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Analyzing the multilevel structure of the European airport network

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Abstract The multilayered structure of the European airport network (EAN), composed of connections and flights between European cities, is analyzed through the *k*-core decomposition of the connections network. This decomposition allows to identify the core, bridge and periphery layers of the EAN. The core layer includes the best-connected cities, which include important business air traffic destinations. The periphery layer includes cities with lesser connections, which serve low populated areas where air travel is an economic alternative. The remaining cities form the bridge of the EAN, including important leisure travel origins and destinations. The multilayered structure of the EAN affects network robustness, as the EAN is more robust to isolation of nodes of the core, than to the isolation of a combination of core and bridge nodes.

1. Introduction

Since its inception in the beginning of the 21st century, the development of aeronautics and air travel has deeply transformed economy and society. The fact that trips that lasted days or even weeks or months can be done today in a few hours has brought closer countries and civilizations, and the impact of air travel can only be paired with the development of the internet. A common feature of air travel and the internet is that both are networked infrastructures. In the case of air travel, the aggregation of commercial decision of airlines has created air route networks, where the nodes are airports or cities connected by edges when there is at least a direct flight between them.

Complex network theory is a powerful tool to investigate networked systems such as air route networks. Taking a systems theory approach, complex network theory investigates the influence of topological features of real-world networks on phenomena such as network robustness or propagation. The results of complex networks theory have been applied extensively to the study of air transport networks. Guimerà and colleagues[1,2] were the first to analyze the world air route network, finding that the central cities were not necessarily the best connected nodes. Lordan et al.[3] analyzed the robustness of the world airport network (WAN), finding that the most effective criterion to break up the WAN is to disconnect the most central nodes (i.e., the nodes with highest betweenness centrality).

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Regional airport networks can have different properties from the world airport network. It has been found that airport networks can have different properties depending on season (summer or winter), species (business or leisure) or scale (route vs origin-destination).[4] Extant research has found that the WAN has a multi-community structure[2] so regional networks can be different from the global network. Regional airport networks share similar topological features, although had remarkable differences in evolution and growth. For instance, while the Chinese airport network is experiencing a rapid development,[5] in the Brazilian network, although the number of passengers has increased, the number of routes has decreased as airlines focus on more profitable routes.[6]

One of the central elements of the WAN is the European airport network (EAN), which includes all routes between European airports that have at least a direct flight. The EAN is a reflection, and a consequence, of the social and economic development of Europe. Considering Official Aviation Guide (OAG) Flights (http://analytics.oag.com/) data from August 2014, the European network has less nodes than the North-American (601 vs 899), but considerably more direct connections between airports (6401 vs 3540).

A distinctive feature of airport networks is that they are the result of the aggregation of decisions taken by airlines about their route portfolio, which in turn are the result of different airline business models and their integration in airline alliances.[7] This fact leads to consider that a more realistic modeling of airport networks can be obtained if its multi-layered structure is taken into account. Cardillo and colleagues[8] modeled the EAN as a network of 15 layers, corresponding to the route networks of the largest European carriers, while Verma et al.[9] and Du et al.[10] analyzed the WAN and the Chinese airport network, respectively, defining three layers for airport networks based on the k-core decomposition.[11] These analyses showed that the analysis of the multi-layered structure of airport networks offered remarkable insights about their properties, such as network structure and robustness.

The aim of this paper is to model and to analyze the EAN as a multi-layered network, to better understand its internal organization and the network properties that determine its robustness to the isolation of nodes chosen either at random (attacks), or chosen intendedly as relevant or central (attacks). In the next section, a topological analysis of the EAN will be undertaken, including the analysis of its core, bridge and periphery layers. Then, a robustness analysis will be carried out, paying special attention to the role that airports of cities belonging to core and bridge play in robustness of the EAN. The results obtained, and a reflection about their operational implications, will be reported in the conclusions section.

2. Topology of the EAN

A sample of the EAN was obtained by including all flights between European cities (including Canary Islands and Madeira) in August 2014 covered by the OAG dataset. The EAN was described through its adjacency matrix $\boldsymbol{A}$, where $a_{ij} = 1$ if cities i and j are connected through at least a direct flight and $a_{ij} = 0$ otherwise. To allow comparison of results with previous research,[2,10,12,13] airports serving the same city (e.g., London City Airport and Heathrow Airport) have been collapsed into one node. The resulting network has 601 nodes and 6401 connections. The degree of a node k_i is equal to its number of connections:

$$k_i = \sum\nolimits_{j=1}^{n} a_{ij} \tag{1}$$

The degree distribution (i.e., the probability distribution of the degree of the network nodes) of EAN follows a two-regime power law, with an average degree of $\langle k \rangle = 12.23$. This result is coherent with previous studies on the European network,[14] and on other regional airport networks such as the United States,[15] India[16] and Brazil.[6] Studies of the world airport network have also found a two-regime exponential degree distribution.[2,3] It must be noted that some recent studies have found that the degree distribution of the Chinese airport network follows an exponential law.[5,17] According to Ref.,[17] an exponential degree distribution in an airport network is a consequence of more dominance of large airports than in the power law.

EAN has a global clustering coefficient of $C = 0.62$ and average path length $L = 4.04$, so it can be considered a small world network. To assess the weight of a connection, a weight matrix $\boldsymbol{W}$ has been defined, where w_{ij} is equal to the number of flights scheduled in August 2014 between cities i and j. The network considered has a total of 652291 flights. The strength of a node s_i is equal to the sum of weights of edges departing from node i:

$$s_i = \sum\nolimits_{j=1}^{n} w_{ij} \tag{2}$$

The multi-layer structure of the EAN can be analyzed through the k-core decomposition of its adjacency matrix. A k-core of a graph is any subgraph which has nodes with degree equal or larger than k.[18] This decomposition allows to classify the nodes of the EAN in three subsets or layers[9,10]: the core contains the nodes belonging to the k-core of maximum k and the periphery the nodes included in the $k = 1$ core. The rest of the nodes belong to the bridge. In Table 1 is reported the number of connections in and between core, bridge and periphery.

To assess the role that a node has in the layer it belongs to, several ratios of connections R_{a} and flows R_{f} have been defined for each node. $R_{\mathrm{a}}^{\mathrm{in}}$ and $R_{\mathrm{f}}^{\mathrm{in}}$ represent the ratio of connections and flights, respectively, that a node has with nodes of the same layer respect the total of connections and flights. R_{a}^{st} and R_{f}^{st} represent the ratio of connections and flights, respectively, that a node belonging to layer s has with nodes of the layer t, respect to the total of connections and flights. For instance, $R_{\mathrm{a}}^{\mathrm{bc}}$ is the ratio of connections a that a node of the core has with nodes of the bridge.

2.1. Core layer: global European city

Data reported in Table 1 shows the importance of the core layer in the European airline traffic. There are 1690 direct connections (26.40% of the total) and 313396 flights (48.05% of the total flights) between the 69 cities (11.48%) belonging to the core of the EAN. Given the dense knit of routes between these cities, it can be argued that they constitute a global "European city". The 17 cities of highest degree belonging to the core are listed in Table 2. Data from that table show a strong relationship between degree and strength ($r_{k,s}^{\mathrm{core}} = 0.9067$), and a negative relationship between degree

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