Comparative Study on Air Transport Network Structure of China, US and EU

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Abstract—Modern air transport is an important part of national economy, however, the air transport construction of China still lags behind developed countries. Here we construct the air transport networks of China, US and EU by taking cities as nodes and airlines as edges to study their characteristics comparatively. Through observing the statistical results of topological indices included degree, excess average degree and betweenness, we find the less branch airlines and the higher workload of hub cities are the factors restricting the air transport network of China. Then based on the indices sorts, we classify the air transport cities into global hub nodes, regional hub nodes and general nodes to show their different importance in the network. We consider that it is necessary to increase the numbers of global hub nodes and branch airlines, and improve their invulnerable abilities. This paper may provide references for guiding the air transport network construction of China.

1. INTRODUCTION

Air transport network (ATN) is a spatial network structure composed of airports and their cities as nodes, airlines as connected edges. From the economic perspective, it supports the rapid development of passengers transport and logistics industries, strengthens international connection, and is one of the main carriers for economic globalization [1]. As an important part of modern comprehensive transportation system, air transport is time-efficient and can ignore the influence of ground conditions, resulting in its advantages in long distance and urgent transport [2]. Although only 1% of the world's total trade volume is transported by air, it is developing towards high-value products, accounting for almost 35% of the value of international trade [3]. The dependence of pharmaceuticals, high-tech products, e-commerce and other products on air transport also shows the specific characteristic of ATN in international trade.

In the past few decades, the theory of complex networks has risen rapidly. The introduction of small-world network, BA “scale-free” network and other network models has brought the research of real networks such as Internet networks, social networks, biological networks, metabolic networks, power grids, and transportation networks to a climax [4-10]. ATN has a large number of node cities and airlines, and its infrastructure is developing rapidly [11]. Due to the complexity and dynamic nature of its topology, it is suitable to use the complex network theory for research.

Through the above analysis, we take ATN of China, US and EU as research objects and use complex network analysis method to compare their structural characteristics. According to the results, the node cities of ATN are classified into three different important hierarchies. We hope this paper can provide references for guiding the ATN construction of China.
2. Data Source and ATN Model Construction

Airports and airlines studied in this paper was based on a database provided by OpenFlights.org, which mainly contained:

- The airport ID, name, main service city and latitude and longitude of each airport.
- The airline ID, source airport and destination airport of each airline.

We screen the airport data of 33 provinces in China mainland (Taiwan is currently divided into international airlines, which is not considered in this paper), 48 states in US excluding Alaska and Hawaii, 27 countries in EU and UK, Switzerland to construct the ATN model. The modelling principles can be seen as:

- A city node contains all airports servicing this city.
- Airlines not within the regions are ignored, different airlines between two cities in the region are merged into “one edge” in the model.

We take cities as nodes, airlines as undirected edges, and combine with latitude and longitude to construct the ATN model in three regions. The number of nodes and edges and network models of three regions can be seen in Table I and Figure 1. Node size represents the node degree, the larger the node is, the more cities it connects. Airlines doesn't take into account the weight so the thickness is the same, the darker the color is, the more airlines it distributes.

| Region | CN   | US   | EU   |
|--------|------|------|------|
| Node   | 163  | 387  | 378  |
| Edge   | 1297 | 2293 | 3546 |
Figure 1. ATN models of China, US and EU

From Figure 1 we can see, the distribution of node cities in US and EU is relatively balanced, airlines can cover most areas and the distribution is dense except for the marginal area. Airlines distribution in China is mainly concentrated in the eastern and central areas, western areas is relatively sparse. In Table 1, the airport number in China is less than half of that in US and EU, considering that CN has the largest area, there is still a large gap of ATN development between China and developed countries, the existing airports can not meet the needs of people's daily travel.

3. **TOPOLOGICAL STRUCTURE COMPARATIVE ANALYSIS OF ATN**

Network topology is a network shape formed by nodes and edges, it only focuses on the connection relationship of nodes, reflecting the structure and function of the network [12]. We model air transportation network topology as an unweighted undirected graph $G=(N,E)$, where $N$ is the set of
nodes (airport cities), and $E$ is the set of undirected edges (airlines between two cities). $G$ is mapped with an adjacency matrix where $e_{ij} = 1$ if a undirected edge connect node $i$ and $j$, 0 otherwise; $e_{ij} = 1$ means node $j$ is reachable from node $i$ with a single step, i.e., node $j$ is a neighbor of node $i$. We analyze the ATN of China, US and EU by comparing network indices as follows.

3.1. Degree distribution

The degree of node $i$ is \( k_i = \sum_{j=1}^{F^{\text{FI}}} a_{ij} \) [13]. In ATN, \( k_i \) represents the number of cities that can reach city $i$ directly, reflecting the convenience of connecting this city with others. Generally speaking, the greater the degree, the more important this city is in air transportation network. We count degree distribution of three regions in Figure 2.

As shown in Figure 2, the three regions differ small in the distribution of nodes with large degree, however, the number of nodes with small degree in China, especially \( k < 10 \), are obviously less than US and EU, illustrating that CN has less “spokes” in the “hub-spoke” transport structure [14]. Less “spokes” results in the majority of air transportation going directly from the source city to the destination city, the utilization rate of the “hub” city is low, increasing flight workload in long distance transport.

3.2. Excess average degree-degree correlation

The excess average degree of node $i$ is \( \langle k_{m} \rangle_i = \frac{1}{k_i} \sum_{j=1}^{k_i} k_j \) [13], it represents the average degree of the neighbors of node $i$, reflecting the network scale formed by node $i$ and its neighbors. In ATN, the greater \( \langle k_{m} \rangle_i \), the more obvious the regional effect with its neighbors. Excess average degree-degree correlation represents the correlation between node degree and its excess average degree, we count that of three regions in Figure 3.
Figure 3. Excess average degree-degree correlation of CN, US and EU

From Figure 3 we can see, the excess average degree-degree correlation of the three regions also obeys the law of first increasing and then decreasing as $\frac{a}{x}$, but overall, $\langle k_{\text{in}} \rangle$ of CN is smaller than that of US and EU in the same degree, i.e., $a$ is smaller. This indicates the air transport scale formed by node city and its neighbors of China is smaller than that of US and EU, there is still a gap on the regional economic effect promoted by ATN between China and developed countries.

3.3. Betweenness-degree correlation

The betweenness of node $i$ is $B_i = \sum_{\sigma_{st} \in N} \frac{\sigma_{st}(i)}{\sigma_{st}}$ [13], where $\sigma_{st}$ is the shortest path from node $s$ to node $t$ and $\sigma_{st}(i)$ the shortest path from $s$ to $t$ through node $i$. The betweenness of node $i$ represents the proportion of the paths number that passing through node $i$ to the total number of shortest paths in the network, in ATN, it reflects the transfer and connection capacity of node city. We count betweenness-degree correlation in Figure 4 to illustrate the correlation between node degree and its betweenness.

Figure 4. Betweenness-degree correlation of CN, US and EU

In Figure 4 we can see “transit” nodes with small degree but betweenness also exist in three regions, including Urumqi, Harbin, Xining of China, St. Louis of US and Helsinki of EU. Despite small degree, most of the airlines that take their neighborhoods as source or destination city have to pass these “transit” nodes to enter a large-scale network, i.e., Urumqi, the capital of Xinjiang Province with 36 degree and 0.0734 betweenness, is the transportation hub in western area of CN and the important transit node for the goods and passengers transportation from east to west, attention should be paid to these “transit” nodes in the construction of air transportation network.
In addition, the node betweenness of China is generally higher than that of US and EU, which is the result of less air transport cities in CN. It shows the importance of these cities in the air transport, however, it also can be seen that these “transit” cities’ workload in China is higher than that of US and EU, which reduces the invulnerability of ATN. When extreme weather or other emergencies make the node lose working ability, it will seriously affect the normal operation of ATN.

4. HIERARCHICAL COMPARATIVE ANALYSIS OF ATN NODES

In this section, we introduce the $k$-core algorithm and sort nodes into three different hierarchies to distinguish their importance in ATN. The k-core in a network is defined to be the remaining sub-graph after all the nodes with degree $\leq k-1$ have been removed successively, if a node belongs to a k-core of a network but will be removed from the $(k+1)$-core, this node is said to have coreness $k$, and the largest coreness is called the coreness of the network [15]. The coreness of the air transportation network and the cities contained of three regions is showed in Table II.

| TABLE II. THE CORENESS AND ITS CITY NUMBERS OF ATN |
|-----------------------------------------------|
| Region | CN | US | EU |
| Coreness | 21 | 37 | 26 |
| City number | 37 | 33 | 61 |

Based on the indices ranking of degree, excess average degree and betweenness and using $k$-core for auxiliary evaluation, we sort nodes into three hierarchies as follows and the final sorting result is illustrated in Figure 5 and Table III. The black nodes represents global hub nodes, gray nodes the regional hub nodes and white nodes the general nodes, and the names of global hub nodes and regional hub nodes are marked in Figure 5.

- Global hub nodes: the intersection of the top 5% of nodes in the three rankings
- Regional hub nodes: according to the city numbers $n$ in the coreness of ATN, the remaining nodes after subtracting the global hub nodes in the intersection of the top $n$ in the three rankings.
- General nodes: the remaining nodes after subtracting the global hub nodes and regional hub nodes in all nodes.

| TABLE III. THE CITY NUMBER OF THREE HIERARCHIES |
|-----------------------------------------------|
| Region | CN | US | EU |
| Global hub nodes | 7 | 16 | 11 |
| Regional hub nodes | 25 | 11 | 33 |
| General nodes | 131 | 334 | 360 |
Figure 5. The final grading result of China, US and EU

5. SUGGESTIONS FOR ATN CONSTRUCTION OF CHINA

1. Increase the construction of global hub nodes. The number of global hub nodes of US and EU are 16 and 11, while that in China is 7, which is significantly less than developed countries. Under the same transport volumes, the air cities’ workload of China is higher than that of US and EU, thus it is
necessary to increase the number of global hub nodes in the construction of ATN to share the workload of other cities, so as to promote the further development of air transport.

2. Improve the ability of global hub nodes to cope with emergencies. The emergencies, i.e., extreme weather, will increase the workload of global hub nodes or even make them incapacitated, under these situations, the transfer of passengers or cargo flows will increase the working pressure of other nodes, and even cause cascading failures in the network [16]. Improving the ability of global hub nodes to cope with emergencies can ensure the normal operation of ATN and improving the invulnerabilities for the whole network, which is significant to protect air transport resources and promote the economic development.

3. Increase the construction of the “spokes” in “hub-spoke” structure. “Hub-spoke” structure is a kind of better transport network structure, compared with US and EU, ATN of China has not been able to form the large “hub-spoke” structures, the proportion of node cities in network structure is high, which increases the network cost and air transport is in the scattered economic mode. Thus it is necessary to increase the construction of the “spokes”, i.e., the number of general nodes and the proportion of the branch airlines to drive the regional economy development.

6. SUMMARY
Air transport is an important part of the modern comprehensive transport system. It adjusts the social and economic spatial structure, supports the economic industries such as passenger transport and logistics. After more than 20 years of development, although China’s air transport network has gradually improved, there are still problems such as uneven development in the central and western regions and insufficient structural optimization. In this paper, we extract airports and airlines to construct the air transport networks of China, US and EU, use complex network analysis method to study their differences and classify air transport cities into different hierarchies, which is significant to discover and protect hub nodes. By the above results, we suggest to increase the number of hub nodes and branch airlines, and improve the invulnerabilities for the hub nodes. We hope this paper can provide references for China’s air transport construction in the future.

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