Network Structure, Capacity Growth and Route Hierarchies: The case of China's Air Traffic System (ATS) revisited

Hans Huber

W.P. No. 2015-04-03
April 2015

INDIAN INSTITUTE OF MANAGEMENT
AHMEDABAD-380 015
INDIA

Network Structure, Capacity Growth and Route Hierarchies: The case of China's Air Traffic System (ATS) revisited

Dr. Hans Huber
Associate Professor,
Indian Institute of Managemement, Ahmedabad
hanshuber@iimahd.ernet.in

Abstract

This paper examines air traffic patterns among China's scheduled airlines in January 2006 and January 2011, using Official Airline Guide data on carrier schedules. The author classifies Chinese carriers into one of 4 classes. Airports are also organized into a classification scheme based on several criteria related to the total volume of traffic, the carriers serving the airports and the nature of the airports to which they are connected. Counts, sums, percentage shares and changes in these calculations between 2006 and 2011 are presented in a small number of tables. Inferences about the fundamental structure and future patterns of capacity growth for the yet not fully emerged Chinese ATS can be drawn.

1. Introduction

For over two decades empirical analyses on the economic impact of liberalization in aviation not only looked at market competition, consolidation, pricing, alliances, but also examined structural aspects of networks, such as connectivity, etc. (Reynolds-Feighan 2010, Shaw 2009, p.293 for references). This research was mostly concentrated on Western air traffic, with relatively little attention given to Asian developments. In spite of the tremendous growth that the Chinese ATS has experienced over the last decades, literature on the structural evolution of its air traffic networks was little.

Jin et al. (2004) analyzed geographic patterns of air passenger transport in China between 1980 and 1998. The authors saw market liberalization as distinct stages of reforms for new policy implementation: the period under investigation concerned the third stage which was called 'post-reform era' which was to lead to consolidation of the industry around three big airline groups (Air China, China Eastern and China Southern) by 11 October 2002 (p.473). In particular, they identified the emergence and establishment of the hub-and-spoke (HS) transport system as a key feature of the evolved ATS (p.485). Measures regarding changes in the ATS included rank orders (passenger numbers) of airports for the system as a whole (p.477). Structural change to the network was done using dominant flow analysis, i.e. only the largest flow from/to cities was used (for passenger numbers again). Hubs would usually show large numbers of such 'priority links' (p.483).

Shaw et al. (2007) examined government-led airline consolidation of 2002 and its impact on domestic network structure and competition. Insofar the authors identified a fourth phase of reforms that had consolidated 11 smaller airlines into the 'Big Three' while another 6 smaller carriers could continue to operate independently as of 2004 (p.296). Changes in the network structure were mostly accounted for by number of airports served, non-stop routes, airport rankings within the airline network, but did not include any flow measures (such as passengers or frequencies).

Zhang (2010, p.190) presents graph-theoretic depictions of city-pairs across China for each one of the 'Big Three'. Their links emphasize connectivity, but remain un-weighted with regards to actual traffic flows, frequency, etc. He then compares both fully-connected (FC) and HS networks using a general equilibrium approach. Through a rather simplistic Cournot model, Zhang arrives at the conclusion that capacity at hub airports is greater than socially efficient in the sense that the marginal reduction in congestion costs is lower than the marginal cost of capacity (p.195). Although HS networks may provide some competitive advantages, it would take a larger investment into infrastructure to operate HS as compared to FC networks in China (Zhang, 2010, p.196).

2. A network and agent-based perspective

This paper seeks to highlight critical network characteristics of the Chinese ATS and to represent it more realistically, mainly by focusing on its distinct topologies and by relating them to its constituent agents. The paper does not intend to present a definite model of domestic air traffic in China, but goes to great lengths in decomposing it and analyzing its key operating agents (airlines versus airports) at separate points in time. This matrix-computational approach is highly compatible with a geographic and spatial representation of airline networks and their changes over time. The fact that different agents interact not only with each other, but also with their local and connected environment is a fundamental feature of complex systems (Railsback and Grimm, 2011, p.10). This implies that agents are subject to change themselves, i.e. that they evolve and may disappear as well. Short of developing a full model, the author claims this logic to be powerful enough to make serious inferences about the observed evolved stage of the Chinese ATS and to provide policy feed-back as well as options for further (agent-based) structural development.

2.1 Heuristics

Our approach is inductive in the sense that empirical observations should help us to recognize patterns within different elements of the Chinese ATS. The choice of where to look for such patterns and regularities (or irregularities, such as thresholds in patterns between groups of cases) needs to be guided, though. We have opted for a combined network and agent-based perspective mainly for the following reasons: First, years of applied research in the field of aviation, industrial economics and strategy have formed the author’s opinion that this particular way of analysis was best suited for describing ATS. Secondly, both network economics and agent-based modeling can no longer be considered marginal disciplines that yet need to emerge more fully in scientific research. In fact, real world applications of both network and agent-based heuristics do already abound in the Aviation industry, while science still struggles to provide meaningful tools for policy making. The repeated application of general equilibrium models to problems of network structure, capacity allocation on routes, and highly stylized competition are examples of this struggle.

The question of scientific falsification of such research is legitimate, with the author reckoning that ideally this process would require a finished ABM-model against which real world developments could be simulated. Any discrepancies with real-world data would need to feed-back into model modifications. By analogy, the author sees his projections for the future development of China's ATS – which are presented in the last chapter – as equally subjected to reality-checks from the real world.

2.1 Data

Data for most of the statistics comes from OAG's Historical Max Plus database. The OAG Historical Max Plus data represents the ex-post schedules of airlines, i.e. the actual capacity offered by carriers. Origin-destination (OD) data provides detailed information on carriers' operations inside the People's Republic of China (PRC) and was taken from OAG for the first quarters of 2006 and 2011. OD in this case refers to flight segments only, i.e. connecting flights or transfers between routes are not accounted for as such. The OAG database also omits information regarding actual passenger demand within the ATS. Although such additional data may be considered useful for further analysis, the author sees valid interest in a supply-sided structural analysis of the rapidly expanding Chinese ATS. If data on effectively transferred (connecting) traffic at airports were available, it could have been accounted for as a distinct class of route within the same analytic framework and its evolution compared against those of other OD-types.

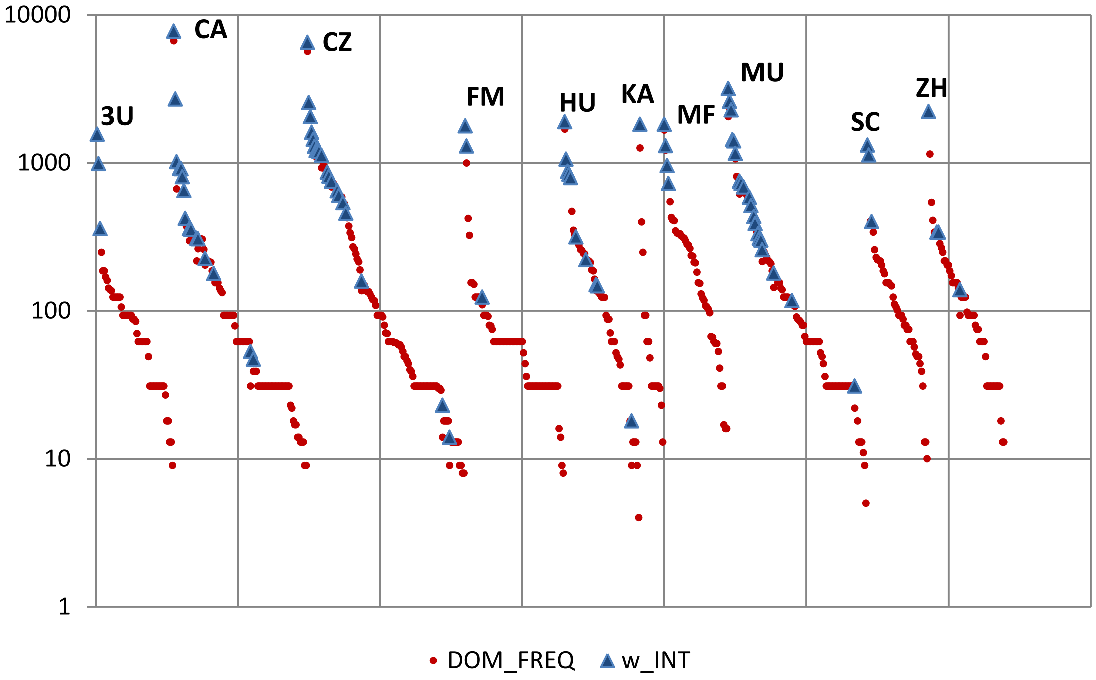
The data was sampled for the months of January 2006 and January 2011, and it included traffic for Hong Kong and Macau. The sampling procedure selected domestic flights performed by domestic carriers that were performed in the time window between 1st and 30th January of these years. Their share for the full quarter was 35,7% in 2006 and 34,8% in 2011, indicating more traffic than for the months of February and March (which both showed comparable figures within the same years).

After compiling the data into matrices of directed flight segments for all operating carriers, some 4,800 (2006) plus 8,400 (2011) cases were listed for the respective months of January. These filtered cases were still in a sufficiently extensive format to allow for further selection and synthesis, depending on the reference of agent for which one had to perform the analysis.

3. Hub-and-spokes as highly skewed traffic distributions

Huber (2010, p.181) plotted rank-ordered traffic distributions (frequencies) across domestic airports for China's 10 largest carriers (including the 'Big Three'). This data had covered the month of January 2007 and was plotted on a log-scale for frequency and a linear scale for each airport. Visual inspection of the 10 airlines showed steeply decreasing traffic distributions (even on a log-scale) with the respective networks top-airport clearly standing over the rest in most cases. If HS can be defined as a concentration of air traffic in space and time (not shown), then China's top airlines – even individually – can be graphically depicted by ranked-order frequency distributions. Traffic concentration in space and time by a single (or few) airlines at the same airport is to be considered essential for hub operations. In the case of an absent dominant carrier at the airport, hub advantages such as density (Brueckner and Spiller, 1994) would need to be shared among more airlines which in turn would increase transaction costs, such as for coordination etc. Figure 1 shows such an updated ranked-order distribution for the month of January in 2011.

Figure 1: Domestic with international frequency distributions (2011)



All frequencies of airlines (depicted are China's top-10 carriers, the 'Big Three' being coded as CA, CZ, MU) at airports served are ordered by decreasing rank, with red dots representing domestic traffic. For illustrative purposes, international frequency (cumulative to domestic) as operated by the airline at the same airport was added to the figure. It is represented by blue triangles.

As Huber (2009, p.382) had pointed out, the aggregate ranked-order distribution of all traffic within the ATS could plausibly be represented by either a power law or by exponential decay, depending on whether airlines concentrated their hub traffic on very few or more airports. In that sense, traffic concentration of China's top airlines at some hub airports may be causal for local congestion and high marginal costs related to capacity expansion for the system as a whole.

3.1 Network characteristics of individual Chinese airlines

27 Chinese airlines serving domestic routes were accounted for in 2011 against 15 during 2006. Apart from highly skewed frequency distributions prevailing among China's 10 largest carriers, smaller carriers organized their traffic in distinctly different networks. Apart from airlines' name, IATA code and year of foundation, critical variables of network operations are shown in the Appendix: 'Size_AP' gives the number of airports being served by the individual carrier's networks, 'No_OD' presents all origin-destination links (i.e. directed flight segments). While these two variables measure size and scope of an airline's domestic network, 'INT_AP' adds an international dimension through the number of airports served abroad. 'SEAT' presents the average size of aircraft used, with numbers below 100 indicating predominant usage of regional aircraft.

'Mx_FRE' shows flight frequency for the carrier's most heavily served airport and 'FRE_AP' the average frequency per airport within each airline's network. From these two scales (together with 'Size_AP') one may infer properties of spatial concentration versus dispersion for the airline. No comparable patterns of 'hubbing' as with the top-10 airlines (see above) was found during the period: values for 'Mx_FRE' within groups 3 and 4 were significantly lower as compared to groups 1 and 2. Even with airlines KN and 8L showing higher intra-group values, these remained distinctly below those of group 2 and even a peak value of 832 for KN (27.7 departing flights per day) would allow the average member airport in the airline network to being served only once daily. This observation is consistent with a 'No_OD' value of 48. Although traffic may be radially organized around a central airport, the traffic provided within this network would lack density. It would neither be fully-connected nor point-to-point. By inter-group comparison, networks within groups 3 and 4 remained smaller and average traffic per airport ('FRE_AP') was significantly less. Two airlines do not follow this description: KA (Group 2) also shows features of radial organization, although its traffic at the central airport is higher in spite of a smaller network. 'FRE_AP' for KA also suggests denser traffic for the served flight segments. The other exception is GS (Group 4): although using regional aircraft, its network structure cannot be radially organized as 'No_OD' is about triple the number of airports. Clearly, instances of central-node bypass must occur in this case as neither fully-connect nor point-to-point seem plausible.

Differences among the individual airlines' network features allowed for grouping each of them into distinct classes: Group 1 (Red) comprised the three leading carriers CA, MU, CZ; Group 2 (Green) represented the other seven main operators that were also shown in Figure 1; Group 3 (Blue) stood for smaller to medium sized airlines, most of which had entered service after 2006; and Group 4 (Grey) defined regional carriers, i.e. a classification made by aircraft technology used.

3.2 Spatial allocation of capacity at China's airport hubs

Figure 1 allows us selecting those airports that were the most densely operated by China's top-10 airlines. As additional criteria, we required that these airports were ranked at the least as second within the airline's network, that they provided international connectivity and that their domestic movements exceeded 1,000 during January 2011. Airports that are lower ranked within China's top-10 carriers or that may have high passenger numbers due to a high number of airlines with high density traffic may not qualify for our criteria of hub selection. By definition, we shall consider hub operations as inseparable from the presence of a dominant airline which is concentrating traffic for reasons of optimization and competition.

Table 1 lists the 10 airports that were thus identified as 'hubs'. When comparing with China's largest airports (Wikipedia, 2012a), we found significant, yet not complete, overlap: including Hong Kong, which was missing from the list, the identified hubs corresponded to 8 out of the 11 largest airports in China. Only Jinan airport, which was Shandong Airlines' (SC) main hub, ranked significantly below at rank 22. Airports that were considered among China's busiest but were not defined as a hub were Xi'an Xianyang (Rank 8) and Hangzhou (Rank 10). Airports that were identified as hubs for CA, CZ or MU were: PEK, PVG, CAN, CTU and CKG. Hubs for the remainder of China's top-10 airlines were: HKG, SHA, SZX, KMG, XMN, TNA.

Table 1: China's hub airports with top-3 carriers' market shares (Passengers, frequency, dom. city-pairs, January 2006-2011)

HUB / AL	**AP_NAME** (# Airlines)	**PAX_2011**	**FRE**_Jan'11	**Chg.'06**	**OD_'11**	**FRE/OD**
PEK	**Beijing Capital (17)**	**78.674.513**	**14.656**	**45,8%**	**103**	**65**
CA	Air China		45,6%	10,4%	75	89
CZ	China Southern		16,9%	-12,7%	39	63
HU	Hainan Airlines		11,6%	-25,9%	34	50
HKG	**H'Kong IntNat'l (12)**	**53.314.213**	**3.198**	**13,3%**	**39**	**42**
KA	Dragonair		39,3%	18,9%	16	79
MU	China Eastern		19,0%	-14,7%	17	36
CZ	China Southern		9,6%	-52,7%	5	61

CAN	**Guangzhou (15)**	**45.040.340**	**10.806**	**48,1%**	**79**	**50**
CZ	China Southern		52,5%	-9,3%	65	87
MU	China Eastern		10,6%	13,5%	22	52
CA	Air China		9,0%	-18,8%	14	70
PVG	**Shang. Pudong (17)**	**41.447.730**	**6.916**	**59,2%**	**62**	**64**
MU	China Eastern		29,7%	-4,0%	37	56
CZ	China Southern		15,8%	-24,4%	23	48
FM	Shanghai Airlines		14,4%	-25,8%	28	36
SHA	**Shanghai H'qiao (15)**	**33.112.442**	**7.217**	**24,5%**	**67**	**48**
MU	China Eastern		30,4%	-21,6%	43	51
FM	Shanghai Airlines		23,6%	0,1%	37	46
CZ	China Southern		8,8%	-25,5%	7	90
CTU	**Chengdu (19)**	**29.073.719**	**7.558**	**68,7%**	**69**	**38**
CA	Air China		35,0%	-11,2%	48	55
3U	Sichuan Airlines		20,4%	-15,6%	40	39
CZ	China Southern		11,7%	4,2%	14	63
SZX	**Shenzhen (12)**	**28.245.738**	**7.279**	**32,4%**	**57**	**51**
ZH	Shenzhen Airlines		29,9%	-4,6%	40	54
CZ	China Southern		27,9%	-1,7%	39	52
CA	Air China		10,9%	7,2%	9	88
KMG	**Kunming (18)**	**22.270.130**	**5.843**	**51,2%**	**52**	**36**
MU	China Eastern		40,2%	1,2%	39	60
CZ	China Southern		16,4%	-31,0%	21	46
CA	Air China		13,8%	-1,5%	20	40
CKG	**Chongqing (19)**	**19.052.706**	**5.230**	**95,0%**	**55**	**35**
CA	Air China		17,2%	-25,2%	15	60
3U	Sichuan Airlines		18,7%	-7,5%	29	34
CZ	China Southern		12,8%	-34,4%	16	42
XMN	**Xiamen (16)**	**15.757.049**	**4.136**	**63,9%**	**43**	**40**
MF	Xiamen Airlines		40,3%	-11,9%	32	52
CZ	China Southern		12,3%	-37,6%	12	42
CA	Air China		11,7%	19,1%	11	44
TNA	**Jinan (13)**	**7.879.707**	**2.844**	**97,9%**	**32**	**33**
SC	Shandong Airlines		45,1%	-14,9%	28	46
CZ	China Southern		11,8%	-27,8%	11	31
MU	China Eastern		11,1%	-19,8%	8	40

The table shows the number of airlines that are providing domestic service at the hubs as well as the total number of passengers transported during 2011. For the top-3 airlines of each hub it compares market shares (derived from frequencies during January 2011), change over the same month in 2006, the number of flight segments (OD_'11) and average density per flight segment served (for January 2011). It shows that China's 'Big Three' indeed had significant – on occasions dominant – control over China's most important airports. In all instances, at least two out of the three highest market-shares of airlines at airport hubs came from this group of airlines (CA, CZ, MU). This level of interconnectedness among China's hub airports clearly stresses the role of the 'Big Three' for China's ATS as a whole. It also raises questions about the agents' quality of interaction – or degree of dependency – in route planning regarding the remaining major airline networks.

3.3 A qualification of the graph-theoretic perspective

Zhang (2010, p.190) suggested a FC network structure for China's three main carriers (CA, MU, CZ) based on a graph-theoretic depiction of city-pair links. The graphs below, in contrast, take into account only the single densest route departing from each airport ('Maximum Frequency') with the scale of frequency represented through the thickness of the link. The colors of the links were attributed to the individual airline that showed the highest market-share on the particular route. Putting weights on the links clearly shows a preference for interconnecting the biggest airports through highest frequency traffic. In that sense, the logic of 'preferential attachment' (Albert and Barabási, pp.47f) would extend to frequency, not only to connectivity with regards to city-pairs. The graph-theoretic layout was obtained by using Ucinet's algorithm for geodesic distances, including the node repulsion and equal edge length function (Borgatti et al., pp.40f).

Figure 2: Only maximum frequencies between airports (January 2006)

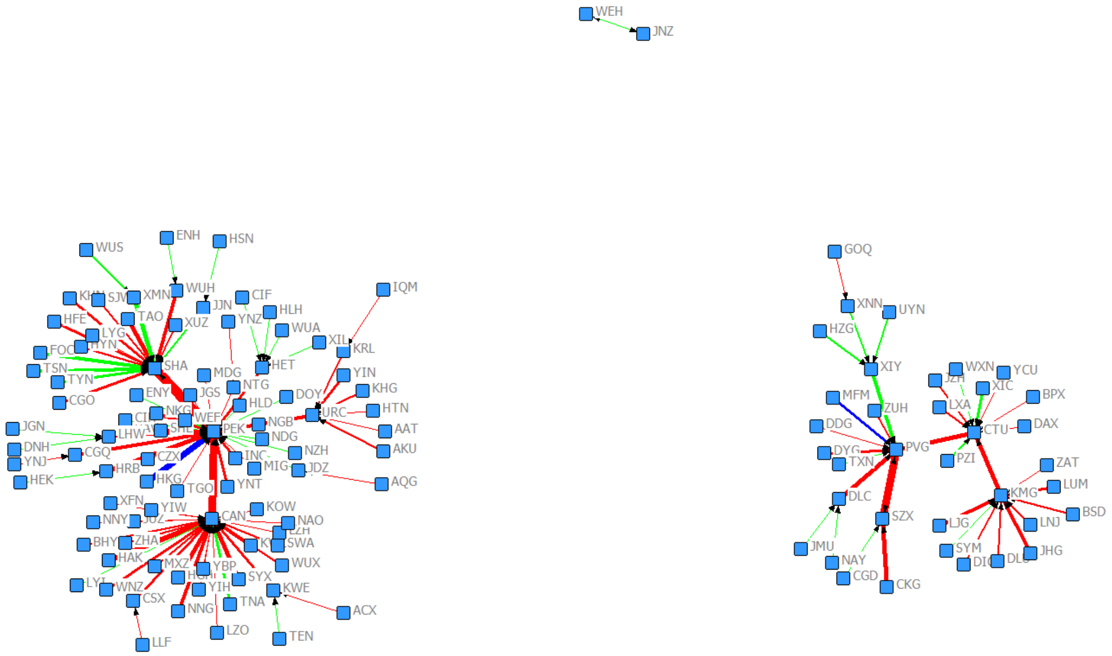
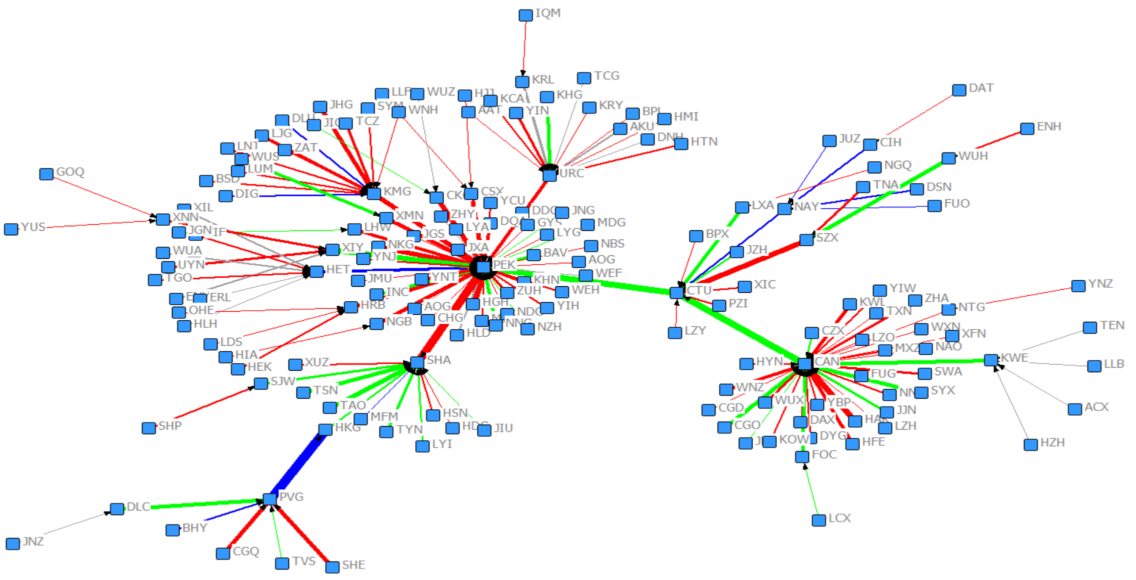


Figure 2 shows how airports' maximum frequencies were feeding into relatively few major airports, which in turn formed two separate complexes (one around SHA-PEK-CAN, the other around PVG-CTU-KMG). Since both PVG and SHA were in the same city, the complex could geographically be considered as one. More importantly, highest frequency connections within the Chinese ATS appeared to be dominated by the three main carriers (red links), with the remaining seven major carriers (green) mainly feeding into both airports in Shanghai. A few selected routes (green) fed into 3-4 airports that had not been identified as hubs before (see Figure 1) and which also appear as spoke airports within the graph. Medium traffic frequency between HKG and PEK was dominated by a smaller airline (blue link).

Figure 3: Only maximum frequencies between airports (January 2011)



By 2011 (Figure 3), the overall system appeared both more extensive (grown in scope and size) as well as being more integrated. Identified hub airports were strongly interconnected and committed their maximum frequencies to each other respectively. China's major airlines (red plus green) still held the highest shares for capacity among almost all of the airports' maximum frequency links, with the green part taking over an increasing stake. HKG's maximum traffic has increased and shifted from PEK (in 2006) to PVG (blue link). The network organization of the entire system appeared more hierarchical, with more spoke airports themselves serving as feeders for maximum frequencies from yet smaller airports. In many instances, these spoke-to-spoke links were controlled by 'red' CA, CZ or MU – significantly more than there were such cases for 'green' carriers. Some regional airlines (grey links) allowed for thinner links (connectivity) from a few sub-spoke airports.

4. Decomposing the HS network

As shown, the debate over optimal capacity and traffic distribution in hub-spoke systems has been treated repeatedly in the literature. This structural approach also extended to the transformation of the ATS, i.e. through de-peaking, bypassing or even more fully-connected network structures (Reynolds-Feighan, 2010). Applied to China, such a transformational scenario would require its top 10 airlines to qualify their hub strategies and review mutual links among them and other airlines. Given the degree of dependency of spoke airports and even spoke-spoke connections on these large hub-based airlines, disruption to the ATS may result. This is consistent with Huber (2010, p.183) who found that great concentration of traffic by the top-10 carriers at hubs actually induced negative variance in wider parts of the network. When applying a graph-theoretic (bi-modal) perspective with weighted links, an elaborate HS system becomes visible. In other words, a meaningful discussion of evolution and transformation of the Chinese ATS would be greatly facilitated through the decomposition of the system into types of linkages between the various airports and groups of airlines involved.

4.1 Distinguishing types of airports

A graph-theoretic network can be decomposed into the constituent airports, while attributing different roles to them. A heuristic that was explained above is the identification of hub airports. Due to findings in literature (Zhang 2010, Shaw et al. 2009), the role of CA, CZ, MU is most fundamental and therefore – by extension – their respective hubs (Hub_1) shall be considered apart from those of the remaining 7 major airlines (Hub_2). Airports that are directly connected to these hubs are treated as 'Spoke' airports. A distinction between spokes connecting to Hub_1 from those connecting to Hub_2 shall not be made at this point, mainly because a great number of spokes would be connected to both types of hubs – a finding that may be better analyzed in the following section. The class of 'Sub-Spoke' refers to airports that are not linked to hubs, but either to spoke airports or to each other.

Table 2: Network decomposition (all frequencies) into airport classes

		AP	**OD**	**FRE**	**a_OD**	**a_FRE**	**FRE/ OD**	**MS_T3**
Hub_1	**Jan'11**	**5**	**365**	**45.779**	**73**	**9.156**	**125**	**63,0%**
	Chg.'06	***0,0%***	***36,2%***	***52,4%***	***36,2%***	***52,4%***	***11,9%***	***-10,0%***
Hub_2	**Jan'11**	**6**	**293**	**29.904**	**49**	**4.984**	**102**	**36,8%**
	Chg.'06	***0,0%***	***26,8%***	***44,0%***	***26,8%***	***44,0%***	***13,6%***	***-22,2%***
Spoke	**Jan'11**	**129**	**1.403**	**93.253**	**11**	**723**	**66**	**52,3%**
	Chg.'06	***29,0%***	***50,2%***	***90,4%***	***16,4%***	***47,6%***	***26,8%***	***-9,9%***
Sub-Spoke	**Jan'11**	**24**	**30**	**1.566**	**1**	**65**	**52**	**64,8%**
	Chg.'06	***33,3%***	***42,9%***	***89,1%***	***7,1%***	***41,8%***	***32,4%***	***20,4%***
TOTAL	**Jan'11**	**164**	**2.091**	**170.502**	**13**	**1.040**	**82**	**53,9%**
	Chg.'06	***27,1%***	***43,8%***	***69,5%***	***13,1%***	***33,3%***	***17,8%***	***-6,2%***

These classes of airports are compared across the following variables: number of airports within a given class (‘AP’), number of origin-destination (directed flight segments) departing from all airports within a given class (‘OD’) as well as their number of scheduled flight movements (‘FRE’) during January 2011. The average number of (directed) flight segments offered by each airport class is ‘a_OD’, that of average domestic airport (departing) movements ‘a_FRE’ and average frequencies per directed route (‘FRE/OD’). Average market-shares[1] of the ‘Big Three’ within the same airport classes are shown through (‘MS_T3’). Changes are over 5-years after January 2006.

The results present information about the Chinese domestic ATS and the contribution of each of its classes of airports: clearly, this summary decomposition reflects the completely distinct features and – by inference – roles of the various classes: Hub_1 maintained its lead over Hub_2 airports in terms of both scale and scope of operations, with each variable having grown faster than with the H_2 class. Market-share of T3 airlines continued to be dominant at H_1 and strong at H_2, although this share had dropped considerably for H_2. Spoke airports were the most numerous within the system and had grown by 29% during the period. Spoke airports collectively represented some 65% of all directed links within the network and almost 55% of all movements. The average number of links (connectivity) of a ‘Spoke’ airport was less than 18% that of the average hub, while the average frequency of a ‘Spoke’ was slightly above 10% of the average hub. The average density on a route departing from a ‘Spoke’ airport was 66, or slightly above twice per day, while on a route departing from a hub it was between 3.4 (Hub_2) and 4 (Hub_1) daily. Although all of these network variables had grown for ‘Spoke’ airports, growth for the average number of OD’s was significantly trailing behind that of hubs: this may be explained by the fact that hubs continued to grow new routes to new airport-spokes, while ‘Spokes’ focused on increasing traffic density on existing routes. As for the ‘sub-spokes’, they were mostly connected to only one other airport and could be seen as a point-to-point, marginal and fragmented, system with less than two daily flights (average) on their OD links. This airport class of sub-spokes was upheld by ‘Big Three’ (with a 65% market-share).

4.2 HS connected-route differentiation for types of traffic flows

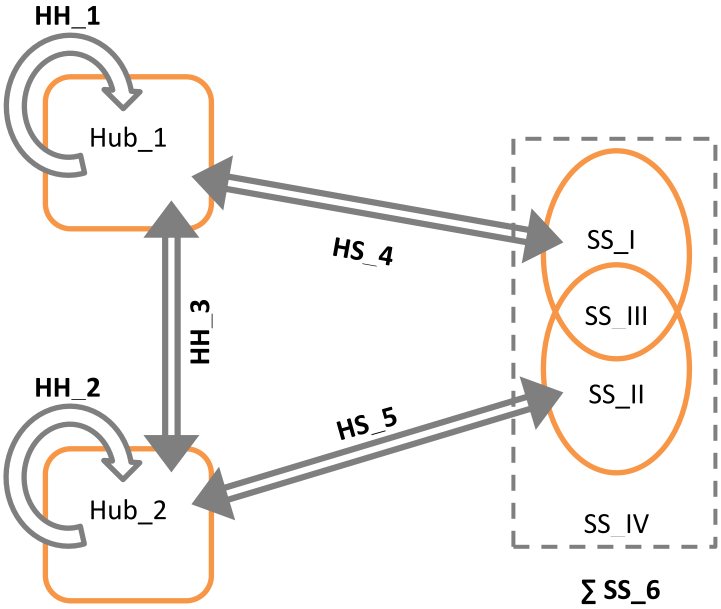
The following analytic template is not an ad-hoc invention, but represents the result of several cycles of analysis of raw origin-destination (OD) data and synthesis of distinct levels of matrix aggregation for the Chinese domestic ATS. It is an abstraction of the Matrix results for the different original agents (airlines,

---

[1] Market share was determined as a fraction of carriers’ movements.

airports) and the patterns (topology) found within the distinct classes of airports and airlines.

Figure 4: A template for analyzing the Chinese ATS



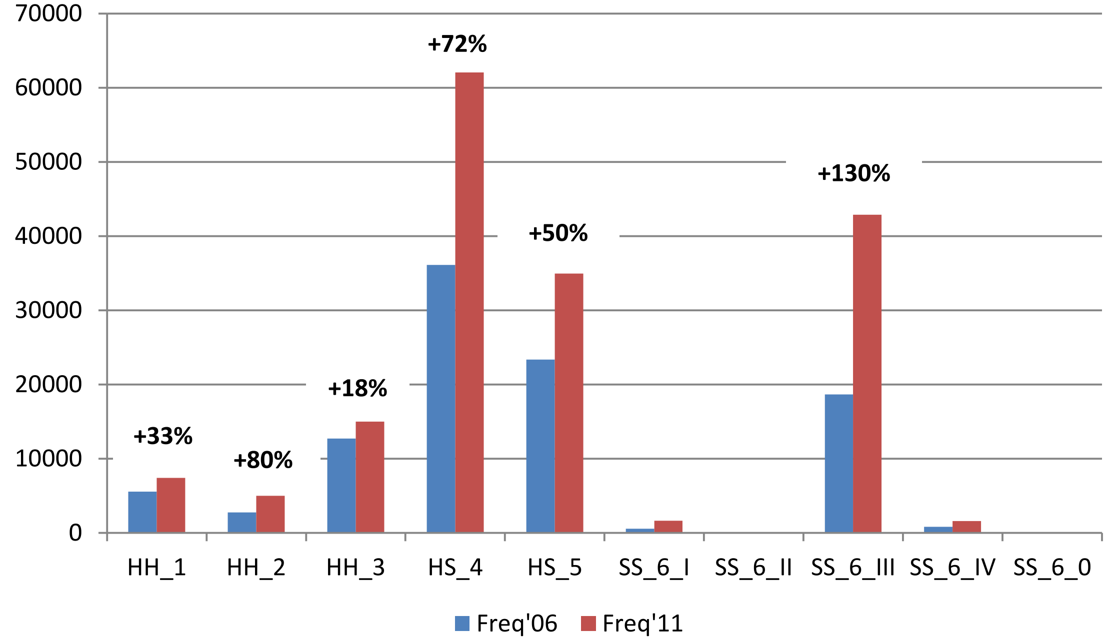
Hub airports had been identified before. Within China's 10 leading airlines which were defined as for hub operations, the 'Big Three' needed to be distinguished due to their incumbency, size and stronger influence on the system as a whole: these were associated with Hub_1, the remaining 7 airlines (HU, ZH, MF, SC, 3U, FM, KA) operated on airports that were coded Hub_2. Routes that connected HH_1 airports on both ends were defined as HH_1, those connecting HH_2 airports on both ends were HH_2 and those hub-to-hub links that had the other class on its end were considered as HH_3.

Other types were hub-spoke links, i.e. links that presented a hub on one end and a non-hub at the other. Depending on whether the hub side was part of Hub_1 or Hub_2, these hub-spoke links were either named HS_4 or HS_5, respectively. There were also non-hub airports that were unconnected to hubs, but linked to airport spokes or to airports outside any hub-spoke system. Links without overlap to HS routes were designated with the pre-fix 'SS'. The ensemble of such sub-spoke or spoke-spoke links can be summarized as ∑ SS_6, although there are different classes: SS_I stands for links outside any HS routes that are connected to a spoke airport which in turn is connected to one or several Hub_1 airports only. SS_II is such a HS non-overlapping route to/from an airport spoke with a connection to one or several Hub_2 airports solely. SS_III routes are linked to airports with one or several connections to both Hub_1 and Hub_2 type of airports. SS_IV represents sub-spoke routes without any connection to spoke airports; in a sense, they are self-organized. All of these linkages are additive with regards to allocated frequencies and flight segments, i.e. the sum would present the total capacity (in air traffic movements) within the Chinese ATS during the observation period.

4.3 A changing topology for China's ATS

Figure 5 shows empirical results after applying the template to real flight data for the month of January in 2006 versus that of 2011.

Figure 5: Frequencies on connected-route types and changes (2011-'06)



Flight frequency between the five hubs for group 1 (red) airlines continued to exceed that between the six hubs of group 2 (green) airlines. However, growth for the latter was much greater. Frequency of flights between both kind of hubs was yet higher which can – in part - be explained mathematically: the possible number of connections between all hub airports being $(5+6)^2$-11, the potential number of HH_3 routes would be $((5+6)^2-11) – (5^2-5) – (6^2-6) = 60$. This well exceeds the number of potential HH_1 plus HH_2 routes (=50).

As for movements that connected hubs and spokes, HS_4 not only exceeded HS_5 during January 2006 and 2011, but also continued to grow much faster during the same period. On one side increased hub-spoke frequencies would allow for more connecting traffic at the hubs, but also support higher densities on intra-hub movements. On the other side, the structural advantages of ‘red’ versus ‘green’ hubs became more emphasized in the process. It shall be noted that the widened gap between HS_4 and HS_5 made increasing spatial and hierarchical differentiation between both HS network types a plausible consequence. Hubs, in turn, would remain highly interconnected with each other.

Another striking finding by applying the template is the near in-existence of sub-spokes that are linked to airports solely with HS_4 or HS_5 either. The dominant type of sub-spokes shows connectivity to spokes of with links to group 1 (red) and others linked to group 2 (green) hubs (SS_6_III). It is these sub-spokes that presented the highest growth rate among all link types and which considerably altered the topology of China’s ATS during the observation period. Such increases in traffic with spoke airports from non-hubs, which in turn provided routes to both group 1 (red) and group 2 (green) hubs, would not only increase traffic on connecting hub-spoke segments. It could also be interpreted as decentralized and alternative routing within the ATS. This meant that spoke airports would not only be seen as feeders into single hubs, but would keep future growth options from the ’bottom’ through sub-spokes as the ATS evolved.

4.4 Network changes of airline groups and impact on the ATS

Table 3 shows the extent to which distinct airline groups determine the ATS as a set of hubs-and-spokes and multiple spoke-spoke connections. Values given are for January 2011 and changes refer to January 2006. Key variables describing the ATS and its constituent route types are ‘No_OD’ (number of flight segments), ‘FRE’ (flight frequencies) and ‘FRE/OD’ (average frequency per OD).

Table 3: Network characteristics for groups of airlines on link-types (Jan. 2011, % changes over January 2006)

Number of directed flight segments (No_OD)

AL_Group	HH1_11	chg_HH1	HH2_11	chg_HH2	HH3_11	chg_HH3	HS4_11	chg_HS4	HS5_11	chg_HS5	SS6_11	chg_SS6	*all_11*	*chg_all*
1 (red)	20	11.1%	22	57.1%	50	4.2%	518	40.8%	272	4.6%	517	82.7%	*1399*	*41.2%*
2 (green)	14	0.0%	24	33.3%	50	4.2%	303	23.2%	312	13.9%	379	2.2%	*1082*	*11.4%*
3 (blue)	4	n.a.	10	400.0%	24	500.0%	152	1166.7%	110	2650.0%	154	862.5%	*454*	*1094.7%*
4 (grey)	0	n.a.	0	n.a.	0	-100.0%	18	n.a.	28	600.0%	178	n.a.	*224*	*3633.3%*
Total	*38*	*18.8%*	*56*	*64.7%*	*124*	*21.6%*	*991*	*58.3%*	*722*	*33.2%*	*1228*	*83.3%*	*3159*	*57.5%*
net OD	*20*	*11.1%*	*28*	*40.0%*	*54*	*8.0%*	*638*	*41.8%*	*477*	*28.2%*	*874*	*60.7%*	*2091*	*43.8%*

Flight frequency (FRE)

AL_Group	HH1_11	chg_HH1	HH2_11	chg_HH2	HH3_11	chg_HH3	HS4_11	chg_HS4	HS5_11	chg_HS5	SS6_11	chg_SS6	*all_11*	*chg_all*
1 (red)	5683	29.6%	1630	79.3%	7967	4.5%	40168	53.9%	12907	10.4%	19619	117.8%	*87974*	*47.3%*
2 (green)	1493	26.2%	2923	59.3%	5711	19.2%	15350	61.9%	17666	55.9%	15809	47.0%	*58952*	*49.7%*
3 (blue)	222	n.a.	434	1569.2%	1328	617.8%	6000	1071.9%	3649	1861.8%	4461	1260.1%	*16094*	*1201.1%*
4 (grey)	0	n.a.	0	n.a.	0	-100.0%	522	n.a.	716	361.9%	6244	n.a.	*7482*	*2916.9%*
Total	*7398*	*32.8%*	*4987*	*80.0%*	*15006*	*18.2%*	*62040*	*71.9%*	*34938*	*49.6%*	*46133*	*129.6%*	*170502*	*69.5%*

Frequencies per flight segment (FRE/OD)

AL_Group	HH1_11	chg_HH1	HH2_11	chg_HH2	HH3_11	chg_HH3	HS4_11	chg_HS4	HS5_11	chg_HS5	SS6_11	chg_SS6	*all_11*	*chg_all*
1 (red)	284.2	16.6%	74.1	14.1%	159.3	0.3%	77.5	9.3%	47.5	5.5%	37.9	19.2%	*62.9*	*4.4%*
2 (green)	106.6	26.2%	121.8	19.5%	114.2	14.4%	50.7	31.4%	56.6	36.9%	41.7	43.9%	*54.5*	*34.4%*
3 (blue)	55.5	n.a.	43.4	233.8%	55.3	19.6%	39.5	-7.5%	33.2	-28.7%	29.0	41.3%	*35.4*	*8.9%*
4 (grey)	0	n.a.	0	n.a.	0	-100.0%	29.0	n.a.	25.6	-34.0%	35.1	n.a.	*33.4*	*-19.2%*
Total	*194.7*	*11.9%*	*89.1*	*9.3%*	*121.0*	*-2.8%*	*62.6*	*8.6%*	*48.4*	*12.3%*	*37.6*	*25.3%*	*54.0*	*7.7%*

n.a. = denominator equals zero

Airline Group 1 (red) dominated HH1 routes on which it continued to outgrow other groups even in percentage terms with FRE. It also allocated more capacity to HH2 although these routes showed quite low values for FRE/OD. Group 1 allocated 45.7% of its total flight capacities to HS4 feeder routes in 2011, a value that had grown faster than the total for Group 1. Relatively high values for FRE/OD on HS4 and above average growth indicate intensification of density by Group 1. Group 1 (and to a lesser extent Group 2) dominated SS6 routes where Group 1 actually had outgrown the latter and became the stronger group. This illustrates the deep penetration of the Chinese ATS by Group 1 beyond a hub-and-spoke. Highly skewed traffic distributions with distinctly denser served routes were due to HH1, HH3 and HS4.

Group 2 (green) exceeded Group 1 in the number of flight segments (OD) and frequency (FRE) for HH2 and HS5 routes (both groups were even on HH3 for OD). Hubs of Group 2 mainly grew by adding new flights to existing HS5 and HH2, i.e. by increasing density. When comparing values in terms of FRE/OD for respective route segments with Group 1, one notes that Group 2 operated with significantly lower densities throughout the system except for HH2 (connecting Group 2 hubs), HS5 (connecting Group 2 hubs with spokes) or SS6 where Group 2 had been growing densities faster. Although intra-hub traffic for Group 2 showed significantly greater values for FRE/OD compared to HS or SS links, its skewness towards hub traffic was much less.

Patterns of traffic distribution for Group 3 (blue) were dynamic compared to other groups as many of the airlines had not existed in 2006 or had commenced service only shortly thereafter (see Appendix). Most of their traffic was distributed on HS4, HS5 and SS6 routes, with lesser presence also on HH2 and HH3. Strikingly, Group 3 route densities (FRE/OD) were significantly below those for Groups 1 and 2 on all link-types, but most so on intra-hub routes. In all, Group 3 had values for FRE/OD distributed more evenly across all link-types at comparatively low levels.

Group 4 (grey), i.e. regional carriers, essentially was serving SS6 routes, although none of these routes had been served by it during January 2006. By 2011 it operated a not insignificant part of this link-type with about average FRE/OD. The most dynamic regional carrier appears to be Tianjin Airlines (GS), which for 2012 was reckoned to hold 90% of China's regional traffic and operated from its own hub in Tianjin Binhai International Airport (Wikipedia 2012b).

4.5 Entry, cooperation and competition in a growing market

Applying the same matrix deconstruction for traffic distributions between airline groups and link-types, one obtains market shares (M.S.) by using FRE as their proxy.

Table 4: Market shares and changes[2] of airline groups for link-types (Jan. 2011, % changes over January 2006)

AL_Group	**HH1_11**	**Chg_HH1**	**HH2_11**	**Chg_HH2**	**HH3_11**	**Chg_HH3**	**HS4_11**	**Chg_HS4**	**HS5_11**	**Chg_HS5**	**SS6_11**	**Chg_SS6**	***all_11***	***Chg_all***
1	76.8%	-1.9%	32.7%	-0.1%	53.1%	-7.0%	64.7%	-7.6%	36.9%	-13.1%	42.5%	-2.3%	*51.6%*	*-7.8%*
2	20.2%	-1.1%	58.6%	-7.6%	38.1%	0.3%	24.7%	-1.5%	50.6%	2.1%	34.3%	-19.3%	*34.6%*	*-4.6%*
3	3.0%	3.0%	8.7%	7.8%	8.8%	7.4%	9.7%	8.3%	10.4%	9.6%	9.7%	8.0%	*9.4%*	*8.2%*
4	0.0%	0.0%	0.0%	0.0%	0.0%	-0.7%	0.8%	0.8%	2.0%	1.4%	13.5%	13.5%	*4.4%*	*4.1%*
Total	*100.0%*	*0.0%*	*100.0%*	*0.0%*	*100.0%*	*0.0%*	*100.0%*	*0.0%*	*100.0%*	*0.0%*	*100.0%*	*0.0%*	*100.0%*	*0.0%*

---

[2] Percent changes to be added/subtracted directly from 2011 percentage value

With the overall Chinese market growing for everyone, new entry – in particular from Group 3 – could be expected to be more easily accommodated. When looking at the patterns of entry and market shares, we find that Group 3 had obtained only a marginal presence within HH1: the sacrifice in M.S. for Groups 1 and 2 was negligible. We see that for all other link-types, M.S. by Group 3 was in a range of 8.7% to 10.4%. Interestingly, different airline groups swapped market share with group 3 at different link-types: for HH2, M.S. obtained by Group 3 almost entirely came from group 2. For HH3, the transfer essentially came from Group 1. With HS4, Group 3 gained to the detriment of Group 2, but mostly Group 1. On HS5, group 3 mostly gained at the expense of Group 1. This may suggest increased collaboration on feeder routes between Groups 3 and 1: not only for feeders into hub airports of group 1, but also those feeding into hubs of Group 2. SS6 was the fastest growing link-type of all. Here it was mostly Group 2 that lost M.S. to group 3 and even more so to the regional carriers of Group 4.

Our findings are consistent with an evolutionary type of growth of China's ATS that is driven both by individual and collective behavior of classes of agents. Although new entry (no exits or mergers) occurred during the observation period, any potential for competition would need to be limited to distinct hierarchical parts of the network, and remain subject to system-wide control (or potential intervention) by the 'red' carriers. Continued growth and increased weight of 'green' networks need not diminish control of 'red', due to dominance and dependency at the hub level. In spite the shown flow control by 'red' agents in the system, this alone may not explain the system's behavior: a higher authority such as the CAAC may still be instrumental for coordinating and regulating such multi-agent, multi-hub, network-wide outcomes.

5. A new phase in aviation reform and ATS development

Our approach allowed us to illustrate interdependency between airline networks and allocate capacity at different hierarchical levels in the Chinese ATS. China's air traffic as a real system has been growing in a sustained, differentiated yet not linear manner. At the beginning of our observation period it had already left the 'consolidation era' which had witnessed the structural strengthening of the 'Big Three' with their respective hub-and-spokes. It had entered a new 5th phase of aviation reform that witnessed entry of new carriers, emergence of HS systems for a new group of carriers and further expansion of the 'Big Three' that actually went beyond the HS logic *strictu sensu*. The 'Big Three's deep penetration of the Chinese system into spoke-spoke and sub-spoke-spoke links is novel and not discussed in research. Due to a highly skewed distribution of traffic flows across distinctly hierarchical parts within their HS system, control of the ATS as a whole by ‘Big Three’ can plausibly be inferred. We found an organization by hierarchical flow control and selected cooperation with multiple smaller HS carriers. As a consequence, the entire ATS is growing quickly in a decentralized and coordinated fashion, with clearly defined interfaces between Group 1 and Group 2 carriers shown at hub levels. The graph theoretic dispute over HS versus FC can hereby be considered as obsolete.

From a complex systems perspective, Chinese domestic air traffic can be seen as an evolutionary system with differentiated path dependencies for each of the identified airline groups. The potential for growth and development remains intact for each of the groups, although it would remain affected by the ‘Big Three’. Further growth of ‘Big Three’ can occur on extra-HS routes. Group 2 carriers would be expected to both grow and continue to densify their HS.

While the post-consolidation era described in the above may continue for several years more, the physical constraint of airport capacity will have to compromise the system at one point. Such issues may not be as acute for ‘green’ hubs as they are for ‘red’ ones. With increasing numbers of spokes and more density per spoke, the question remains whether hub-hub linkages will suffice for ‘red’ airlines to maintain influence over ‘green’ carriers. From a certain moment on ‘green’ HS will have to compete more fiercely against ‘red’ on a route level. Spatial segmentation of air traffic in China is already under way: ‘green’ airlines have emphasized growing frequency on hub-spoke routes to/from hubs that they already dominate, mostly to the local detriment of ‘red’ carriers. In the end, this made capacity growth for ‘green’ spoke-spoke routes viable (although most spoke-airports involved were also linked to ‘red’ hubs at the same time). In that sense, both ‘red’ and ‘green’ carriers are increasing their networks’ scope into SS6.

One option for maintaining structural balance between ‘red’ and ‘green’ at saturated hub airports would be to allow for entry by third party ‘blue’ carriers at the hub-spoke routes, even allowing them to operate denser frequencies there. Such a development has already started during the observation period and it would facilitate the ‘blue’ carriers’ growth and organization of traffic around smaller hubs of their own. Very dense connectivity that is being maintained through the larger ‘red’ and ‘green’ networks could thus be balanced against newer emerging ‘blue’ hubs offering new routes. With these ‘blue’ airlines growing connectivity and frequency around their own hubs, they could progressively gain market share on ‘red’ and ‘green’ hubs. Although new entry by ‘blue’ and ‘grey’ airlines may follow such logic in the long run, the scenario still needs to emerge more fully.

In conclusion, China’s ‘Big Three’ were able to control the network system while allowing for entry and growth around certain airports. In the same time, these ‘red’ carriers have grown their presence throughout the ATS, including at smaller airports through spoke-spoke and sub-spoke routes. One could plausibly interpret the role of China's 'red' agents as evolutionary-catalytic, i.e. as one of opening routes, establishing connectivity among a diverse set of airports, and even encouraging competing connections to 'green' hubs. Its spatial presence seems accommodating to other agents' for several route types and able to forgo local dominance on critical routes. There is no indication of rigid planning in the sense that China's 'red' (and probably 'green' agents at a later stage) were unable to adjust their network strategies over time. These were some of the critical patterns and trends of the Chinese ATS that our research could find and which contrast with the fully-connected versus single hub-and-spoke dichotomy often advocated in Western thinking.

6. Appendix: Groupings for airline networks, characteristics (Jan. 2011)

Carrier	Code	Size_AP	No_OD	Mx_FRE	FRE_AP	SEAT	INT_AP	since
China Southern	**CZ**	111	823	5671	345	151	20	1991
China Eastern	**MU**	98	635	2346	268	130	20	1988
Air China	**CA**	94	403	6687	248	157	16	1988
Group 1 (Red)	***Avg.:***	***101***	***620***	***4901***	***287***	***146***	***19***	
Hainan Airlines	**HU**	53	314	1694	218	163	10	1989
Shenzen Airlines	**ZH**	54	241	2174	193	152	4	1992
Xiamen Airlines	**MF**	45	299	1668	277	126	4	1984
Shandong Airlines	**SC**	43	202	1284	178	144	3	1994
Sichuan Airlines	**3U**	54	208	1545	130	143	3	1986
Shanghai Airlines	**FM**	70	202	1701	106	131	3	1985
Dragonair	**KA**	17	32	1258	148	193	1	1985
Group 2 (Green)	***Avg.:***	***48***	***214***	***1618***	***178***	***150***	***4***	
Hong Kong Airlines	**HX**	8	14	229	57	202	1	2001
Hong Kong Express[3]	**UO**	6	10	158	53	164	1	1997
Air Macau	**NX**	11	20	311	57	142	1	1994
Spring Airlines	**9C**	34	73	496	64	180	0	2004
Grand China Air	**CN**	6	10	186	62	180	0	2007
China United	**KN**	25	48	832	70	171	0	1986
Juneyao Airlines	**HO**	34	73	620	67	155	0	2005
China West	**PN**	23	48	465	54	141	0	2007
Beijing Capital	**JD**	27	80	263	86	140	0	1995
Chengdu Airlines	**EU**	25	62	430	61	124	0	2004
Lucky Air Co.	**8L**	31	68	806	79	122	0	2004
Hebei Airlines	**NS**	6	10	155	52	110	0	2010
Cathay Pacific[4]	**CX**	3	4	74	50	294	1	1946
Group 3 (Blue)	***Avg.:***	***18***	***40***	***387***	***62***	***163***	***0***	
Tianjin Airlines	**GS**	52	160	666	100	83	1	2004
China Express	**G5**	20	40	181	45	50	0	2006
Okay Airways[5]	**BK**	13	28	186	76	50	0	2004
Joy Air	**JR**	6	10	142	68	50	0	2008
Group 4 (Grey)	***Avg.:***	***23***	***60***	***294***	***72***	***58***	***0***	

---

[3] Part of Group 4 in 2006

[4] Data for January 2006

[5] Part of Group 3 in 2006

7. References

Albert R. and Barabási A.L., 2002. Statistical mechanics of complex networks. *Reviews of Modern Physics*, 74 (January), 47-97

Brueckner J.K. and Spiller P.T., 1994. Economies of Traffic Density in the Deregulated Airline Industry. *Journal of Law and Economics*, 37 (2), 379-415

Borgatti S.P., Everett M.G. and Freeman L.C., 2002. *Ucinet 6 for windows software for social network analysis – user's guide.* Lexington: Analytic Technologies, Inc.

Huber H., 2010. Planning for balanced growth in Chinese air traffic: A case for statistical mechanics. *Journal of Air Transport Management*, 16, 178-184

Huber H., 2009. Statistical mechanics for analytic planning: An application to domestic air traffic in China. *International Journal of Management & Network Economics*, 1 (4), 378-393

Jin F., Wang F. and Liu Y., 2004. Geographic patterns of air passenger transport in China 1980-1998: Imprints of economic growth, regional inequality and network development. *The Professional Geographer*, 56 (4), 471-487

Railsback S.F. and Grimm, V., 2011. *Agent-Based and Individual-Based Modeling: A Practical Introduction*. Princeton: Princeton University Press

Reynolds-Feighan A., 2010. Characteristics of airline networks: A North American and European Comparison, *Journal of Air Transport Management*, 16, 121-126

Shaw S., Lu F., Chen J. and Zhou C., 2009. China's airline consolidation and its effects on domestic airline networks and competition. *Journal of Transport Geography*, 17, 293-305

Wei W. and Hansen M., 2006. An aggregate demand model for air passenger traffic in the hub-and-spoke network. *Transportation Research Part A*, 40, 841-851

Wikipedia, 2012a. *List of the busiest airports in the People's Republic of China* [online]. CAAC. Available from:

http://en.wikipedia.org/wiki/China%27s_busiest_airports_by_passenger_traffic [Accessed 28 May, 2012]

Wikipedia, 2012b. *Tianjin airlines* [online]. Official website. Available from: http://en.wikipedia.org/wiki/Tianjin_Airlines [Accessed 29 May, 2012].

Zhang, Y., 2010. Network Structure and capacity requirement: The case of China. *Transportation Research Part E*, 46, 189-197