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Identifying vital edges in Chinese air route network via memetic algorithm

Du Wenbo [a,b], **Liang Boyuan** [a,b], **Yan Gang** [c], **Oriol Lordan** [d], **Cao Xianbin** [a,b,*]

[a] *School of Electronic and Information Engineering, Beihang University, Beijing 100083, China*
[b] *Beijing Key Laboratory for Network-based Cooperative Air Traffic Management, Beijing 100083, China*
[c] *School of Physics Science and Engineering, Tongji University, Shanghai 200092, China*
[d] *Universitat Politècnica de Catalunya-BarcelonaTech, C/Colom no.11, Terrassa 08222, Spain*

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Abstract Due to rapid development in the past decade, air transportation system has attracted considerable research attention from diverse communities. While most of the previous studies focused on airline networks, here we systematically explore the robustness of the Chinese air route network, and identify the vital edges which form the backbone of Chinese air transportation system. Specifically, we employ a memetic algorithm to minimize the network robustness after removing certain edges, and hence the solution of this model is the set of vital edges. Counterintuitively, our results show that the most vital edges are not necessarily the edges of the highest topological importance, for which we provide an extensive explanation from the microscope view. Our findings also offer new insights to understanding and optimizing other real-world network systems.

1. Introduction

With the increasing people and goods transport demand during the accelerating globalization process, the air transportation system plays a more important role than ever before due to its high-speed and high-security advantages. For example, the air transport volume of China grows at an average annual speed of over 10% in the past decades, and now it possesses over one seventh of the total comprehensive transport volume (including roadways, railways, shipping and air transport), which was only 7.9% in 2000. Hence the air transportation system has been drawing much attention from different research communities. One of the most interesting directions is to analyze the structure and function of air transportation systems within the framework of complex network theory.

The air transportation system can be represented as a network, in which nodes denote airport and an edge will be created if there is a direct flight between two airports. In the vast majority of previous literature, the air transport network (ATN) was primarily classified into two scales: worldwide and national.

* Corresponding author at: School of Electronic and Information Engineering, Beihang University, Beijing 100083, China.
E-mail address: xbcao@buaa.edu.cn (X. Cao).

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For the worldwide scale, Amaral et al. firstly found that worldwide ATN is a small-world network with a power-law degree distribution, and the highest-degree airport is not necessarily the most central node, prompting them to propose a network model where both geographical and political factors are taken into account.[1,2] Barrat et al. investigated the worldwide ATN from a perspective of complex weighted networks and found the nonlinear positive correlation between flight flow and topology properties.[3,4] They proposed a weighted network model, enlightening the understanding of weighted feature of complex systems. Verma et al. decomposed the worldwide ATN into three distinct layers via k-core decomposition and found that this network is robust to the removal of long distance edges, but fragile to the disconnectivity of short and apparently insignificant edges.[5,6]

For the national scale, ATNs of several major nations, such as US, Brazil, India and China, are extensively studied[3,7–11], and the national ATNs usually exhibit different features from the worldwide ATN. Gautreau et al. studied US ATN during 1990–2000.[3] A remarkable result they presented is that although most statistical properties are stationary, an intense activity takes place at the local level. Fleurquin et al. proposed a delay propagation model via quantifying the network congestion for US ATN, revealing that even under normal operating condition the systemic instability risk is non-negligible.[11] Rocha investigated the Brazilian ATN during 1995–2006, and found that it shrank in topology but grew in traffic volume.[7] Bagler et al. studied the Indian ATN, and found its signature of hierarchy feature.[12] As the most active economy, the Chinese aviation industry ranks second to US in the past decade and keeps a high increase rate. Consequently, Chinese ATN attracts continuous attention in different aspects from topology to dynamics and evolution,[8–10,13,14] one of which is to investigate the backbone of ATN, the air route network (ARN).

ATN is actually a logic network with origin-destination (OD) relationships. In real air traffic operation, a flight does not straightly fly from departure airport to landing airport, but along some air route waypoints. ARN consists of air route waypoints and connections between them. In 2012, Cai et al. firstly investigated the Chinese ARN[15] and found that the degree distribution of Chinese ARN is homogeneous but the traffic flow is rather heterogeneous. Vitali et al. then investigated the horizontal deviation and delays in Italian ARN.[16] The analysis of ARN is quite a novelty in the literature. However, the network robustness, which is an important issue for infrastructure systems[17] and has been extensively studied in ATN,[18,19] is still rare in ARN. In the typical network robustness model, edges are removed by different targeted attack strategies and the size of giant component estimates the robustness of the network.[20] When a small amount of edges are removed, the size of giant component is of a very small change. In this paper, we focus on identifying the vital edges in Chinese ARN by examining the robustness of the new network after removing an edge set via memetic optimization. Remarkably, we find that the most vital edges are not necessarily the edges of the highest topological importance.

The rest of this paper is organized as follows. In the next section, we demonstrate Chinese air route network and its basic properties. Section 3 describes the optimization model and the memetic algorithm. Section 4 presents the simulation results and corresponding analysis. Finally, the paper is concluded in Section 5.

2. Chinese air route network

The latest data of the Chinese air route network are provided by the Air Traffic Management Bureau (ATMB) of China. In the Chinese ARN, airports or air route waypoints are nodes and edges are represented by the air route segments. An air route waypoint is a navigation marker which keeps the pilots informed about the desired track. In the air transportation system, the flights will fly along the air route waypoints, but not directly fly from one airport to another. Fig. 1 is an illustration of ARN, where airlines are depicted by the dotted line and air route segments are denoted by the solid line. Fig. 2 shows the structure of the Chinese ARN, which contains $N = 1499$ nodes and $M = 2242$ edges.

In Ref. 15, the authors found that the topology structure of the Chinese ARN is homogeneous, yet its distribution of flight flow is quite heterogeneous. If we compare the Chinese ATN with the Chinese ARN, we found significant differences. On one hand, the Chinese ATN is a typical small-world with low average shortest path length and large clustering coefficient. On the other hand, the Chinese ARN is not a small-world network due to its low clustering coefficient, large average shortest path length and exponential spatial distance distribution.

3. Model

3.1. Optimization model

The static robustness of complex networks has been extensively studied in the past decades. In Ref. 21, it is quantified by the relative size of the largest connected component $G = N'/N$ where N is the total number of nodes in initial network and N' is the number of nodes in the largest component after attack. The larger value of G represents a more robust network. Based on the largest connected component, Schneider et al. proposed a measure R to evaluate the robustness against targeted attack on nodes.[17]

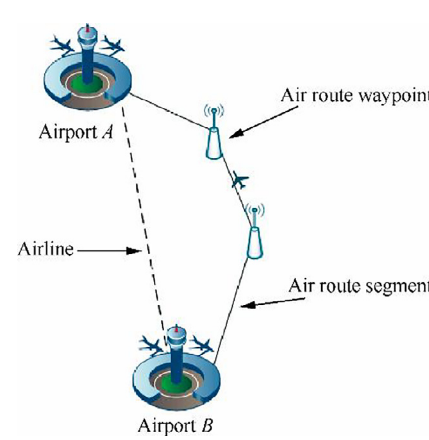

Figure 1 Illustration of ARN.