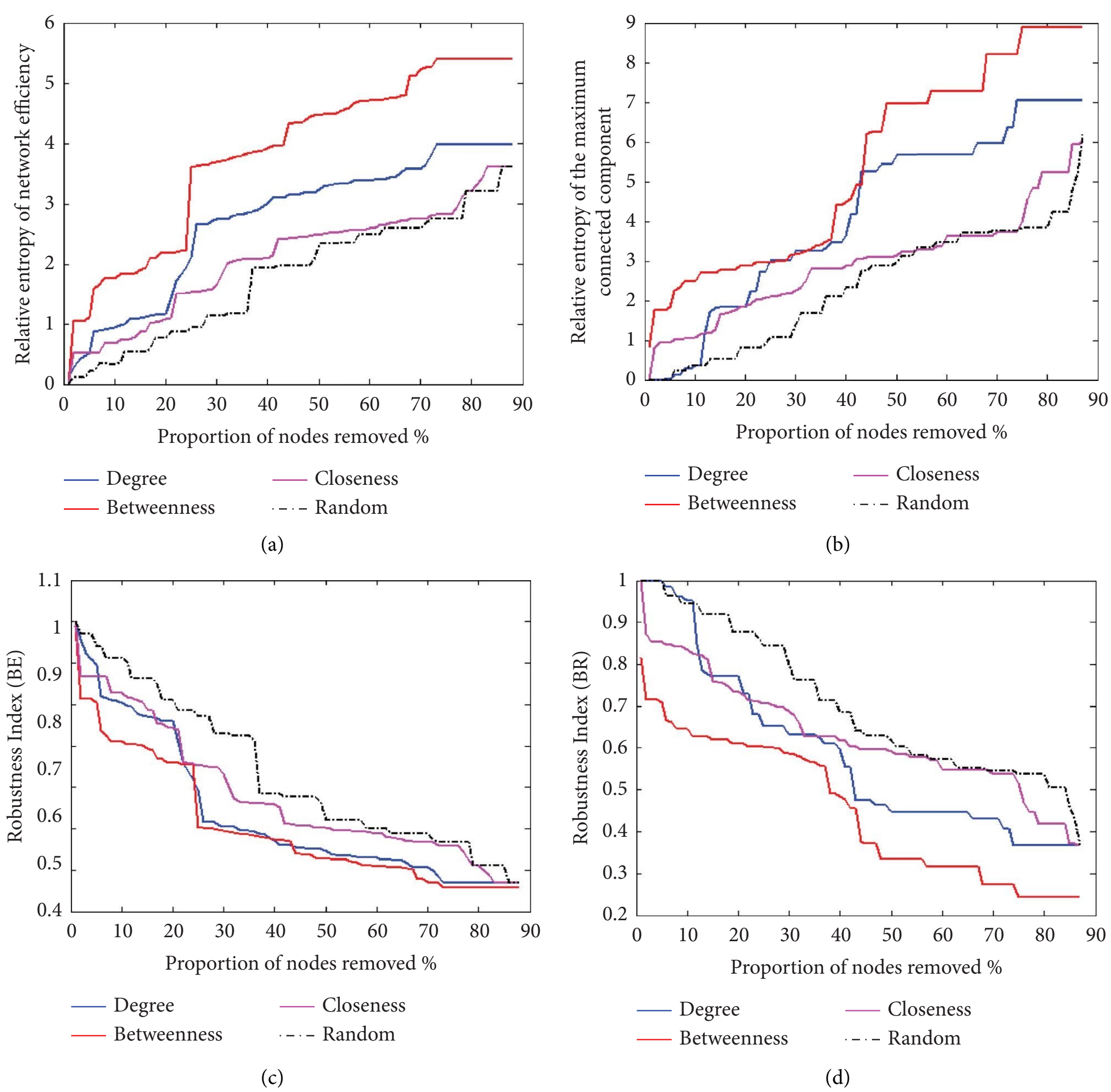


Figure 16: The robustness of ACMN is based on relative entropy. (a) Relative entropy of network efficiency. (b) Relative entropy of the maximum connected component. (c) The BE of a multilayer network. (d) The BR of a multilayer network.

6. Conclusions

This paper analyzes the state of aircraft on the route in the airspace, as well as the relationship between each aircraft and the air sector, and builds the ACMN. Then, considering the centrality methods of degree, betweenness, and closeness in complex network theory and introducing relative entropy theory, a robustness evaluation model based on a multilayer network is proposed. Finally, taking the state of the aircraft in BCA as an example, the ACMN model is established, and the centrality method is used to evaluate the centrality of the aircraft. The results are verified under deliberate attack and random attack strategies, with network efficiency and maximum connected components as evaluation indicators. The analysis shows that degree and betweenness have obvious effects on node centrality. Simultaneously, it shows that the proposed method is effective and reliable for the robustness analysis of multilayer networks.

In fact, the stability of ASTN reflects the orderliness and normality of the operation of the aircraft group in the airspace. In addition, the stability of ASCN represents the structural integrity of the airspace. Their global stability is the guarantee of the safety and reliability of air transport, and of course, it is also the basis for ensuring the smoothness of ATC. So, an accurate analysis of the robustness and node centrality of the ACMN model is conducive to improving the safety, reliability, and orderliness of air transport and promoting ATC. This proposed model lacks consideration of the dynamic characteristics of aircraft; in the future, based on ATC, a real-time dynamic ACMN model (considering the dynamic characteristics of aircraft) can be established to optimize the distribution of traffic flow in the airspace, improve the efficiency of the airspace, and reduce air delays.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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