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## **STRUCTURAL CENTRALITY RELATIONS IN THE GLOBAL AIR TRANSPORT SYSTEM**

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### **Abstract**

This paper presents an analysis of the relational structures and hierarchies in the global air transportation system through the use of network analysis and graph theory. Using the global air transport network and annual jet air passenger service data for all commercial airlines over the period 1996-2012 inclusive, we analyse the relative position of airports in the global, European, North American and Asian air transport networks through indicators of centrality. Results illustrate the impact that recent air transport policy developments such as market deregulation and the liberalisation of air transport have had on the spatial distribution of airline services and networks. Because of different airline network organisation strategies employed by carriers in continental regions, the European airports are prominent in the global structures identified.

### **1. Introduction**

The objective of this paper is to understand the hierarchies and substructures in the global air transport system and examine the position and role of global, European, North American and Asian airports within that system. Global daily air transport schedules for all of the world's airlines are used to compile annual traffic movements for the period 1996-2012. Graph theory methods are used to characterise and classify airports based on metrics evaluating the role of airports in the network in terms of their importance in facilitating connections in the system. Connectivity is gaining importance relative to other variables used to assess airport performance and to understand the business strategies adopted by different airlines. The analysis of connectivity is also of interest to regional and local authorities for the improvements of air transport accessibility to their territories [1]. Results are reported for measures of centrality and power among subsets of airports. In the next section, the growing literature on complex network theory is briefly reviewed. Metrics of network centrality and power are described and some empirical results pertaining to transportation networks are highlighted. In section 3, the data used in the analysis are described and the research approach is outlined. Section 4 includes a brief description of the global, European, North American and Asian air transport systems in the 1996-2012 period. Section 5 reports the results and section 6 summarises the key findings and outlines important issues that will be the subject of future research.

### **2. Air transport systems: hierarchies and complex networks**

The interdisciplinary study of the network structure of transportation systems has generated an increasing body of literature on applications to airline network analysis in recent years. This has been further driven by the advancement of complex network theory, which offers a set of analytical and modelling tools to identify the topological properties of networks [2]. These models have been extensively applied in social, biological and ecological contexts as well as to transportation and communication networks.

As with many other economic activities, the air transport industry is characterised by network features with high degree of complexity [3]. Modelling complex airline networks involves not only the understanding of their topological structure, but also the comprehensive analysis of the spatial socio-economic implications of the type of connectivity structure of air transport networks.

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An important trend observed in many real networks is the so-called small-world effect. These are networks with a small average path length and a large clustering coefficient [4]. Barabassi and Albert (1999) [5] introduced the so called scale-free network to incorporate the mechanisms of growth and preferential attachment<sup>1</sup>, which are common to many real networks. The scale-free network is a network whose degree distribution conforms to a power-law function [6] and characterises networks with a small number of high-degree nodes, while the majority of nodes have a few links [7]. Alternatively, when the majority of nodes have approximately the same number of links – close to the average degree- and the vertex degree distribution follows a Poisson distribution [8], a random network is described [5]. Most of the interesting features of real world networks and the motivation for the increased attention of researchers over the last few years concern the ways in which networks are not like random networks [6].

Complex network measures have been used for evaluating the worldwide air transport network [9],[10] and the air transport network of countries, regions and individual airlines [11], [12], [13]. Some air transport applications of the network models described above relate to the identification of hub-and-spoke versus point-to-point network configurations [14], which are generally characterised by the presence of scale-free and random networks respectively.

A number of measures of connectivity can be found in the literature on air transportation. Centrality is a basic concept for the analysis of complex networks. Several classic centrality measures are based on shortest paths. These are some of the most fundamental and frequently used measures of network structure. A number of studies on air transport network analysis have assessed the role of centrality measures to the stability of the network and the efficient flow of traffic [15]. Through various mathematical formulations, centrality measures evaluate the relative importance of a node within a network [16]. In this paper, three indicators of centrality – degree centrality, closeness centrality and betweenness centrality - are computed to identify the patterns of connections between airports in the global, European, North American and Asian networks for the years 1997, 2002, 2007 and 2012.

### 3. Methodology

A network – also known as a graph in mathematics literature - is a set of items, usually called nodes or vertices, with connections between them, called edges. In the case of air transport networks, nodes represent airports and a link between two nodes is created whenever there is a direct flight between the two airports represented by the nodes. This is a simple directed graph where two directed links can exist between two nodes A and B, one describing the number of flights from A to B and from B to A. These are usually known as flight networks [17] or unweighted networks where only topology matters. Using flight networks for the global, European, North American and Asian air transport systems, three measures of centrality are computed in this paper: (i) degree centrality, (ii) closeness centrality and (iii) betweenness centrality.

Degree centrality, also known simply as degree, refers to the number of edges that a node shares with others, and therefore represents the importance of a node in a network [18], [19]. In mathematical terms, the degree  $k_i$  of a vertex  $i$  is  $k_i = \sum_{j=1}^n a_{ij}$  where  $a_{ij}$  are the elements of the adjacency matrix.

Closeness centrality and betweenness centrality measures are based on the concept of network paths, which refer to a series of vertices traversed by following edges from one to another across the network [6]. The geodesic path or distance, which represents the shortest of all distances between two nodes [19] is used to compute closeness and betweenness.

Closeness centrality is defined as the reciprocal of the average shortest path between a node  $i$  and all other nodes reachable from it. Mathematically, closeness is defined as  $C_i = 1/\sum_{j \in V} d_{ij}$  where  $V$  is the connectivity component which contains all the network vertices reachable from vertex  $i$ . Nodes with high closeness value are more central in the network and therefore, all other nodes can be reached more easily from them. Some authors have referred to closeness as an indicator of proximity, and it has also been interpreted as an indicator of the accessibility of an airport [20],[13].

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<sup>1</sup> In the case of incremental growth in a complex network, new nodes are more likely to connect with nodes that already have the highest number of links.

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The betweenness centrality of vertex  $i$  measures the extent to which a particular node stands between others in a network. First defined by Anthonisse (1971)[21] and Freeman (1977)[18], betweenness is computed as the ratio of the number of shortest paths passing through  $i$  to the total number of shortest paths in the network. Thus,  $B_i = \sum_{i \neq k \neq j \in V} \sigma_{kj}(i) / \sigma_{kj}$  where  $\sigma_{kj}$  is the sum of all shortest paths between nodes  $k$  and  $j$ , and  $\sigma_{kj}(i)$  is the number of shortest paths that pass through vertex  $i$ .

Data for this study comes from the Official Airline Guide Historical MaxPlus data sets. These data sets give comprehensive coverage of ex-post airline schedules for each year from 1996 to 2012 and cover scheduled and non-scheduled operations. Airline schedules are published one year ahead and the MaxPlus dataset presents the revised ex-post schedules. The OAG coverage of airlines is far more extensive than in either ICAO or IATA databases, and includes almost all passenger operators globally. The main problem with these datasets is that the activity measured is either seating or freight capacity available, rather than actual traffic performed. The categorisation of states and regions follows ICAO and IATA conventions rather than reflecting liberalised air transport markets such as the European Common Aviation Area (ECAA) or NAFTA. However, the comprehensive and consistent coverage of domestic and international air transport activity globally allows for comparative analysis of major continental air transport markets.

#### 4. Description of Global, European, North American and Asian air transport systems, 1996-2012

The global air transport systems expanded significantly between 1996 and 2012, with a 75% increase in the total number of routes and a 20% increase in the number of airports receiving passenger jet air services. The European region increased its share of routes over this period, with intra-European routes increasing from 24% of global routes in 1996 to 35% in 2012, with all European originating routes accounting for 41%. European airports accounted for 22% of global airports in 2012, while Asian airports accounted for 25% and North American airports 18%. Intra-North American routes declined from 19% in 1996 to 15.6% in 2012, while intra-Asian routes increased slightly from 15.6% in 1996 to 16.4% in 2013.

Figure 1 shows the proportion of global routes within the North American, European and Asian networks. The European ratio of internal routes to airports is significantly higher than for other regions. These high ratios mean that there is a higher level of interconnectivity among the European airports within the global air transport system and this is reflected in the results of the network structure analysis in the next section.

Figure 2 shows the average degree for the global and intra-regional networks in the 1996-2012 period. The intra-European air transport network ranks at the top in terms of average degree, which shows an increasing pattern from 2003 to 2010.

Figure 3 shows the regional distribution of global seating and departure movement capacity in the same period. The significant decline in the North American traffic shares is apparent as is the rapid rise in the Asian shares of both movements and seating capacity from the mid-2000s. While North America has the largest share of movements, these are much more concentrated on a smaller network of routes.

#### 5. Centrality of airports in the Global, European, North American and Asian networks

Figures 4-7 show the graph representation of the top 30 airports in the global and inter-regional air transport networks ranked by degree centrality, closeness and betweenness centrality for the years 1997, 2002, 2007 and 2012.

European airports – FRA (Frankfurt) and CDG (Paris) - show the largest levels of degree and betweenness centrality at the global network level. The relative position of Asian and Middle-Eastern airports – PEK (Beijing) and DXB (Dubai) – regarding betweenness centrality has improved, in particular in 2012.

In Figure 5, the network graphs for the intra-European air transport network illustrate the effect of market liberalisation in the European airline industry and the subsequent expansion of low-cost carriers. The 2012 degree centrality graph shows a relatively large number of airports with similar levels of degree centrality. The relative position of European airports with

regard to their ability to act as hubs (or betweenness centrality) has evolved towards the prominence of STN (London Stansted) in 2007 and more recently, of DME (Moscow) and IST (Istanbul).

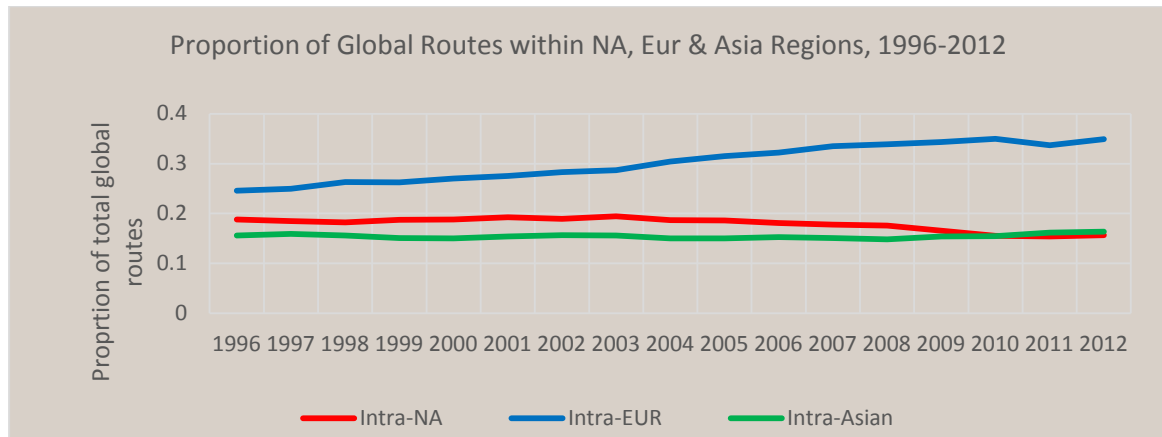


Figure 1: Proportion of global routes within the North American, European and Asian regional networks, 1996-2012

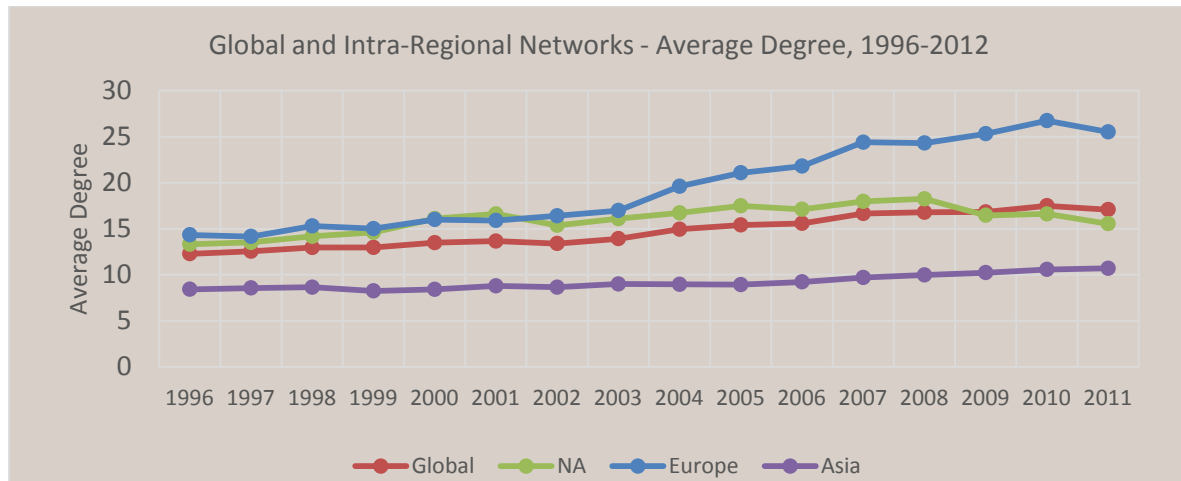


Figure 2: Average degree – global and inter-regional networks, 1996-2012

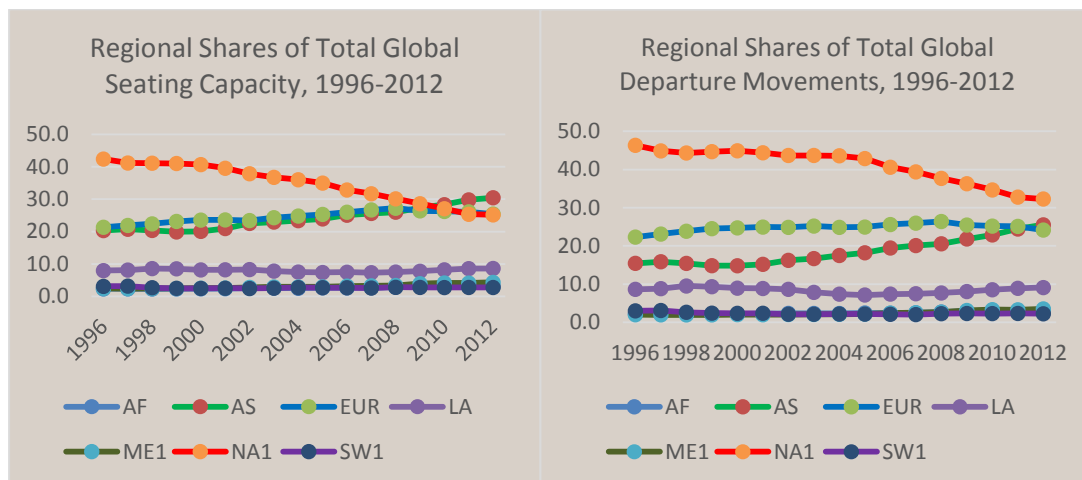


Figure 3: regional distribution of global seating capacity and departure movements, 1996-2012

Significant network structural changes have taken place in the North American intra-regional air transport network with respect to centrality – see Figure 6. While the top ranked airports in terms of degree have not varied much since 1997, the ranking according to betweenness centrality has experienced significant changes.

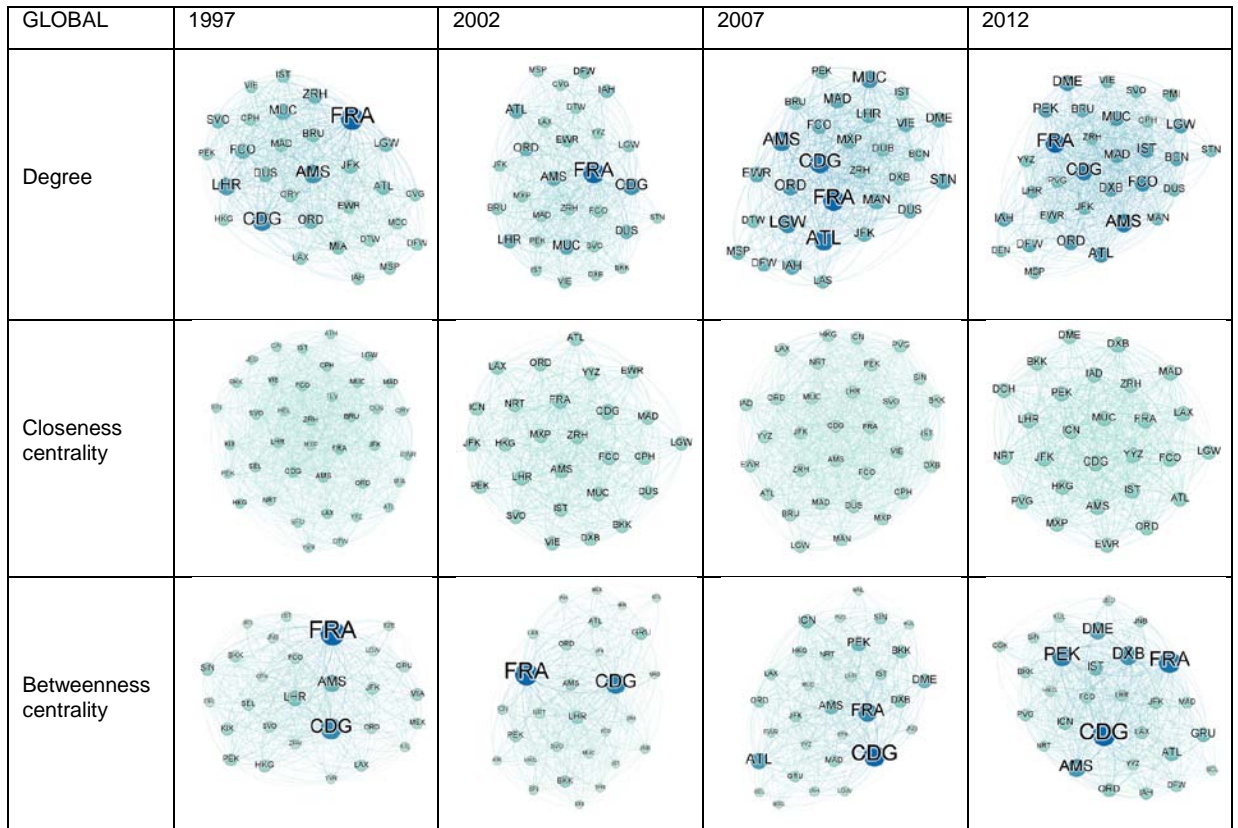


Figure 4: Multiple centrality assessment of the Top 30 airports in the global air transport network

The recent mergers in the US airline industry and the business strategy of individual carriers have had an effect on the levels of betweenness centrality as shown in Figure 6. In 2012, three years after the Delta Airlines/Northwest Airlines merger, a new set of airports has emerged in terms of their relative level of betweenness centrality or their ability to act as hubs for the entire North American air transport system. In 2012, MSP (Minneapolis/St. Paul) and DFW (Dallas/Forth Worth) airports rank at the top for betweenness centrality together with ORD (Chicago) and ATL (Atlanta) airports.

Figure 7 shows the network graphs according to degree, closeness and betweenness centrality for the Asian intra-regional air transport network. While the relative position in terms of degree of Chinese airports – PEK (Beijing) and CAN (Guangzhou) airports – has not changed significantly in the periods under study, the level of betweenness centrality has evolved towards the dominance of PEK (Beijing) airport. Other Asian airports such as BKK (Bangkok), which enjoyed some prominence in terms of betweenness centrality in the Asian air transport network, are no longer at a top position in the 2012 ranking. This does not necessarily mean that these airports are performing worse in terms of connectivity/centrality, but that there are other airports that are performing better and therefore, rank higher for that particular period.

In contrast to the other networks, the network graphs for closeness centrality in the Asian air transport network, which can be interpreted as proximity or an indicator of accessibility to other airports within the region, allow for the identification of a set of airports that clearly rank at the top. This is particularly evident in 2007 and 2012 for PEK (Beijing), BKK (Bangkok) and HKG (Hong Kong) airports.

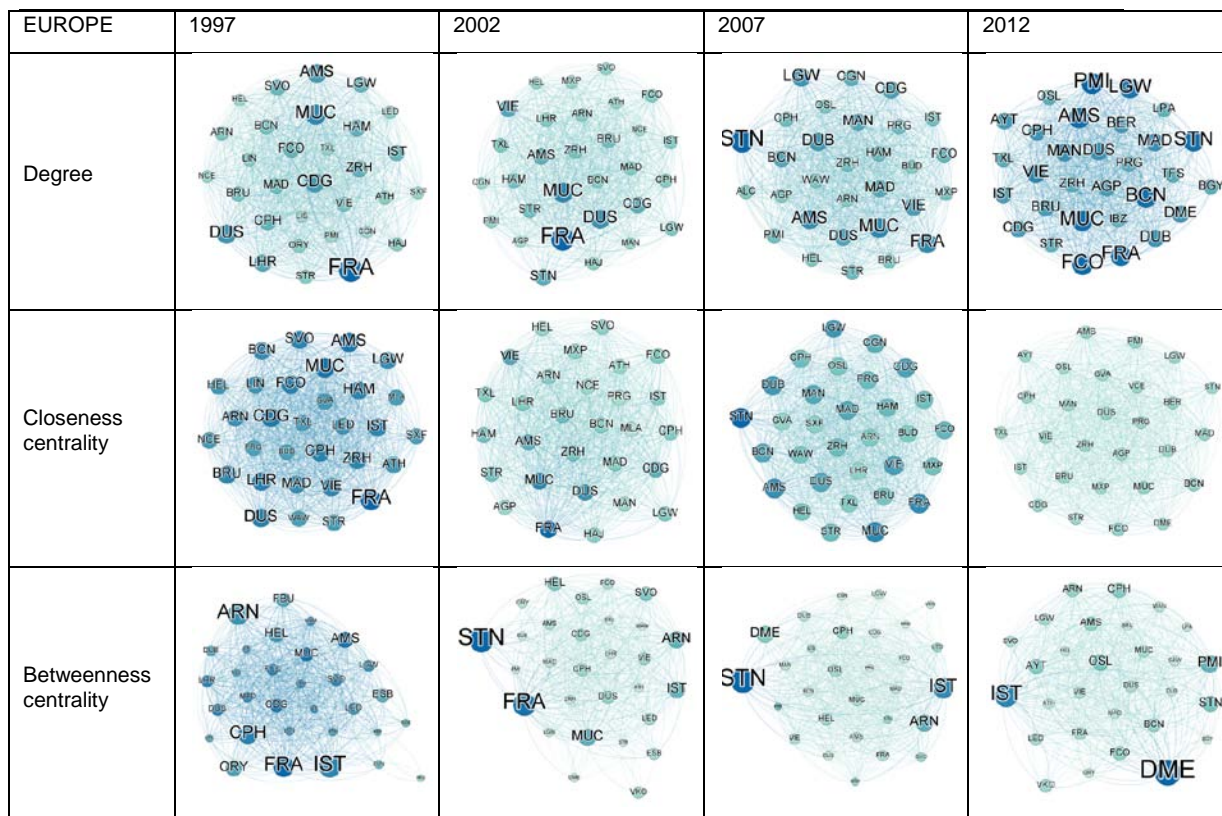


Figure 5: Multiple centrality assessment of the Top 30 airports in the European air transport network (Intra-European air services only)

## 6. Summary and discussion

The objective of this paper was to describe and understand the hierarchies and substructures in the global air transport system and examine the position and role of global airports within that system. Data from global daily air transport schedules for all of the world's airlines have been used to compile annual traffic movements for the period 1996-2012. Graph theory methods are used to characterise and classify airports based on measures of network centrality and power for four periods - 1997, 2002, 2007 and 2012 – and four networks – global, Europe, North America and Asia.

The analysis focuses on the linkage structure between the global and various regional networks. The degree centrality measures reflect the number of direct routes operated from each airport. In the global network, the dominance of several of the largest European airports reflects the substantial expansion of air services particularly in the ECAA countries following liberalisation (1997) and the accession of the 12 central and eastern European states to the EU in 2004 (10) and 2007(2). The low cost carriers, in particular Ryanair, Easyjet and Air Berlin, have driven this expansion of intra-European air services, with a proliferation of new point-to-point services many being operated less than daily.

The lower scores associated with the North American airports, particularly from 2007 onwards, reflects the network strategies operated by most of the large US carriers. While these carriers provide far greater capacity in terms of seating and movement offerings, the aggregate proportionate numbers of non-stop routes operated per airport are smaller than for European and Asian airports. The interactive hub-and-spoke systems operated by the large US carriers result in high capacity and frequency and large numbers of single-route airports directly connected to a relatively small number of hub airports.

The most important nodes in terms of betweenness and closeness are the hub airports with extensive 'spoke' connections. The mergers of several of the largest US carriers in the last 7 years have given rise to a rationalisation of capacity and re-organisation of the linkage pattern.

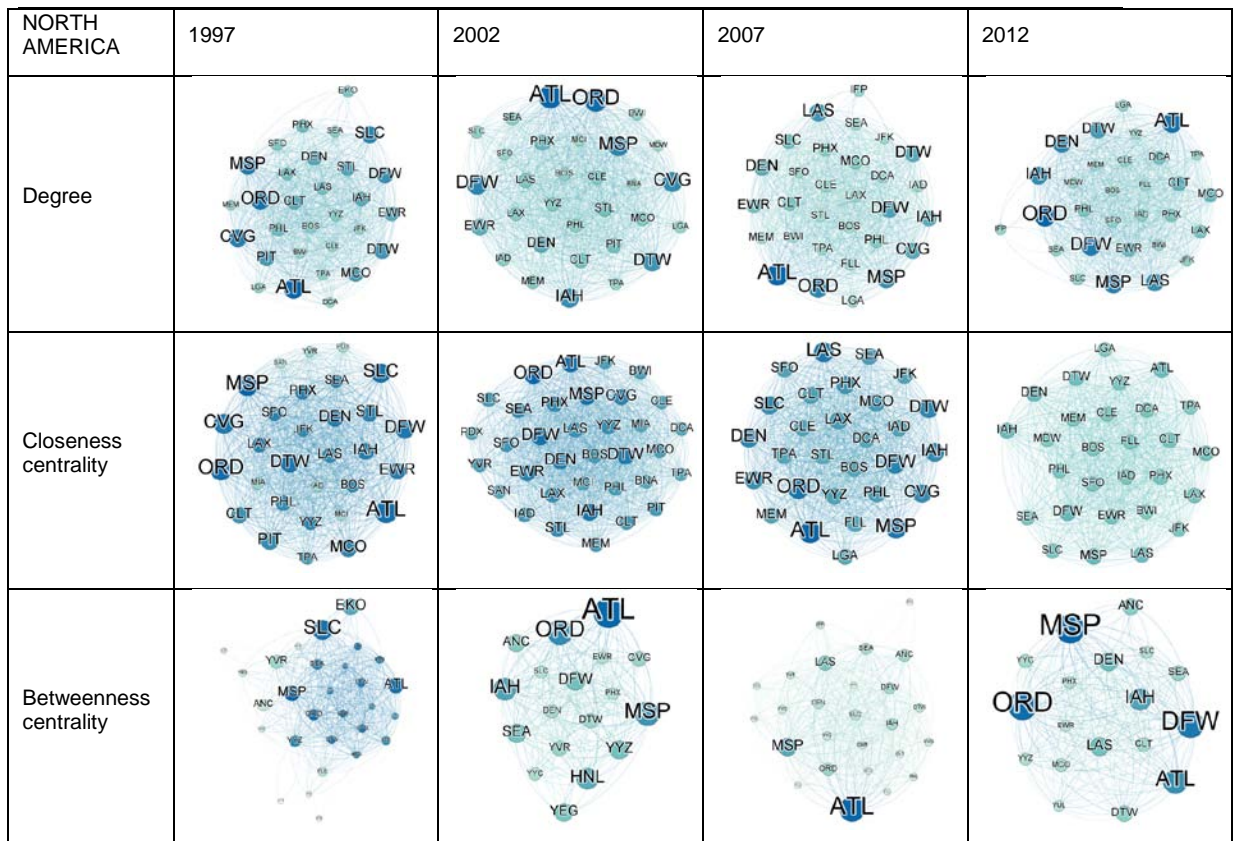


Figure 6: Multiple centrality assessment of the Top 30 airports in the North American air transport network (Intra-North American services only)

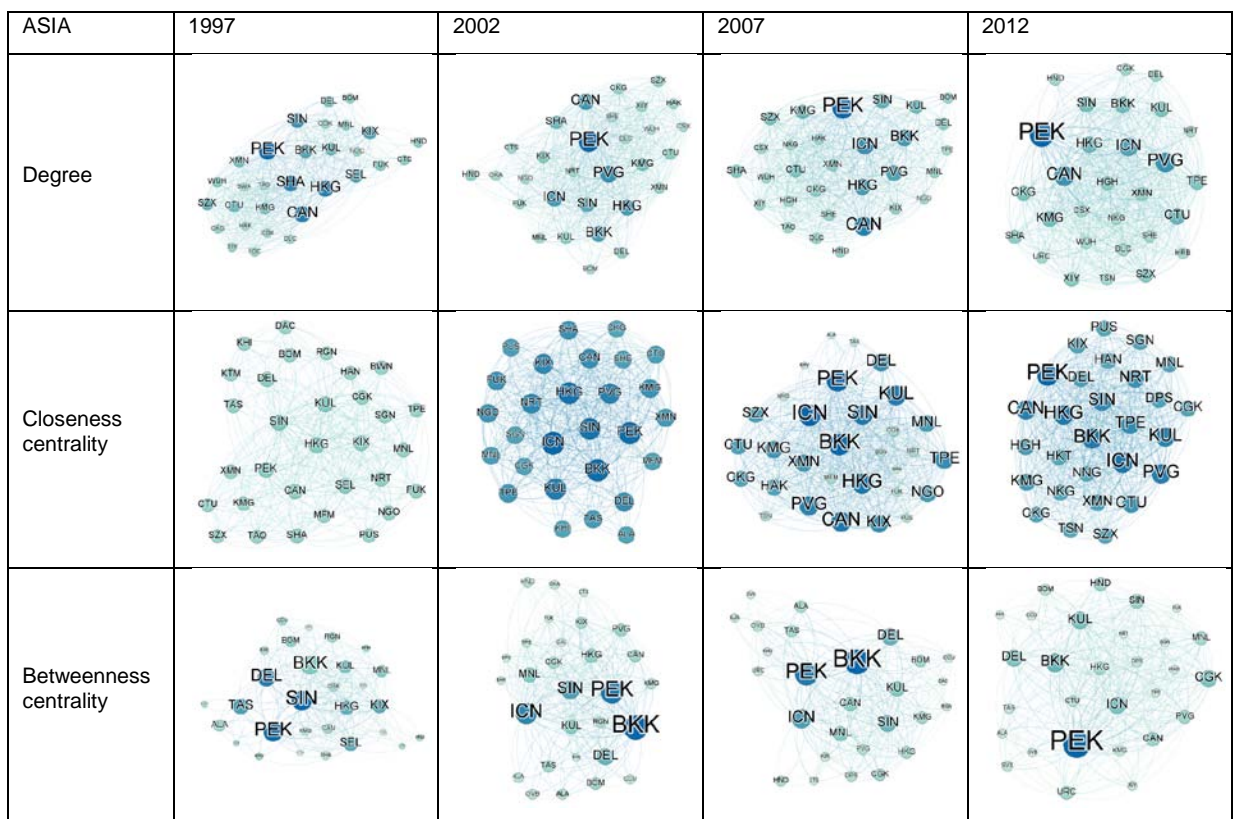


Figure 7: Multiple centrality assessment of the Top 30 airports in the Asian air transport network (Intra-Asian air services only)

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These results illustrate the impact that recent air transport policy developments such as market deregulation and the liberalisation of air transport services have had on the spatial distribution of airline services and networks. Because of different airline network organisation strategies employed by carriers in continental regions, the European airports are prominent in the global structures identified.

Future research will focus on further exploring the evolution of the structural characteristics of these networks. In particular a variety of graph clustering methods will be used to identify subgroups at the global and continental region scales. The implications for assessing the vulnerability and accessibility characteristics of local and regional air transport services will also be examined.

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