Does the Chinese Airline Network Become More Robust Over Time?

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***Abstract*— Currently, China has the fastest growing air transportation market in the world. Resilience to external events is critical to ensure an efficient and reliable transportation of passengers. This study investigates the robustness of the Chinese airline network under disruptions at their critical airports as well as the evolution of the networks' robustness from the year 2010 to 2015. Among the 24 Chinese airline networks in our study, we find that the topological properties of the networks differ significantly for these airlines. Each airline has its own few dominating hubs, where the number of hubs varies among airlines. Analysis of the robustness for the 24 Chinese airline networks show that they are quite robust against random failures, but the networks disintegrate quickly under targeted attacks. Evolutionary analysis of the robustness on a monthly resolution from 2010 to 2015 showed that the robustness does not change significantly over time for individual airline network, although the robustness measure R values vary for different airlines. This shows that the ongoing efforts to increase the resilience should be adjusted to better meet future needs for more reliable transportation. Our work contributes to a better understanding of the Chinese air transportation systems.**

Keywords-air transportation, airline networks, robustness

I. INTRODUCTION

Despite the fast spreading of the Chinese High-Speed Rail (HSR) system [11] in recent years, with the HSR tracks summing up to 19,000 km and approximately one billion passengers carried, China has the fastest growing number of air passengers in the world; and it has been the second largest air transportation market for more than a decade. In 2013, the number of air passengers carried in China is more than 352 million and Beijing Capital International Airport (PEK) has handled more than 77 million passengers, which is the second busiest airport in the world, following ATL (Hartsfield-Jackson Atlanta International Airport). It is predicted that the number of aircraft operated by the Chinese airlines will be more than 4000 in the year 2020. Because of the key importance roles of such hub nodes for the functionality of the Chinese air transportation system [6], it is critical to assess the system robustness under disruptions as well as the evolution of the system robustness over the years [10].

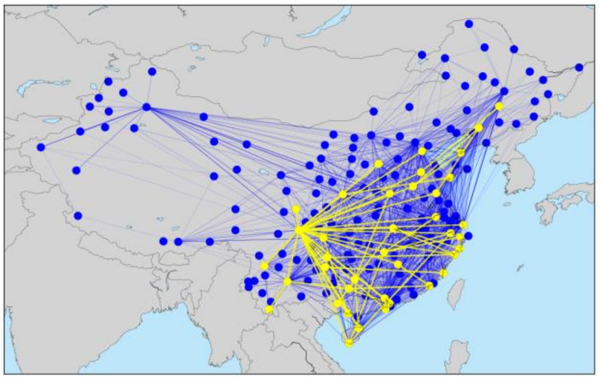
In this study, we model the Chinese air transportation system from a complex network point of view: Airports are modelled as nodes; and there exists a link between two airports if there is direct flight connection between both airports. In general, different airlines have their own network structures, depending on their business model and strategical decisions. In the Chinese airline industry, there are three dominating airlines: Air China, China Eastern, and China Southern, whose network structures are following the typical hub-and-spoke network model. The rest of the Chinese airlines are significantly smaller and they often have mixed network structures. For instance, the network of Spring Airlines, the first low-cost carrier in China (established in Shanghai in 2005), has been transformed from a star structure to a complex one with multiple hubs [2].

Figure 1 shows an example for the airline network of Chengdu airlines (yellow color), on top of the aggregated Chinese airline network (blue color). Chengdu Airlines was founded in 2004 and revenue flights were commenced starting from 2005, with CTU (Chengdu Shuangliu International Airport) as its operational hub. Based on the air traffic data for August 2015, Chengdu airlines served 39 airports with 50 direct flight connections, carrying approximately 0.15 million passengers. We can observe from Figure 1 that airlines often serve some sub-region of China only, with a strong focus on a few hub airports. Note that in the Chengdu airline network, only airports served by this airline are highlighted with yellow color; while in the aggregated Chinese airline network, airports served by any Chinese airlines are modelled as nodes (yellow color and blue color).

This paper is organized as follows. Section II provides the literature on the robustness of air transportation networks. Topological properties of the 24 Chinese airline networks are presented in Section III. Section IV assesses the robustness of the 24 Chinese airline networks and presents the evolutionary analysis of the network robustness with a monthly resolution from 2010 to 2015. Finally, conclusions are discussed in Section V.

II. LITERATURE REVIEW

This section provides the literature on the robustness of air transportation networks. The robustness of the worldwide airport network with twelve different attacking strategies and three robustness measures was studied in [5], the goal was to



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identify commonalities and differences under these scenarios. It was found that degree and Bonacich-based attacks harm the passenger weighted network the most. It was also revealed that the worldwide airport network is a redundant and resilient network for long distance air travel, but otherwise breaks down completely due to removal of short insignificant connections [8]. In order to improve the resilience of worldwide air transport system under targeted node attacks, [3] proposed reroute of flights within certain distances of original destination airports, using an estimated number of stranded passengers in the giant component as a robustness metric.

The robustness of US and European air transportation networks has been intensively studied as well. [15] analyzed individual structures of seven US largest passenger airline networks and the networks' resilience to random node/link deletion and targeted node deletion based on degree/betweenness centralities. The size of giant component and a relative global travel cost were used to quantify the network performance under various deletion processes. [12, 13, 14] introduced the flight routes addition/deletion problem and used algebraic connectivity as the robustness measure to optimize the network robustness; the Virgin America network was used as a case study. The resilience of European air transport network against random link failures was analyzed, with each airline as an interdependent network [1]. It was found that the multi-layer structure strongly reduces the system's resilience under disruptions.

Recently, the computational efficiency for the robustness analysis of complex networks has drawn attention as well. Based on the combination of cheap-to-compute network metrics, [9] proposed a new framework and implementation for estimating the robustness of a network in sub-quadratic time, QRE (Quick Robustness Estimation). Experiments on twelve real-world networks showed that QRE estimates the robustness better than betweenness centrality-based computation, while being at least one order of magnitude faster for larger networks.

III. Data in this Study

An overview of the 24 Chinese airlines in this study is presented in Table 1, including the IATA codes, full names of the 24 airlines, passengers carried, number of airports (nodes), number of flight connections (links), network density, ASPL (Average Shortest Path Length, representing the average number of hops between all airports inside an airline network), and average degree (the average number of connections an airport has).

There are three state-owned airlines (Air China, China Southern Airlines, and China Eastern Airlines) and they dominate the Chinese airline industry. As we can see from Table 1 (see appendix), China Southern Airlines (CZ) has the most number of passengers (3.57 Mio) and the highest number of flight connections (479) in August 2015; while China Eastern Airlines (MU) served most number of airports (124). The density of the Chinese airline networks varies significantly from 4% to 25%; while the average number of hops between airports is between 2.11 to 3.66. The average number of connections per airport also differ for the 24 airlines, ranging from 1.8 to 8.1.

Figure 2 (see appendix) visualizes the top nine Chinese airline networks, according to the number of passengers carried in August 2015 in our study: China Southern Airlines, China Eastern Airlines, Air China, Hainan Airlines, Shenzhen Airlines, Xiamen Airlines, Sichuan Airlines, Shandong Airlines, and Tianjin Airlines. In this figure, green nodes represent all airports inside an airline network and green lines represent direct flight connections; while red nodes indicate that these airports are hubs, who are connected to more than 45% of all airports in the respective airline network. Hubs, in general, have the function to transfer passengers from origin to destination by taking into account cost discounts. In a hub-based network, the transportation is significantly cheaper compared to point-to-point networks, at the price of increased transportation times.

It is interesting to note that most of the nine airlines indeed have a few dominating hubs, from which more than 45% of all other airports can be reached within one hop. For instance, Sichuan Airlines has two hubs (Chengdu Shuangliu International Airport and Chongqing Jiangbei International Airport); while none of the airports meets the threshold of 45% connections with other airports for Tianjin Airlines. Since there is no unique and standard definition of hubs in the literature, in this study we choose the threshold of 45% connections with other airports. Note that the appearance of the hub airports for an airline depends on the threshold of 45% and the hubs identified by this definition are not necessarily the same as the operational hubs of the airlines.

IV. Robustness of the Chinese Airline Networks

The robustness of an airline network can be studied from its topological perspective: Once airports are closed due to disruptions (such as extreme weather conditions, mechanic failures or employee strikes), how is the connectivity of the airline network affected? The Giant Component (GC) is one of the mostly common used measure for the network connectivity.

The GC size is the number of nodes inside the largest connected component of a network. There are different strategies to simulate the airport closure inside an airline network: Random removal or targeted attacks. In this study, we use three different strategies: Random failures, degree-based attacks, and betweenness-based attacks. We compute the R values as a robustness measure for the network after an attack. The R value is defined as follows [4]: Given a network with N nodes, $R = \frac{1}{N}\sum_{Q=1}^{N} s(Q)$, where $s(Q)$ is the size of the giant component (GC size) after removing Q nodes. The R values range from 0 to 0.5; smaller R values indicate more fragility and larger R values indicate more robustness for a network

Figure 3 (see appendix) visualizes the robustness curves for the 24 Chinese airline networks in this study, induced by different attacks to the network: Random failures (red), degree-based attacks (blue), and betweenness-based attacks (green). The R values under the betweenness-based attacks are shown as well. We can observe that most airlines are rather robust against random airport failures, but they are quite fragile under targeted attacks. It is also interesting to observe that the attacking strategies based on degree and betweenness behave quite similar in the Chinese airline networks, indicating that it only takes a few nodes to break down the connectivity of the network, once sufficient knowledge about the network (such as the structural properties) is obtained. Note that the effectiveness of random failures and targeted attacks become similar for very small networks, such as Joy Airlines in this study.

Figure 4 (see appendix) shows the evolution of the robustness for the 24 airline networks in China, these networks are built on a monthly resolution from 2010 to 2015. The robustness is measured by the R values. It can be observed that for most airline networks, although the R values vary for different airline networks, the robustness does not change significantly over the time for individual airline networks. Note that because of the lack of data, the R values for the following three airlines (bottom of the chart): Tibet Airlines (commenced operations since 2011), Joy Airlines (commenced operations since 2009), and JSC Starline (also named as Donghai Airlines, commenced operations since 2006), are discontinuous.

V. CONCLUSIONS

This study investigated the robustness of the Chinese airline network under disruptions at their critical airports as well as the evolution of their robustness from 2010 to 2015. Among the 24 Chinese airline networks in our study, the topological properties of the networks differ significantly for these airlines. Each airline has its own few dominating hubs. Analysis of the robustness curves for the 24 Chinese airline networks showed that they are quite robust against random failures, but the networks disintegrate quickly under targeted attacks. Evolutionary analysis of the robustness on a monthly resolution from 2010 to 2015 showed that the robustness does not change significantly over time for individual airline networks, although the robustness measure R values vary for different airlines. Future work could take into account passenger flows on top of the topological network [5]. The multiple-airport regions (MARs) could also be studied, since passengers are more likely to be re-accommodated to other nearby airports in case of disruptions [7]. Since the fast-growing Chinese high-speed rail system triggers increasing competition between air and rail, it would be also interesting to investigate the competition/cooperation effects between rail and air transport.

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APPENDIX

Table 1: List of airlines in our study, ordered by the number of passengers carried (descending), data for August 2015. The topological parameters differ significantly for these airlines. ASPL=Average shortest path length. The maximum values for each column are highlighted in bold.

IDIATA	Name	Passengers	Nodes	Links	Density	ASPL	Avg. degree
1CZ	CHINA SOUTHERN AIRLINES	**3.57 Mio**	118	**479**	6.94%	2.38	**8.1**
2MU	CHINA EASTERN AIRLINES	2.94 Mio	**124**	406	5.32%	2.45	6.5
3CA	AIR CHINA LIMITED	1.83 Mio	102	251	4.87%	2.13	4.9
4HU	HAINAN AIRLINES COMPANY LIMITE...	1.19 Mio	59	196	11.46%	2.23	6.6
5ZH	SHENZHEN AIRLINES	1.17 Mio	61	187	10.22%	2.15	6.1
6MF	XIAMEN AIRLINES	1.02 Mio	57	178	11.15%	2.17	6.2
73U	SICHUAN AIRLINES CO. LTD.	1.01 Mio	76	205	7.19%	2.36	5.4
8SC	SHANDONG AIRLINES	0.74 Mio	55	140	9.43%	2.33	5.1
9GS	TIANJIN AIRLINES CO. LTD	0.53 Mio	80	152	4.81%	2.89	3.8
10FM	SHANGHAI AIRLINES CO. LTD.	0.50 Mio	62	80	4.23%	2.72	2.6
119C	SPRING AIRLINES LIMITED CORPOR...	0.49 Mio	46	78	7.54%	2.49	3.4
12JD	BEIJING CAPITAL AIRLINES CO. L...	0.45 Mio	52	122	9.20%	2.55	4.7
13HO	JUNEYAO AIRLINES CO. LTD.	0.36 Mio	47	67	6.20%	2.41	2.9
148L	LUCKY AIR CO. LTD.	0.31 Mio	43	65	7.20%	2.50	3.0
15PN	CHINA WEST AIR CO. LTD.	0.21 Mio	35	46	7.73%	2.36	2.6
16BK	OKAY AIRWAYS COMPANY LIMITED	0.19 Mio	44	60	6.34%	2.85	2.7
17EU	CHENGDU AIRLINES	0.15 Mio	39	50	6.75%	2.50	2.6
18KY	KUNMING AIRLINES	0.12 Mio	26	29	8.92%	2.18	2.2
19OQ	CHONGQING AIRLINES CO. LTD	0.10 Mio	24	24	8.70%	2.06	2.0
20G5	CHINA EXPRESS AIRLINES	0.09 Mio	51	55	4.31%	**3.66**	2.2
21NS	HEBEI AIRLINES CO. LTD.	0.09 Mio	24	28	10.14%	2.38	2.3
22TV	TIBET AIRLINES CORPORATION LIM...	0.06 Mio	18	21	13.73%	2.40	2.3
23JR	JOY AIR	0.05 Mio	17	17	12.50%	2.87	2.0
24DZ	JSC STARLINE.KZ	0.03 Mio	8	7	**25.00%**	2.11	1.8

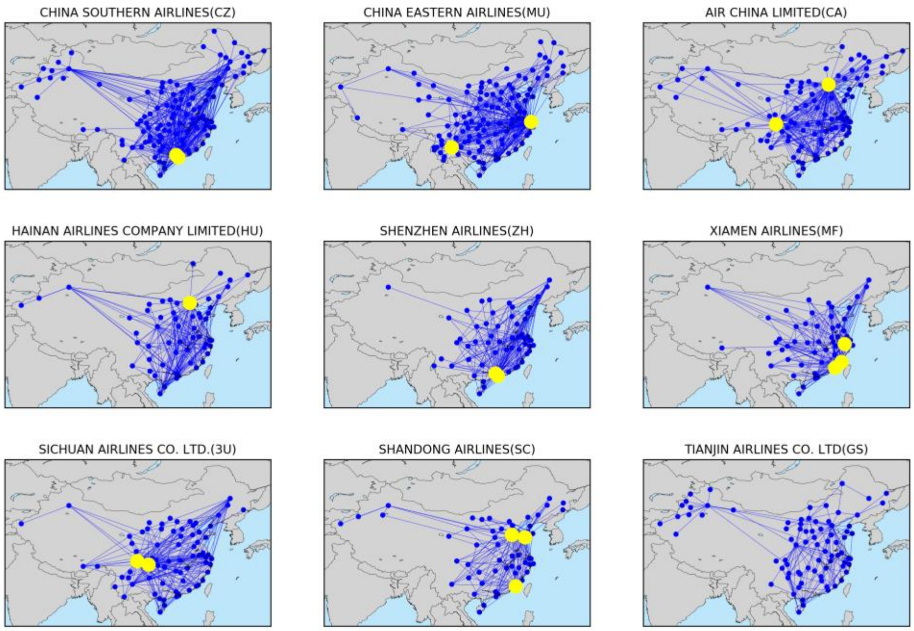

Figure 2: Visualization of the top nine Chinese airline networks, according to the number of passengers carried in August 2015 (the ranking in Table 1. In each sub-figure, blue nodes represent all airports inside an airline network and blue lines represent direct flight connections; while yellow nodes indicate that these airports are hubs, who are connected to more than 45% of all airports in the airline network.

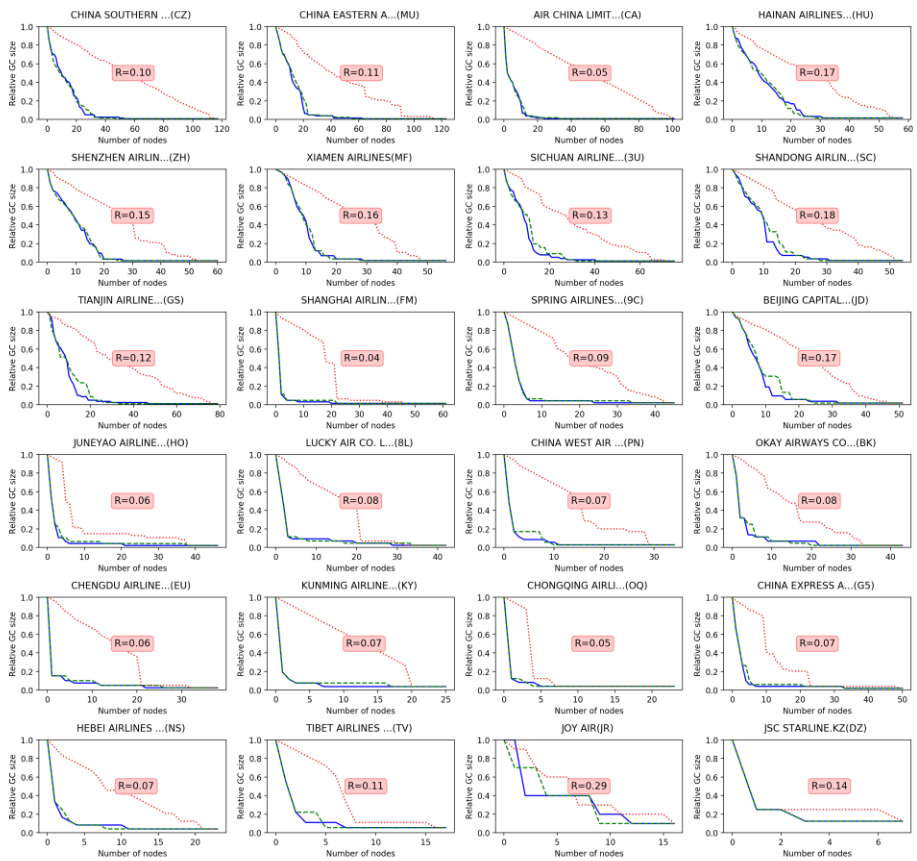

Figure 3: Visualization of robustness curves for the 24 Chinese airline networks in this study, induced by different attacks to the network: Random failures (red, dotted), degree-based attacks (blue, line), and betweenness-based attacks (green, dashed). The R values under betweenness-based attacks are shown as well.

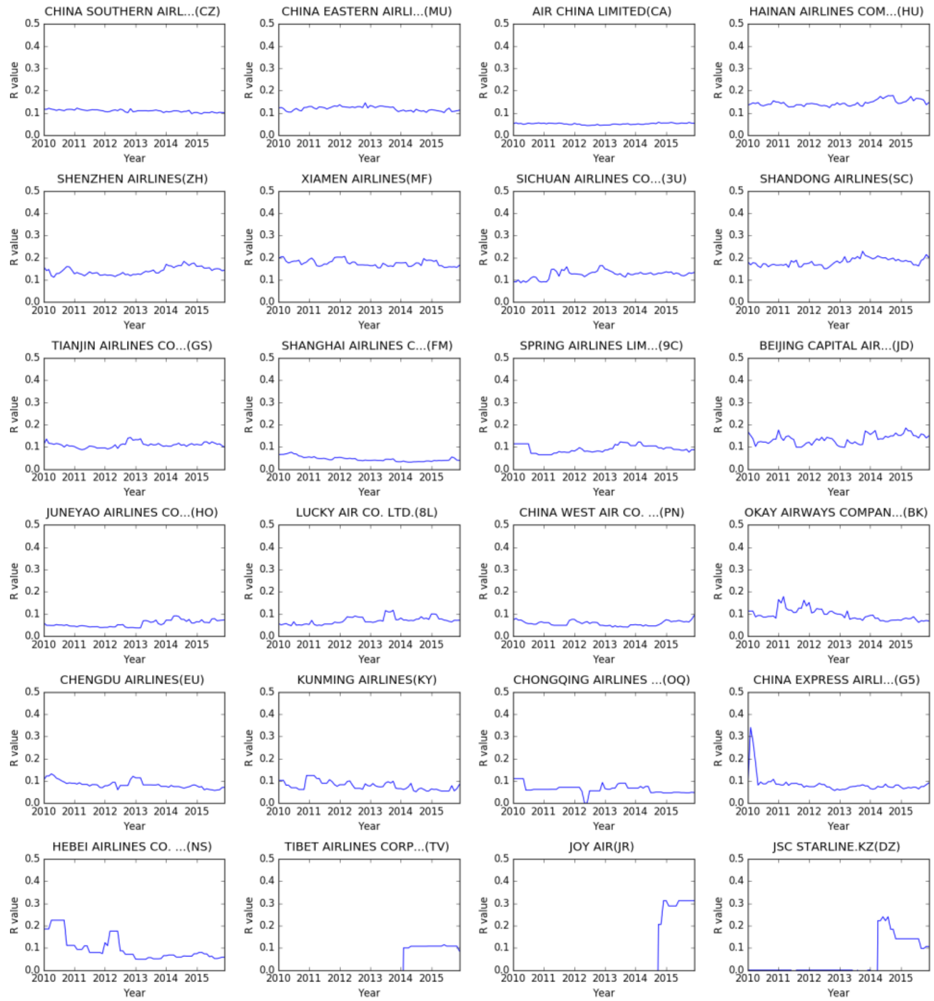

Figure 4: Evolution of the robustness on a monthly resolution for the 24 airline networks in China from 2010 to 2015. The robustness is measured by the R values. For most airline networks, although the R values vary for different airline networks, the robustness does not change significantly over the time for individual airline networks.