Distance dependence in the spatial structure of China aviation system: A complex network perspective

Jingyi Lin

Division of Geoinformatics, Department of Urban Planning and Environment
Royal Institute of Technology 100 44 Stockholm, Sweden
Email: jingyilin2008@gmail.com

1. Abstract

Aviation systems are constructed by cities and airlines, which can be analyzed under a complex network framework. In this paper, considering the unique construction mechanism of airlines, we firstly clarify that China's aviation system presents a hierarchical structure under the form of a network by detecting a scaling relation between clustering coefficient and node degree. It also indicates a more complex spatial pattern to be revealed. In the second section, in terms of the node strength and traffic flows on China's aviation network, we conclude that the distance dependence effects should be explored on different geographic distance scales. Only for medium- and long-distance travel, a gravitational law can be detected. This result paves the way as a reasonable reference for optimizing aviation systems and understanding the spatial organization of complex networks.

2. Introduction

Aviation systems, as an indispensable part for a country, have gained extensive attentions from various disciplines for a long time. In the last decade, the complex network theory introduced an innovative perspective to this field, and many real aviation systems have been studied under worldwide or national scales (Guimerà et al 2005, Liu and Zhou 2007, Bagler 2008). Various network characteristics have been studied and results consistently show that aviation systems present small world effects and scale-free properties. However, compared with statistical measurements, the spatial patterns of complex system have not earned enough attentions from network perspective until recently. Some researchers have began to discuss the geographical structure and distance effect of social networks and public infrastructure systems (Lambiotte 2008, Jung et al 2008, Hu et al 2009, Krings et al 2009, Levy 2010). In terms of the statistical measurements, Ravasz and Barabasi (2003) discovered some networks, whose clustering coefficient and degree satisfy $c(k)\sim k^{-1}$, should present a hierarchical architecture, while some distance-driven networks, such as power grids did not. Based on this conclusion, Liu and Zhou (2007) detected a hierarchical architecture in China's aviation network and considered that the spatial impact was negligible for it. However, it seems undeniable that any aviation system will have some spatial component. In this sense, how do aviation systems really get rid of spatial effects, if, indeed, they do? What is the underlying spatial mechanism and how does the mechanism influence the traffic flows? In this paper, we will go beyond the general topological properties and put more focus on the unique distance dependence effect within China's aviation system from a complex network perspective.

3. Explicate the research question under a network framework

It is worth mentioning that airlines are not physically constructed as links on the ground, and this feature may endow an aviation system with distinctive network topology and spatial pattern to some extent. In this part, we will explicate the problem step by step under a complex network framework. Before this, we would like to briefly introduce the network representation pattern. Due to the hop-by-hop architecture of aviation systems, we can construct China's aviation network easily in terms of graph theory. A city is regarded as a node no matter how many airports it possesses, and a link is established as long as there is a directed flight between two cities. An aviation network with 140 nodes and 1044 edges is obtained.

As a starting point, Fig.1 depicts the correlation between node degree and clustering coefficient for 140 nodes in China aviation network. It is worth noting that the clustering coefficient is not independent of node degree but follows a scaling law in terms of degree. Such a relationship implies a hierarchical architecture for China's aviation network. It means that some vertices form lower-level communities, which are then entangled into a higher-level community. In other words, the neighbors of hub cities are not mostly linked to each other. On the contrary, geographic organizations can not display hierarchical structures due to the spatial limitations on the link length (Ravasz and Barabasi, 2003). To understand this inference, we should preliminarily introduce the unique construction of aviation systems. Compared to other ground transportation systems, such as railways or metro networks, aviation systems are less limited by geographical conditions or investment cost because physical links are not constructed. But on the other hand, every airport has its precise geographic position, so the whole aviation system is undoubtedly space-embedded. Medium-length airlines are dominant in China's aviation system, and flight flows also concentrate upon such routes. In comparison, extremely short or long routes are both rare out of cost considerations (Fig.2). In this sense, these seemly incompatible judgments actually indicate a more complex and challenged spatial pattern to be revealed. We can conjecture that China's aviation network possesses an intermediate architecture between that of a social network and geography-involved system.

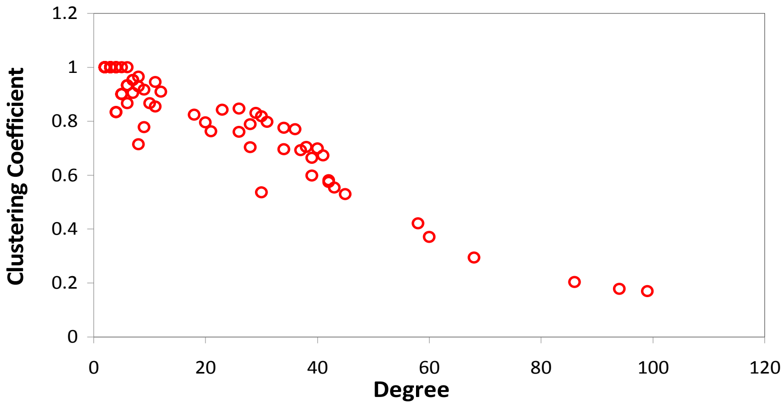

Figure 1. The scaling correlation between node degree and clustering coefficient

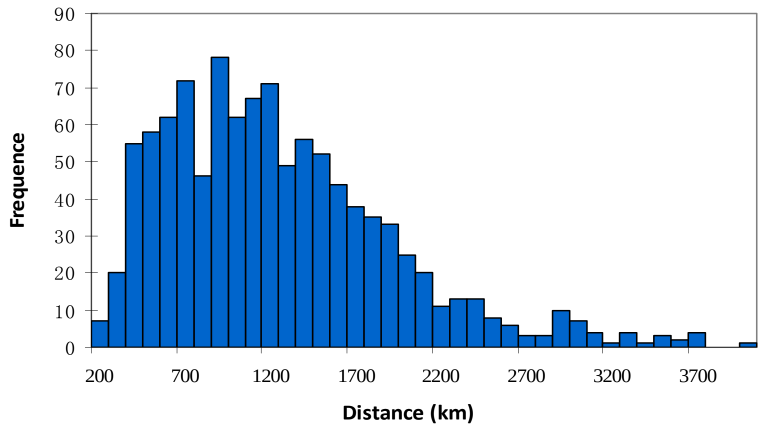

Figure 2. The histogram of geographical distance between city pairs for CAS（Most geographical distances between two cities fall into the ranges of 500-2000 km）

4. Distance dependence for different distance scales on China's aviation network

To explore the dynamics of the aviation network, we collect the weekly flight numbers between each connected city pair, and consider them as edge weights of the network. Firstly, we will depict the correlation between edge weight and spatial distance on China's aviation system in Fig.3. In order to denote the pattern more clearly, 1044 values for two variables are respectively clustered with an equidistant interval. Remarkably, the plot shows a two-regime distribution, and the critical threshold is around 500km.

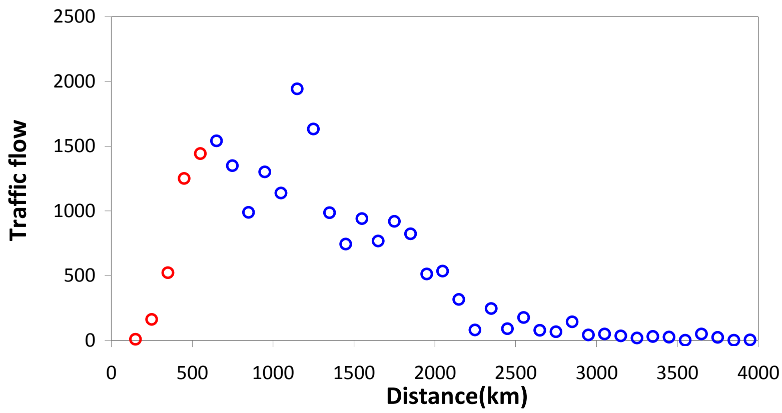

Figure 3. Dependence of the traffic flow on spatial distance (For better illustration, we set the distance interval between data points is 100 km. The result shows two-regime pattern and two different colors serve as a guide to distinguish)

Then the traffic flow is investigated in terms of node strength and spatial distance. The result is presented by Fig.4. Similarly, the correlation should be considered in terms of two separate parts, and the critical distance is 474 km. No clearly dependence effect can be found for the first part. However for the second part, a gravitational law can be detected as,

$$\frac{w_{ij}}{s_i s_j} \propto f(d_{ij}) \tag{1}$$

In which s_i is the node strength for city i, and w_{ij} is the edge weight in the aviation network, denoting the traffic flow between two cities. $f(d_{ij})$ represents the distance dependence function. In this case, it can be generalized as a scaling relation. The decay coefficient is 0.697, which is even smaller than 1. This result is reasonable. Powerful ground transportation may impose huge competitions on short-distance travel so that the advantages of aviation transportation only focus on the medium and long distances. On the other hand, due to the small-world property of the aviation network, people can transfer in some hub cities instead of constructing extremely long trips to minimize the cost.

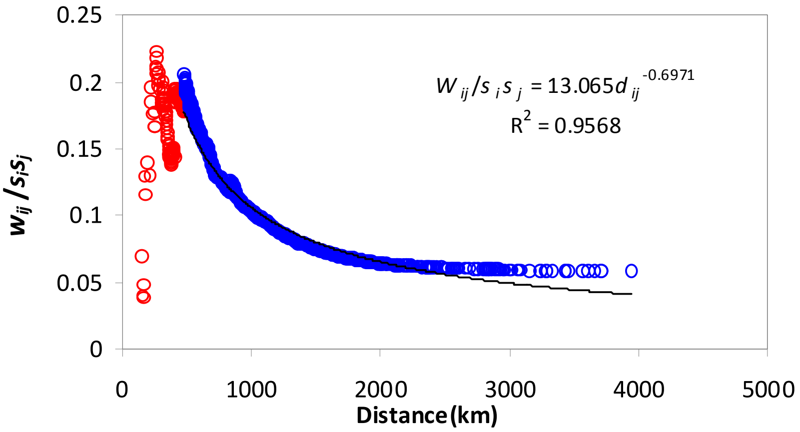

Figure 4. Regression results of dependence function based on the node strength (The red dots represent city pairs whose distances are less than 474km, while the blue dots are those with medium and long distances)

5. Conclusion

In this paper, we conclude that the unique construction of aviation system does imply a complex spatial mechanism. Although China's aviation system presents a hierarchical structure from a complex network perspective, it still displays spatial effects. This directly contradicts the proposal of Rabasz and Barabasi (2003) that geographically constrained networks would not show hierarchical organization. In part this is because geographical effects are not as simple as an elementary limitation by spatial distance. On the contrary, more complex distance dependence effects show up when edges are analyzed under separate distance ranges. We cannot find a clear law for short-distance travels, while for the medium- and long-distance travels in the system, a gravitational law can be summarized as a distance dependence function. The dynamic simulation can be examined by introducing more detailed and real-time data in the future. This would be a significant addition to understanding how to optimize the aviation network and to exploring the geography of spatial networks.

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