Towards a Hub-and-Spoke Network: a Study on the Chinese Mainland Hub Airport Planning

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Abstract: The airlines reorganization will accelerate the switch of the Chinese mainland civil aviation system from a former point-to-point (PP) structure to a hub-and-spoke (HS) network. In such a context, the major efforts of our paper are put into identifying hub airports in mainland China. We first analyze the HS network’s competitive advantages and find four desirable hub characteristics. A three-level method is developed to incorporate the required hub features and applied to the hub airport planning. Roles of the hubs in the planning scheme are mainly in three categories. Further discussion is extended to network adjustment as well as its dynamic evolution.

Key Words: HS network; PP structure; hub airport planning; Chinese mainland

1 Introduction

The airlines reorganization in mainland China completed in Oct. 2002 is a key step in the switch from a former point-to-point-dominant structure to a hub-and-spoke (HS) network. More than twenty domestic airlines have merged into three groups: Air China, China Eastern, and China Southern. In addition, Hainan airlines, a regional airline before, became the fourth largest passenger air carrier by combing several of its former rivals. Meanwhile, airlines have more freedom to reconfigure their routes. Most airlines choose to adopt the HS system, which is most popular among worldwide top 20 airlines. Related research began in the mid 1980s in the western world; early researchers include Kanafani and Ghobrial (1985), Morrison and Winston (1986), and Oum and Tretheway (1987), who have identified this phenomenon and offered explanations for the increase in HS routing in the era of deregulation. To address hub airport selection issue, the ‘uncapacitated single allocation p-hub median problem’ was first proposed by O’Kelly (1987), followed by T. Aykin (1990) and J. G. Klincewicz (1991). Further development of the models were made by J. F. Campbell (1996), and T. Ernst and M. Krishnamoorthy (1996 and 1998). These models are, however, usually mathematically difficult to solve; moreover, many approximations in them render the results sometimes far away from reality.

Relevant study of the HS network is comparatively less in mainland China, which could be attributed to the fact that the airline industry network in China still to some extent remains in a point-to-point (PP) form. Zhang (2000) discussed some prerequisites of the operation of a HS system. Jin (2001 and 2005) gave an overview of the country’s passenger airline network development of the past two decades and constructed an ideal network organization model. In his research the hub airports were selected based on an index evaluation system in which weights were predetermined in a quite subjective manner. Bai (2006) provided a method including hub selection and main routes design. However, the results of the first part were obtained through a similar index evaluation process which only considers the local features, e.g. airport operations.
The recent emergence of complex network has shed some lights on the aviation network research. It has been found that HS structure is a prime example of a ‘small-world’ network (L. A. Schintler 2001). Involved in this area are primarily physicists, among which R. Guimera and L. A. N. Amaral (2004) studied the world airports system and concluded that it embodies the small world properties; Cai et al. and Ganesh Bagler did some statistical research of Chinese and U.S., and Indian airport system respectively and found similar results. Their outcomes, however, are mainly focused on the network’s mathematical and statistical properties. No suggestions are seen to our knowledge in practical terms while applying the complex network theories to aviation network study.

To fill these gaps, an attempt is made in our paper to determine hub airports in the mainland China in the context of a HS structure. The rest of the paper is organized as follows: in section 2 we analyze the competitive advantages of such structure by comparing it with a PP network. Hub characteristics are subsequently derived. After exploring the current Chinese mainland airport system and its problems in section 3, a three-level method incorporating the above desirable hub characteristics is given and applied to finding out hub airports in section 4. Further implications are discussed in the following section which includes network adjustment and dynamic evolution. In the end, conclusions are given and further studies are directed.

2 Analysis of HS Aviation Network

2.1 Competitive Advantages of HS Aviation Network

A typical HS strategy is that all passengers departing from any non-hub origin to other cities in the network proceed first to the hub. Similarly, all passengers traveling to non-hub destinations arrive at those destinations from the hub. In order to understand the competitive advantages of the HS system over its PP counterpart, we start with a simple case which contains 9 airports. Under the PP structure, a minimum of 72 flights and 36 aircrafts are needed; if it is transformed into a HS system with 3 hubs, however, a minimum of only 18 flights and 9 aircrafts are required. The reduction is significant, and therefore would considerably save operations costs for airlines.

In addition, cost advantages are also gained by creating the economy of density which manifests itself mainly in two parts. First, the consolidation of passengers from many routes on a single spoke increase the density of service along each spoke. Although hubbing need not change which airports an airline serves or the number of passengers it transports, hubbing does decrease the number of routes on which an airline operates its planes and therefore increasing density. Secondly, the potential increase in frequency along each spoke may increase demand and therefore also density.

2.2 Hub Characteristics

The competitive advantages of a HS system are highly dependent on the hub cities. Not just any city can serve as a hub airport. There are four desirable characteristics of a hub city which are: airport performance, economic support, network connectivity, and central location. The high-frequency flights between hubs requires sufficient traffic volume, which holds the central portion of a hub airport’s throughput, a most reliable and significant measure of the airport performance; on the other hand, traffic volume is also closely related to the economic situations of the city where an airport locates. Stronger local economy generates more commercial and business interactions between the city and other areas, which is an important source of air transportation for
both passenger and cargo traffic. From the study of Jin and Wang (2005), the role of tourism attractiveness alone in influencing the air passenger traffic is still petty; as a result it is not our primary concern in this paper. The connectivity form between an airport and its neighboring counterparts is also important. If many links already exist within the neighboring airports, regional travelers do not have to pass through the studied airport, therefore weakening the hub role of the studied airport. At last, central location is certainly preferred since it minimizes the distance traveled on each spoke. The importance of topological and physical travel distance may vary according to the actual stage length, e.g. in short-haul air travel, passengers seem to be more concerned with the number of transfers. Such a consideration is reflected in the following section.

3 The Current Airport System in China and its Problems

Since the implementation of the Reform and Open-up policy in the 1970s, the civil aviation industry of mainland China has witnessed a rapid growth. By the end of 2004, there are 1035 domestic flights (those from/to Hong Kong/Macao are not included), and 1551186 km in terms of operational mileage. It ranked the 3rd among 188 IATA members. However, the airline network structure is still largely remains a PP form with too much emphasis on the trunk lines; whereas feeder lines do not receive enough attention they deserve (Bai 2006). Although this may be partially due to the difference of living standards and social-economic development between metropolises and smaller cities, and between eastern and western part of the country, the primary reasons are from the air transportation system itself. Firstly, short-haul flights are unable to attract passengers from surface transportation such as rail and long-distance coach transportation, which can be attributed to the uncompetitive airport accessibility, much higher prices, and the low frequency of scheduled flights. This problem is crucial in that a strong support of short-haul feeder lines is a key point in the success of a real HS structure. Secondly, the phenomenon that airport infrastructure level is higher than needed widely exists. Table 1 illustrate the class distribution of all the airports in mainland China, from which we find that the distribution is far less than proportional in forming a HS structure. This also illustrates that the air transportation network still maintains PP characteristics. Too many high-class airports only result in a waste of construction, operation, and maintenance expenses, thus affecting the global efficiency and competitiveness of the HS system.

| Table 1 Airport class distribution in mainland China (year: 2004) |
|----------------|----------|----------|----------|----------|
| Airport Type   | 4E       | 4D       | 4C       | 3C       |
| Number of Airports | 25       | 34       | 52       | 26       |
| Aircraft Size Max | B747     | B767, B757, MD82 | B737 | Smaller than B737 |

With the continuity of national economic prosperity and the central government’s policy preference, in the decades ahead the above regional gaps would be greatly shortened and air traffic in the less-developed regions or cities would definitely experience a more remarkable increase. It at the same time provides the Chinese mainland airport system with an ideal opportunity to accelerate its pace towards an efficient HS network. To accomplish it, the first step is to configure the hub airports.
4 Hub Airport Planning

We consider the selection of a hub airport from local, regional, and global levels to incorporate the four desirable characteristics discussed in section 2. In the first stage we consider the local effects of airports by employing the cluster analysis method. Then complex network theories are applied to measure the extent of connectivity and central location of each airport. The final planning scheme is based on all the former analysis. Details are given as follows.

4.1 Local Effects

In the four characteristics, airport performance and economic support are classified as the local factors. To more accurately represent their effects, the two factors are divided into four elements: passenger throughput, cargo throughput, local GDP, and non-agricultural population, which are defined as the input variables for cluster analysis. Relative data are collected for the year 2004. In the cluster analysis we use the following Minkowski distance to measure the similarity between each two airports,

$$d_{ij} = \left[ \sum_{k=1}^{n} (x_{ik} - x_{jk})^{2} \right]^{1/2}$$

where $x_{ik}$ and $x_{jk}$ represent the $k$th input variable of the $i$th and $j$th airports respectively, and $d_{ij}$ denotes the similarity between the two airports. In gauging the similarity between two sample classes, Ward method is adopted:

$$D_1 = \sum_{x_i \in G_1} (x_i - \overline{x})^T (x_i - \overline{x})$$

$$D_2 = \sum_{x_j \in G_2} (x_j - \overline{x})^T (x_j - \overline{x})$$

$$D_{1+2} = \sum_{x_k \in G_1 \cup G_2} (x_k - \overline{x})^T (x_k - \overline{x})$$

in which there are

$$\overline{x}_i = \frac{1}{n_1} \sum_{x_i \in G_1} x_i$$

$$\overline{x}_2 = \frac{1}{n_2} \sum_{x_j \in G_2} x_j$$

$$\overline{x} = \frac{1}{n_3} \sum_{x_k \in G_1 \cup G_2} x_k$$

We define the distance between two sample classes is

$$D(G_1, G_2) = D_{1+2} - D_1 - D_2$$

More details can be found in Yang et al. (2004), and we opt to form 4, 6, and 8 clusters successively. Part of the results is given in table 2. Simply from the local effects, we find that the airports of Beijing, Shanghai, and Guangzhou are in a well distinct cluster, although the airport of Guangzhou is a little different from the other two in certain cases. The airports of Shenzhen, Tianjing, Chengdu, Chongqing, and Hangzhou are very alike. In the 3rd cluster the cities where airports are located are not necessarily provincial capitals; instead, many in it are economically dynamic cities in the eastern part of China.

4.2 Regional Effects

An airport’s regional effects capture the effect of its regional network connectivity, which can be measured by the extent of passing through that airport for a regional trip. In the complex
networks theories, clustering coefficient is used to assess the regional effects of each vertex in the network. Since the Chinese airport network has proven to exhibit properties of a small world, one form of the complex networks, the clustering coefficient is also employed in our study. We first simplify the airport network by transforming it into an undirected graph $G (V, E)$ with each vertex representing an airport and every edge corresponding to a route (two directions are regarded as one in the graph) between two airports. The definition of an airport’s clustering coefficient is as

$$C_v = \frac{M}{C_n^2}$$

where $M$ is the number of the real connections within airport $v$’s direct neighborhood $N_v$ consisting of $n$ airports, and $C_n^2$ is the total number of all possible connections among its neighboring airports. Obviously we have $C_v \in [0,1]$. If we define variable $\delta_{ij}^v$ as

$$\delta_{ij}^v = \begin{cases} 1 & \text{if edge } l \text{ is linked with } v \\ 0 & \text{otherwise} \end{cases}$$

$M$ can be calculated as

$$M = \sum_{l \in E, x,y \in N_v} \delta_{ij}^x \cdot \delta_{ij}^y$$

Figure 1 shows the clustering coefficients of the first 27 airports with values in an increasing order. It should be noted that for the airports who have only one direct link, its clustering coefficient is defined as zero. They are excluded from our consideration. For the rest of the airports, evidently a smaller clustering coefficient means a higher regional importance (effects) because in such a case the communication among the neighboring airports is more likely to pass through the studied airport first. Therefore in figure 1 we use the term 1-clustering coefficient to represent the regional effect of the airports. The dominance of Beijing, Shanghai, Guangzhou, Shenzhen, and Kunming is significant. The reasons for Kunming is that many Provincial tourism flights depart exclusively from Kunming; in other words, the airport network in Yunan already exhibit some features of a HS structure. Similar phenomenon can be found in Xinjiang, where Urumchi plays an equivalent role (Jin and Wang 2005).

<table>
<thead>
<tr>
<th>No. of Clusters</th>
<th>1st Cluster</th>
<th>2nd Cluster</th>
<th>3rd Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Beijing, Shanghai</td>
<td>Guangzhou, Shenzhen</td>
<td>Chengdu, Kunming, Xi’an, Hangzhou, Qingdao, Dalian, Nanjing, Chongqing, Wuhan, Shenyang, Harbin, Changsha, Fuzhou, Zhengzhou, Wenzhou, Jinan</td>
</tr>
<tr>
<td>6</td>
<td>Beijing, Shenzhen, Tianjing, Shanghai, Guangzhou</td>
<td>Chengdu, Chongqing, Hangzhou</td>
<td>Fuzhou, Quanzhou, Shijiazhuang, Zhengzhou, Harbin, Changchun, Dalian, Shenyang, Jilin, Qingdao, Wuhan, Nanjing, Yantai, Ningbo, Wenzhou</td>
</tr>
<tr>
<td>8</td>
<td>Beijing, Shanghai, Guangzhou</td>
<td>Shenzhen, Tianjing, Chengdu, Chongqing, Hangzhou</td>
<td>Fuzhou, Quanzhou, Shijiazhuang, Zhengzhou, Harbin, Nanjing, Jinan, Qingdao, Wenzhou, Xiamen, Nanning, Guiyang, Xi’an, Hangzhou, Qingdao, Dalian, Shenyang, Harbin, Changsha, Fuzhou, Zhengzhou, Wenzhou, Jinan</td>
</tr>
</tbody>
</table>
1The passenger and cargo throughput of Shanghai are the sum of the two airports (Hongqiao and Pudong). Such consideration is also applied to the 6 and 8 cases.

2In the 8 case, Shanghai is classified in an individual cluster which is near to {Beijing, Guangzhou}. We regard the two as one cluster for the sake of simplicity.

4.3 Global Effects

In the four characteristics stated in section 2, central location is used to measure the global effects of an airport. It can be reflected by the number of the shortest routes in which the studied airport is either the origin/destination, or an intermediate stop. In effect, the larger the number, the more important the role the airport plays in shortening travel distance over the whole network. Such a concept in complex theory is defined as betweenness, and is calculated as the fraction of shortest paths between vertexes pairs that pass through the vertex of interest. Let \( S_{ij} \) denote the set of the shortest routes and the airport \( v \)'s betweenness is defined as

\[
B_v = \sum_{i,j \in E} \frac{\delta_{ij}^{v}}{|S_{ij}|},
\]

We employ the Floyd algorithm (Wang 1993) to find the shortest route between any two airports in the network. Although in many instances the high speed of air transportation makes passenger more concerned with transfer than actual stage length, for the long-haul trips the impact of actual distance on passengers’ choice is more perceptible. As a result, we reconstruct a weighted graph in which the weight of each edge represents the physical distance between two airports. Each airport’s betweenness is calculated both in the weighted and unweighted graphs. Major results are shown in figure 1.

Figure 1 Results of clustering coefficients and betweenness of the selected airports

Clearly, Beijing Capital Airport owns the highest values of betweenness with either topological or physical distance. In the topological structure, the betweenness of Beijing is followed by Kunming, Shanghai, Guangzhou, Urumchi, Shenzhen, Chengdu, Xi’an, and Wuhan, successively. While the actual distances are taken into account, the decreasing order becomes Urumchi, Xi’an, Guangzhou, Chengdu, Shenyang, Shanghai, Qingdao, Harbin, and Wuhan. The comparatively high degree of betweenness of Urumchi, Xi’an, Qingdao, and Shenyang in the
latter case might be attributed to their geographic locations. For example, if passengers from Chongqing fly to Hohhot, they have to make one transfer since no direct flight exists. There are several transfer choices such as Beijing or Xi’an. Their positions are ‘equal’ providing that only topological connections are considered. However, the actual trip length via Xi’an is much shorter because the two segments of the travel are almost in a line. Similar circumstances can be found in trips from southeast cities to the northeast part of the country where there are not many direct air transportation services. Geographically, Qingdao provides an ideal location for one-stop transfers.

4.4 Planning Scheme of National Hub Airports

If we comprehensively take into account the local, regional, and global effects of all the airports, we find the airports in Beijing, Shanghai, and Guangzhou are obviously predominant in all the airports. Shenzhen Airport is very next to them. What follows are Chengdu, Tianjing, Chongqing, and Hangzhou in terms of local effects, Kunming, Chengdu, Urumchi, Changsha, and Xi’an for the regional effects, and Urumchi, Xi’an, Chengdu, Kunming, Shenyang, Qingdao, and Wuhan if we consider global effects. The airport of Chengdu is somewhat less influential than those in Beijing, Shanghai, Guangzhou, and Shenzhen, yet its global effects are much stronger than any of the rest airports. Although Tianjing, Chongqing, and Hangzhou show strong local effects largely due to their economic support, they are not included as primary hubs in that in their neighborhoods primary hubs already exist which are Beijing, Chengdu, and Shanghai. For the same reason the airport of Shenzhen is not identified as a primary hub. Kunming, Urumchi, and Xi’an show their regional and global competence as well; however, their local effects are not as strong as the other airports and thus might rather serve as a hub whose main function is to provide a place for transfers. Furthermore, the airports of Shenyang, Qingdao, and Wuhan are similar in terms of all the three aspects by holding comprehensively secondary positions; in addition, their geographical locations are rather independent of the above airports: Shenyang is in the northeast; Qingdao is located in the centre of the northern coastal area; the distances between Wuhan and its nearest airports mentioned above, e.g. Shanghai, Guangzhou, Xi’an, and Chengdu, almost equal to each other and are approximately 800-1000 km.

Our above considerations can be summarized as a preliminary planning scheme of the hub airports in the mainland China, which is shown in figure 2. The four national primary airports are: Beijing Capital Airport, Shanghai Airport (Hongqiao and Pudong are regarded as one), Guangzhou Baiyu Airport, and Chengdu Shuangliu Airport, who are responsible for the major transfer tasks in the North, East, South, and West China. Secondary airports include Urumchi, Xi’an, Chongqing, Kunming, Wuhan, Tianjing, Shenyang, Qingdao, Hangzhou, and Shenzhen. In a geographic sense they are evenly distributed; however, their roles are not exactly the same. Tianjing, Chongqing, Hangzhou, and Shenzhen serve as auxiliary hub airports of their neighboring primary hubs respectively. In addition to accommodating ‘original and terminal’ traffic, their function could be extended to sharing part of the passenger and freight transfer traffic to avoid potential congestion at their nearby primary hubs. For the other airports, Urumchi, Xi’an, Shenyang, Wuhan, Qingdao, Kunming, they are expected to rather act as independent regional hubs.

5 Further Discussions

5.1 Network Adjustment

The HS structure departs from centralizing traffic and promoting efficiency of aircrafts use.
Those objectives are realized by increasing flights frequency between hubs and strong support of feeder lines. These would, however, very possibly result in potential congestion especially during peak hours at primary hub airports. In addition to adopting some operational strategies such as ‘arrival-departure mix’ to form flights waves in order to alleviate this problem (Jin and Wang 2005), it is important for planners and decision-makers to note that the starting point of implementing a HS network is to enhance global efficiency by evading excessive direct links among medium- and small-size cities or towns, rather than to deny the coexistence of PP structure particularly between large cities or province capitals where traffic volume is substantial. Even when the origin and destination are not hubs, city-pair flights are still encouraged. On the other hand, the planning of four secondary hub airports (Tianjing, Hangzhou, Shenzhen, and Chongqing) is in effect also an effort to mitigate potential congestion at primary hubs by switching part of the transfer traffic to its nearby partners.

![Figure 2 Hub airports in mainland China](image)

**5.2 Dynamic Evolution**

With network development, hub airports will continually evolve. New hubs will appear and old ones will gradually lose its influence, or primary hubs will be replaced by secondary ones due to economic, geographic, and political changes. An interesting issue is the role of Guangzhou Baiyun Airport. First, the nearby Shenzhen airport bears closer similarity to Baiyun Airport than any of its ‘parallel’ airports to the rest three primary hub airports in terms of airport performance, economic support, location, and airline connectivity, which poses considerable challenges to Baiyun Airport. Secondly, for international transfers, Hong Kong is definitely better than Guangzhou for the sake of much more international scheduled flights there; on the other hand, many mainland cities have connected to Hong Kong by direct flights, the number of which is still rapidly increasing. As to domestic hub-and-spoke air travel and regional transfer service within the mainland, nevertheless, Hong Kong can not substitute Guangzhou because of the administrative restraints at least in the short term. In the long run this trend would be very possible if restraints no longer exist and Hong Kong and the mainland are more closely integrated. Furthermore, the realization of ‘three exchanges’ associated with closer social and economic interactions between
the two sides of the Taiwan Straits in the long run would definitely extend the role of Taipei Taoyuan Airport as a new hub in the southeast China, in addition to its function as the air transportation center of the island.

6 Conclusions

Different from previous studies which are based on either sophisticated mathematical models or simple yet quite subjective index assessment, our research gives a new hub airport planning process. We first find airport performance, economic support, network connectivity, and central location are four desirable hub characteristics. These characteristics have been incorporated into local, regional, and global effects by applying cluster analysis and complex network theories to study each airport in mainland China. The airports in Beijing, Shanghai, Guangzhou, and Chengdu are proposed as national primary hubs that are responsible for national major transfer tasks. Tianjing, Hangzhou, Chongqing, Shenzhen, Shenyang, Qingdao, Xi’an, Urumchi, Wuhan, and Kuming are defined as secondary hubs. Their role is in general accommodating local transfer traffic in addition to city-pair flights between itself and other major cities. Tianjing, Hangzhou, Chongqing, and Shenzhen can furthermore serve as auxiliary airports of primary hubs mainly owing to their geographic positions. Part of the transfer traffic can be switched from the primary hubs to these airports, which help avoid potential congestion problems at primary hub airports. Along the route where traffic volume is significant, city-pair flights are still encouraged. Hub airports is never static. New hubs can replace old ones; it is also possible for secondary hubs to substitute primary ones. In particular, Guangzhou Baiyun Airport faces considerable challenges from that of Shenzhen. For foreign/domestic transfers, Hong Kong is a better place, although for domestic and regional transfers, Hong Kong airport is currently powerless due to administrative barriers. With the realization of ‘three exchanges’, Taipei Taoyuan Airport is very likely to become a new hub of southeast China in the long run.

Some aspects of our studies deserve further work. In the planning process, the clustering coefficient is used to measure an airport’s regional effects. However, the two concepts sometimes do not totally overlap. It might be more precise if certain physical distance limitations are introduced to judge whether the airport which has a direct link with the studied one really belong to its neighborhood. Moreover, how to add international connections in the consideration would also be an interesting area of future research.

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