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Empirical analysis of airport network and critical airports

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Abstract Air transport network, or airport network, is a complex network involving numerous airports. Effective management of the air transport system requires an in-depth understanding of the roles of airports in the network. Whereas knowledge on air transport network properties has been improved greatly, methods to find critical airports in the network are still lacking. In this paper, we present methods to investigate network properties and to identify critical airports in the network. A novel network model is proposed with airports as nodes and the correlations between traffic flow of airports as edges. Spectral clustering algorithm is developed to classify airports. Spatial distribution characteristics and intraclass correlation of different categories of airports are carefully analyzed. The analyses based on the fluctuation trend of distance-correlation and power spectrum of time series are performed to examine the self-organized criticality of the network. The results indicate that there is one category of airports which dominates the self-organized critical state of the network. Six airports in this category are found to be the most important ones in the Chinese air transport network. The flights delay occurred in these six airports can propagate to the other airports, having huge impact on the operation characteristics of the entire network. The methods proposed here taking traffic dynamics into account are capable of identifying critical airports in the whole air transport network.

1. Introduction

As the important components of air transport network, airports have a great impact on the operational performance of the air transport system. For instance, the European Organization for the Safety of Air Navigation (EUROCONTROL) holds a view that "understanding the variety of airports in Europe, their distribution, their traffic patterns, their aircraft mix, their strengths and their weakness is essential to understanding the strengths of the whole air traffic network".[1] Given

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the geographic locations, demographics and economics, airports play different roles in the air transport system. Special states of an airport, such as flights delay and congestion, can propagate to the other airports, and may finally disseminate over the whole network. There is a "do less for more" effect of identifying critical airports in the network when managing the air transport system. However, there is no existing universal method or criteria to identify whether an airport is critical.

In the past decades, researchers and engineers have long sought the way to assess the performance of airport. In the field of performance assessment, key performance areas (KPAS) are determined based on airport operation characteristics at first. Then key performance indicators (KPIS) are selected according to the KPAS.[2,3] Capacity, delay, and safety are the most common KPAS that have been widely investigated in the past. As one of the most important KPAS, capacity is normally evaluated based on mathematical models or simulation models. Airport's efficiency can be reflected by capacities under certain time horizons and operating conditions.[4–6] Parameters, such as punctuality, predictability, flight efficiency, and on-time performance, can be derived from flights delays.[7–9] Blom et al. constructed multi-agent models to assess safety risk of airport operation.[10–12] Safety level of airports can also be reflected through statistics such as rate of accidents/serious incidents/incidents.[2,3] Integrated comprehensive transportation capability of an airport can be analyzed in terms of instrument flight rules (IFR) flights, average number of annual IFR movements, average number of annual passengers, passengers per IFR movement, annual IFR movements per runway, and so on.[2,3] While some researchers apply data envelopment analysis to assess productivity, others decompose efficiency into production and efficiencies then assess them separately.[13–15] It is thought that critical airports can be identified by comparing these KPIS. A major drawback of such methods is that airports are treated as isolated objects rather than inter-connected parts in the network.

Research on complex networks has been advancing our knowledge of air transport network. The airport network structure has been widely studied both at the international levels and at domestic levels. Network properties have been examined, including degree distribution, average path length, diameter, clustering coefficient, in-out degree correlation, degree–degree correlation, clustering coefficient–degree correlation, betweenness, and rich-club coefficient. Empirical analyses show that air transport networks of Italy, Brazil, India, China, and the entire world are small-world networks.[16–25] From complex network perspective, airports with higher degree or betweenness are the important nodes in the air transport network. Although topological structures of the network may reveal the importance of the airport, it is unable to identify the dominant airports due to the lack of consideration of traffic flow and the interactions among airports.

Here we propose a novel method to analyze airport network and to identify the most critical airports. Airport-pair correlations are calculated using traffic flow data. Airport network is then constructed with airports as nodes and airport-pair correlations as edges. All airports are categorized into groups by the proposed spectral clustering algorithm. Network topological structure is illustrated preliminarily. Distance-correlation and power spectra are used to demonstrate whether airport network is a self-organized critical system. We assume that the network criticality originates from a certain group of airports. Finally, the most critical airports are identified by analyzing the distribution of critical state (delay) transition intervals. In a critical system, there should be critical components influencing the whole system.

The rest of this paper is organized as follows. In Section 2, the original data and processing principles are presented. In Section 3, spectral clustering algorithm is developed and applied to classify airports into different categories. Section 4 analyzes the relationships between airport-pair correlation and spatial distance. In Section 5, $1/f$ spectra is used to probe the long-range memory effects of traffic flow time series. Section 6 gives the transition intervals distributions for the highest delay contribution rate of critical airports or critical airport-pairs. Conclusions are presented in Section 7.

2. Data

Empirical flights data operated within mainland China from January 1st, 2011 to June 30th, 2011 was obtained from the Operation Center of Air Traffic Management Bureau. After data cleaning, there are about two million pieces of record of flight data left for analysis. Each piece of record contains key information of a flight, including departure airport, arrival airport, scheduled time of arrival/departure, and actual time of arrival/departure.

Since the main focus of this study is to identify critical airports in the network, the following airports are out of scope of analysis:

(1) International airports (including Hong Kong, Macao, and Taiwan).
(2) Airports without traffic flow.
(3) Airports with arriving traffic flow or departure traffic flow only.

In total, 161 airports are examined in the presented work.

3. Airport network topology

Clustering algorithms have been used in various airport networks to discover potential community structures or to group airports with the maximum similarity.[26–29] To analyze airport network topology, airports with similar traffic patterns should be identified according to one or more characteristics. The spectral clustering algorithm is widely used which derives from spectral graph theory. It is assumed that each sample is regarded as node V. We assign weighted value W to the edge E according to the similarity among samples. Therefore, there is an undirected weighted graph $G = (V, E)$. Clustering is then transformed to the optimal partitioning of the graph.[30]

Here we develop a spectral clustering algorithm to study airport network based on the correlations between time series of traffic flow of airports. We can uncover spatial topology of the correlation among airports through the clustering results and compare correlation characteristics of different categories of airports.[30] We assume that the sample set contains N airports, and let $f_i(t)$ represent the traffic flow value of the ith airport at the tth slot. T is number of time slots every day. The spectral clustering algorithm is depicted in the following.