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A complex network approach towards modeling and analysis of the Australian Airport Network

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ABSTRACT

An airport network forms the backbone of any air transportation system. The relationships among the origins and destinations of flights result in a complex network of routes which can be complemented with information associated with the routes themselves, for instance, traffic load and distance. In this paper, we modeled the Australia's civil domestic airport infrastructure as a network and analyzed the resulting network structure and its features using complex network tool. This case study identifies and investigates complex network measures, such as the degree distribution, characteristics path length, clustering coefficient and centrality measure as well as the correlations among them to understand the topology of an airport network. This analysis of the Australian Airport Network (AAN) indicates that it has a cumulative degree distribution described by the power-law function. As it has an average path length of 2.90, it is considered to have small-world properties. It is also found that it has a clustering coefficient of 0.50 which is higher than that of a random network of the same size which indicates that the transitivity and cohesiveness of AAN is different from a random network. In contrast to the World-wide Airport Network (WAN), the AAN is found to have disassortative mixing similar to the airport networks of China and India.

1. Introduction

An air transportation system (ATS) is probably one of the most complex man-made system that operates on the edge of chaos and exhibits emergent behavior whereby small changes in one part of the system can cause major changes in another or in the system as a whole. An ATS and, more generally, any transport infrastructure, plays a strategic role in our society in terms of both its economic significance and social impact.

In recent years, the transportation domain has witnessed a renewed interest in network and graph theory due to the understanding that many natural (Strogatz, 2001; Milo et al., 2002; Watts and Strogatz, 1998; Girvan and Newman, 2002), artificial and combinatorial optimization problems (Barabási and Crandall, 2003; Zhou, 2003; Hossain et al., 2010; Roli, 2005a,b) can be explained in terms of complex networks. More recently, the advancement in complex network theory has generated a huge interest in the area of airport networks (Guimera et al., 2005; Xu and Harriss, 2008; Wang et al., 2011; Bagler, 2008a; Amaral et al., 2000).

To analyze the topology and uncertainty of an ATS at a regional, national or global level, it is best to abstract and integrate its various complex and heterogeneous elements in a way that allows its uncertainty and other properties of interest to be assessed without requiring too much detail. Complex network theory provides a theoretical framework that may help the development of appropriate models and analyses of the topology of an ATS network. From the complex network point of view, ATS can be modeled as graphs (networks) consisting of airports as vertices linked by flights connecting them. Interestingly, many real networks, including airport ones, typically exhibit one of following two distinct topological properties:

- A *small-world* (SW) property, defined by the average path length, that is, the average distance between any pair of nodes, increases very slowly (usually logarithmically) with the network size (N) (Watts and Strogatz, 1998); or
- A *scale-free* (SF) property whereby the network's degree distribution conforms to a power law (Newman, 2003). If its connectivity distribution ($P(k)$) is the probability that each node is connected to k other nodes, a SF network is characterized by a

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power-law behavior ($P(k) \sim k^{-\gamma}$, where γ is a characteristic exponent) (Costa et al., 2007).

There have been a few studies applying the SF and SW concepts to analyzing air transport networks, notably the World-wide Airport Network (WAN) which has been studied from both topological and traffic dynamics perspectives (Guimera and Amaral, 2004). Guimerá et al. observed that the WAN is a SW network which, because its most connected nodes are not necessarily its central ones through which most of the shortest paths pass, implies an anomaly in its centrality values (Guimera et al., 2005). In 2004, Guimerá et al (Guimera and Amaral, 2004). proposed a model incorporating geo-political constraints to explain this anomaly. Apart from its topological features, Barrat et al. (2004a)., studied the WAN in more detail by considering its traffic dynamics, particularly the strength of interactions among its nodes. They also proposed a model for determining the evolution of weighted networks to understand the statistical properties of real-world systems (Barrat et al., 2004b). Complex network measures have also been used to analyze the air transport networks of particular countries and airlines, such as those of Italy (Guida and Maria, 2007), India (Bagler, 2008a), Brazil (da Rocha, 2009), China (Wang et al., 2011) and the Lufthansa airline (Reggiani et al., 2009), with each found to have different characteristics and connectedness properties.

While uniquely modeling the AAN in terms of new complex network measures, such as centrality analysis, this study also attempts to provide insights into the nature of the connectivities among regional and hub airports, and identify the underlying network of airports that serves as the backbone of the main trunk routes in Australian regions.

2. Australian Airport Network (AAN) model

The Australian airspace extends from 2 to 90° south in latitude and 75–163° east in longitude, an area of almost 20 million square nautical miles (51.7 million square kilometers) or approximately 11 percent of the world's total airspace. Most of the country's major airports are concentrated along its coastline and form a typical 'J-curve' which implies that the traffic is highly concentrated and vulnerable. Annual movements in the Australian airspace involve 75 million passengers on more than three million flights originating from over 131 airports. Furthermore, given the large distances between cities and lack of a passenger rail network in Australia, air travel is the most preferred means of public transport. Understanding and analyzing this network can provide useful insights into the future development of airports, redesigns of airspaces by offering an important source of information for policy-makers.

The AAN consists of domestic and international airports which conduct regular passenger flights and more than 20 airlines (domestic and regional) connecting them. Air movement data among Australian airport-pairs for the year 2011 was obtained from the Bureau of Infrastructure, Transport and Regional Economics (http://www.bitre.gov.au), Australia, and the Official Airline Guide (OAG) (http://www.oag.com).

2.1. Unweighted AAN

For the purpose of developing the AAN, links were created between each airport-pair if any passenger flight connected these two airports. As, from the resulting network, we found that the AAN is a directed network in which all major airports have direct connections, it is represented as a connected network $G = (V, E)$ by V and E, where $V = v_i : i = 1, 2, \ldots, n, n = |V|$ is the number of nodes and $E = e_i : i = 1, 2, \ldots, m, m = |E|$ the number of edges (links). This network is represented by an adjacency matrix ($A_{n\times n}$) such that $a_{ij} = 1$ if a flight link exists between a city-pair (i and j), otherwise $a_{ij} = 0$. The resulting AAN consists of 131 airports and 596 direct air routes.

2.2. Weighted AAN

As for many other complex networks, knowing details of the information flow (traffic load) is a crucial factor for a transportation network. To accommodate information about the amount of traffic flowing in it, the AAN is represented as a weighted network by considering the number of flights on a route as the 'weight' of that particular link. These weights are defined by a weight matrix (A^w), in which each element (w_{ij}) represents the total number of flights from airport i to airport j. The AAN is shown in Fig. 1 in which the proportional circles represent the number of links of the airports (number of routes) and the widths of the links the average monthly traffic volumes.

Table 1 summarizes the air traffic volumes and air routes (number of connected airports) of the top 20 cities in the AAN from January 2011 to December 2011. The passenger data includes the major domestic airlines (Qantas, Jetstar, Virgin Blue and Tiger Airways) and regional airlines which conduct scheduled services, and the air-route data all the airlines (domestic and regional) that provide connectivity between airport-pairs. Of all the airports, Sydney has the highest numbers of air-route connectivities and passenger and flight movements.

3. Characterization and topological features of network

Network structures exist in a wide range of different contexts, such as technological and transportation infrastructures, social phenomena and biological systems. Each class of network presents specific topological features which characterize a network's connectivity, interactions and dynamic processes (Barrat et al., 2004a). Therefore, a complex network's analysis, discrimination and synthesis rely on using measurements that are capable of expressing its most relevant topological features in order to enable characterization of its complex statistical properties (Costa et al., 2007). Several metrics are used to measure the topological configuration of the AAN. Table 2 summarizes the key metrics used to characterize a network and their important roles in a transportation network, with the notations and variables having the following meanings.

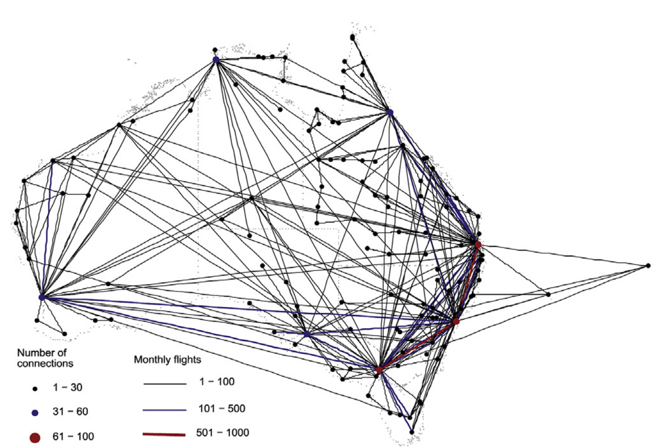

Fig. 1. Australian airport network.