Chaos, Solitons and Fractals 86 (2016) 28–34

Contents lists available at ScienceDirect

Chaos, Solitons and Fractals

Nonlinear Science, and Nonequilibrium and Complex Phenomena

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

Structural properties of the Chinese air transportation multilayer network

Chen Hong[a,b], Jun Zhang[a,b,*], Xian-Bin Cao[a,b], Wen-Bo Du[a,b]

[a] School of Electronic and Information Engineering, Beihang University, Beijing 100191, PR China
[b] National Key Laboratory of CNS/ATM, Beijing 100191, PR China

ARTICLE INFO

Article history:
Received 24 December 2015
Accepted 27 January 2016
Available online 8 March 2016

Keywords:
Multilayer network
Chinese air transportation network
Structural property
Complex network

ABSTRACT

Recently multilayer networks are attracting great attention because the properties of many real-world systems cannot be well understood without considering their different layers. In this paper, we investigate the structural properties of the Chinese air transportation multilayer network (ATMN) by progressively merging layers together, where each commercial airline (company) defines a layer. The results show that the high clustering coefficient, short characteristic path length and large collection of reachable destinations of the Chinese ATMN can only emerge when several layers are merged together. Moreover, we compare two main types of layers corresponding to major and low-cost airlines. It is found that the small-world property and the rich-club effect of the Chinese ATMN are mainly caused by those layers corresponding to major airlines. Our work will highlight a better understanding of the Chinese air transportation network.

1. Introduction

During the last fifteen years, the studies on complex networks are flourishing, such as network modeling [1,2], evolutionary games [3–5], traffic dynamics [6–9], cascading failures [10,11], network controllability [12–14] and optimization [15–17] and so on. However, some constraints of the traditional complex network approach have been highlighted recently [18]. One of the major constraints is the multilayer nature of realistic systems: the nodes have different kinds of relationships and each relationship is represented by a layer [18–20]. For instance, in social networks, each individual can has several kinds of ties: friendship, kinship, or partnership, etc. For such kind of networks, a multilayer model represents the realistic situation suitably, because it can better catch different dynamics developing in each layer [21].

Due to the critical role in the economy, the air transportation network (ATN) has attracted a great of interest in past years [22–24]. Guimerà et al. [25] studied the worldwide ATN and found that the network is a scale-free small-world network and the most connected cities are not necessarily the most central. Besides, some national air transportation networks, including the air transportation network of America [26,27], China [28–31], India [32] and Brazil [33], are also extensively studied. It is shown that the national ATN can exhibit different properties, such as the two-regime power-law degree distribution, small-world, disassortative mixing and so on. In these works, the air transportation network is considered as a single-layer network, in which all the connections between airports are considered to be equivalent.

Recent studies have pointed out that the ATN is a multilayer network, where each layer is an airport network operated by a commercial airline (company) [34–36]. Due to the interactions and dependencies between these layers,

* Corresponding author at: School of Electronic and Information Engineering, Beihang University, Beijing 100191, PR China. Tel.: +86 10 82338282.
E-mail address: buaazhangjun@vip.sina.com (J. Zhang).

http://dx.doi.org/10.1016/j.chaos.2016.01.027
0960-0779/

the framework of single-layer network cannot reflect well the state of the entire air transportation network, and may result in not fully capturing the details of the ATN. Therefore, in order to understand how the multiple layers affect the global properties of the ATN, it is of utmost importance to take into account the multilayer structure in the ATN. Recently, Cardillo et al. [37] analyze the features of the European air transportation multilayer network (ATMN). They examine how several structural measures evolve as layers are progressively merged together. The results demonstrate that the topological properties of the European ATMN are the consequence of an emerging phenomenon intimately related to the multilayer character of the system. Nevertheless, several important structural properties of ATMN, such as the global efficiency [38], the connectivity coefficient [39] and the network polarization [40], are not yet investigated. Meanwhile, the structural properties of the Chinese ATMN are still unexplored. In this paper, we investigate the structural properties of the Chinese ATMN extensively. Also, we compare two main types of layers corresponding to major and low-cost airlines and analyze their different contributions to the properties of the global Chinese ATMN.

The paper is organized as follows. In the next section we demonstrate the Chinese ATMN and the network structural properties in detail. In Section 3, simulation results and correspondent theoretical analysis are provided. Finally, the work is summarized in Section 4.

2. The model

2.1. The Chinese ATN as a multilayer network

The latest data of the Chinese air transportation network are provided by the Air Traffic Management Bureau (ATMB) of China. In the Chinese ATMN, airports are nodes and an edge exists if two airports are connected by a direct flight. We only consider internal flights, i.e., flights whose origin or destination is outside China are disregarded. The network contains $x = 26$ different layers, where each commercial airline (company) defines a layer.

To investigate the properties of the Chinese ATMN, we study the features of aggregate networks obtained by merging a growing number of layers together, from the lowest level of a single layer ($x = 1$), up to the fully aggregate network ($x = 26$). Such aggregate network is constructed by projecting all x layers into one layer and overlap edges are projected into one edge. Following the research of Cardillo et al. [37], we choose these x layers randomly from the 26 layers. For a fixed value of x, the number of possible mergers from 26 layers is $C_{26}^{x} = \binom{x}{26}$, when the number of possible mergers goes beyond a certain threshold $60,000$, we perform a sampling with $60,000$ mergers [37]. In Fig. 1, we show the structure of the fully aggregate Chinese ATN constructed by merging $x = 26$ layers.

2.2. Network structural properties

To address the structural features of the Chinese ATMN, we investigate some properties widely used in complex network literature [41–43], including the cumulative degree distribution, the clustering coefficient, the average shortest path length, the network assortativity coefficient, etc.

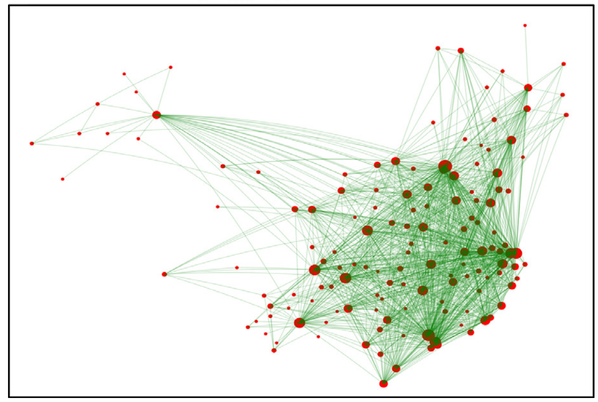

Fig. 1. The structure of the fully aggregate Chinese ATN constructed by merging all 26 layers. Here the network contains $N = 145$ nodes and $M = 1341$ edges. The size of the nodes is proportional to the degree. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

• **The cumulative degree distribution** $p(k)$:

The cumulative degree distribution denotes the probability of finding a node with the number of connections not less than k. As a crucial property of complex networks, the degree distribution has been commonly used to character the structural and dynamical features of real systems [42,44,45]. In the paper, the cumulative degree distribution is used to reflect the structural heterogeneity of the Chinese ATMN.

• **The clustering coefficient** C:

The clustering coefficient C is an important property of complex networks [18,20,42,46]. It quantifies the tendency of nodes to form triangles, i.e., the probability that two nodes with a common neighbor are connected together. The clustering coefficient of a node is defined as

$$C_i = \frac{2e_i}{k_i(k_i - 1)}, \tag{1}$$

where e_i is the actual number of edges between neighbors of node i, and k_i is the degree of node i. The clustering coefficient $C = \sum_{i \in N} C_i / N$, where N is the total number of nodes in the network. Since the clustering coefficient reflects the density of triangular motifs, we use it to estimate the probability of performing round trips of length 3 in the Chinese ATMN.

• **The average shortest path length** $\langle L \rangle$:

The average shortest path length is the average length of the shortest paths among all the pairs of nodes in the network, i.e.

$$\langle L \rangle = \frac{2}{N(N-1)} \sum_{i,j \in N, i \neq j} d_{ij}, \tag{2}$$

where N is the total number of nodes in the network, and d_{ij} is the length of the shortest path from node i to j. The average shortest path length gives a measurement of