Transportation Research Part E 89 (2016) 108–116

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Analysis of the Chinese Airline Network as multi-layer networks

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ARTICLE INFO

Article history:
Received 17 August 2015
Received in revised form 16 March 2016
Accepted 17 March 2016
Available online 23 March 2016

Keywords:
Air transport network
Chinese Airline Network
k-core decomposition

ABSTRACT

This paper encapsulates the Chinese Airline Network (CAN) into multi-layer infrastructures via the "*k*-core decomposition" method. The network is divided into three layers: Core layer, containing airports of provincial capital cities, is densely connected and sustains most flight flow; Bridge layer, consisting of airports in Tier 2 and Tier 3 cities, mainly connects two other layers; and Periphery layer, comprising airports of remote areas, sustains little flight flow. Moreover, it is unveiled that CAN stays the most robust when low-degree nodes or high flight flow links are removed, which is similar to the Worldwide Airline Network (WAN), albeit less redundant.

1. Introduction

Given the important role of the transportation system for the modern society, transportation problems have attracted much attention, both theoretical and experimental (Faturechi and Miller-Hooks, 2014). The study of four typical means of transport: roadway, railway, shipping and airway, has also permeated a myriad of scientific disciplines (Helbing, 2001). Though the contribution of airway is quite small compared with the other three, it has three significant advantages: (i) speed: many jet planes' cruise speed is faster than 850 km/h. The reduced travel time can keep perishable goods from decaying, can deliver goods such as newspapers or first-aid medicines on time, and can save passengers' valuable time. (ii) safety: the accident rate of air transport is still among the lowest. (iii) cost-saving: on the one hand, companies can reduce inventory level and accelerate turnover via fast air transport. On the other hand, air companies often provide less complex packaging and lower insurance expense. These elements can reduce companies' implicit cost. Due to the acceleration of the globalization process, the air transport system plays an increasingly more critical role in local, national, and international economies (Camelia and Mihai, 2010) and scientists from different communities pay special attention to the air transport infrastructures.

Complex network theory is naturally a useful tool to investigate the transport infrastructures. During the last decade, complex network theory has been widely applied to different transport methods, including urban traffic (Crucitti et al., 2006; Porta et al., 2006), railway (Sen et al., 2003), subway (Latora and Marchiori, 2002, 2006), and especially the air transport system (Gautreau et al., 2009; Li and Cai, 2004; Zhang et al., 2010; Liu et al., 2009; Bagler, 2008; da Rocha, 2009). A great

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http://dx.doi.org/10.1016/j.tre.2016.03.009
1366-5545/

variety of publications has unveiled the topological structure and the dynamic behaviour of the air transport network, where airports are denoted by nodes and flights between airports are denoted by edges. For example, the Worldwide Airline Network (WAN) has been extensively studied. Barrat et al. (2004) studied the correlations between weighted quantities of the WAN and found a strong correlation between the traffic flow and the network's topological properties. Colizza et al. developed a model to simulate the mobility of individuals from an airport to another and found the important role of air transport network for the global pattern of emerging diseases (Colizza et al., 2006). Guimera et al. investigated the network of flight segments between city-pairs (Guimera et al., 2005). A remarkable result they present is that the most connected nodes in the WAN are not necessarily the most central nodes, which means critical locations might not coincide with highly-connected hubs.

Since the national air route network is often associated with the economy and image of a country, it has been also extensively studied. For instance, Gautreau et al. studied the US airport network during the period from 1990 to 2000 and showed that an intense activity takes place at the local level though the statistical distributions of most indicators are stationary (Gautreau et al., 2009). Bagler et al. studied the Airport Network of India which is a small-world network with a truncated power-law distribution and signature of hierarchy feature (Bagler, 2008). Rocha investigated the structure and evolution of the Brazilian airport route network and found that it has shrinked at the route level but it has grown in number passengers and amount of cargo (da Rocha, 2009). Especially, as the largest developing country and the most active economy in the world, the aviation industry of China has undergone a rapid development in the past few decades. Now the Chinese air transport system ranks only second to the US and there are 25 airports with more than ten million annual passenger movements. Consequently, the Chinese Airline Network (CAN) has been extensively studied on its topology, traffic dynamic and evolution (Li and Cai, 2004; Zhang et al., 2010; Liu et al., 2009).

However, most of the previous research ignores the multi-layer nature of real systems. In fact, a multiplex model fits the real situation more suitably, as it can define more accurately how the different dynamics develop in each layer of a complex system. Therefore, the concepts strongly related to multiplex networks have been introduced into the study of air transport networks. Cardillo et al. (2013) established the European Air Transport Network (EATN) where 15 biggest airline companies in Europe are considered as 15 layers. These authors found that the multi-layer structure strongly reduces the robustness of the system. Verma et al. (2014) illustrated three distinct layers of the WAN based on the *k*-core decomposition and found that the WAN is a redundant and robust network for long distance air travel, but otherwise breaks down completely with the removal of short and apparently insignificant connections.

Inspired by these works, we want to analyse if a regional network such as the CAN can be described as a multi-layer framework. It is well-known that Chinese air transportation has experienced a rapid growth during the past decades. For example, the aircraft movement number of 2015 will reach up to 8 million, which is 2.6 times to the number in 2005, namely, the average annual growing rate is nearly 12%. Moreover, according to the statistics of IATA (International Air Transport Association), the air transportation in China will keep growing at a annual rate of 6.4% in the next 15 years. To achieve the aforementioned purpose, we will analyse each layer and identify its particularities given the unique demographic and geographical properties of China. Furthermore, we will look at which airports and connections have the most important role in maintaining the CAN completely connected. It is worth mentioning that, different from the above-mentioned work exploring the robustness of WAN (Verma et al., 2014), we here pay our main attention to the topological characters and flight flow distribution of CAN. After identifying the structure property, a very brief discussion of robustness of CAN is provided.

The paper is organized as follows. The following section makes detailed discussions on the topological properties of CAN. Afterwards, the robustness of CAN is analyzed and finally, conclusions are presented.

2. Topological properties of the CAN

The Chinese Airline Network (CAN) comprises all domestic flights within China scheduled in 2015 provided by the Civil Aviation Administration of China (CAAC). We define the CAN as an unweighted and undirected network where nodes are airports and there is an edge between two airports if they are connected directly, as in Guimera et al. (2005) and Lordan et al. (2014a,b, 2015)).

Following these treatments, the CAN has $N = 203$ nodes (i.e. airports) and $E = 1877$ edges (i.e. connections) between airports. We define a binary adjacency matrix $A(N \times N)$ where $a_{ij} = 1$ if there is a direct connection between airport i and j, otherwise $a_{ij} = 0$. Similar to previous works (Li and Cai, 2004; Zhang et al., 2010; Liu et al., 2009), once there are two airports in the same city (like Beijing, Shanghai, Chongqing), these two airports will be emerged into one, which also simplifies the adjacency matrix. Take Shanghai as one example: if one city has airline to either (Pudong or HongQiao airport) or both, a_{ij} will take 1. The degree of a node is the number of connections of that node and it is defined as $k_i = \sum_{j=0}^{N} a_{ij}$. Interesting, the CAN exhibits a two-regime power-law degree distribution with two different exponents as in Li and Cai (2004), Zhang et al. (2010), and Liu et al. (2009). The average degree of the CAN is about $\langle k \rangle = 18.48$. The top 3 airports with the highest degree are Beijing ($k = 136$), Shanghai ($k = 120$) and Guangzhou ($k = 100$). The average cluster coefficient[1] is 0.73 and the average

[1] The cluster coefficient is usually employed to measure the transitivity of a network. Its value c_i corresponds to the ratio of exiting links to all the possible links among the neighbours of a given node, and the cluster coefficient for the enter network C means the average of the clustering coefficients of all the nodes, i.e. $C = \sum_{i=1}^{N} c_i / N$. A high clustering coefficient for a network is another indication of a small world.