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Robustness analysis metrics for worldwide airport network: A comprehensive study

Sun Xiaoqian [a,b,c], **Volker Gollnick** [d], **Sebastian Wandelt** [a,b,c,*]

[a] *School of Electronic and Information Engineering, Beihang University, 100191 Beijing, China*
[b] *Beijing Key Laboratory for Network-based Cooperative ATM, Beijing 100191, China*
[c] *Beijing Laboratory for General Aviation Technology, Beijing 100191, China*
[d] *Institute of Air Transportation Systems, German Aerospace Center, Blohmstrasse 18, 21079 Hamburg, Germany*

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Abstract Robustness of transportation networks is one of the major challenges of the 21st century. This paper investigates the resilience of global air transportation from a complex network point of view, with focus on attacking strategies in the airport network, i.e., to remove airports from the system and see what could affect the air traffic system from a passenger's perspective. Specifically, we identify commonalities and differences between several robustness measures and attacking strategies, proposing a novel notion of functional robustness: unaffected passengers with rerouting. We apply twelve attacking strategies to the worldwide airport network with three weights, and evaluate three robustness measures. We find that degree and Bonacich based attacks harm passenger weighted network most. Our evaluation is geared toward a unified view on air transportation network attack and serves as a foundation on how to develop effective mitigation strategies.

1. Introduction

Air transportation is one critical network infrastructure for a nation and it is becoming extremely important for public policy considerations. Disruptions of air transportation systems, either due to extreme weather conditions or terrorist attacks, can lead to huge economic losses. The eruption of Eyjafjallajoekull volcano in 2010 caused airline losses of approximately 1.7 billion US dollars and more than 10 million passengers were affected.[1] An overnight snowstorm on March 12, 2013 disrupted the transport across northwestern Europe; in particular, Frankfurt airport was closed and airlines canceled about 700 flights. In order to avoid such high socio-economic costs, it is extremely critical to assess the robustness of air transportation systems against natural or intentional disruptions.

Complex network theory[2] provides powerful tools to understand the structures and dynamics of air transportation systems. Airport networks have often been analyzed, where nodes are airports and links exist between two airports if there

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* Corresponding author at: School of Electronic and Information Engineering, Beihang University, 100191 Beijing, China.
E-mail address: wandelt@buaa.edu.cn (S. Wandelt).

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are flight connections.[3–7] Several research focused on how delay is propagated in airport networks.[8–10] Based on fuzzy soft sets, Ref. 11 evaluated the airport importance and network efficiency with US and China's airport networks as case studies, and the vulnerability of these two networks was also compared. Ref. 12 showed that the vast majority of all Intra-European passengers travel direct and the directness of the overall system increased from 2002 to 2012. Ref. 13 studied the robustness of US airport network, using attacking strategies based on betweenness, closeness, hyperlink induced topic search (HITS), and degree, with giant component as robustness measure. Ref. 14 studied the resilience of European air transport network against random flight failures, based on a multiplex network formalism, where the set of flights for each airline is considered as an interdependent network. Robustness of Australian network, based on degree, betweenness, strength, and random attacks, with giant component and network reachability robustness measures was investigated.[15] The worldwide airport network was studied under random attacks as well as degree and betweenness-based attacks with the shortest average path length and giant component as robustness measures.[16]

In air transportation networks, random failures correspond to the closure of an airport (node failure) or the cancellation of a flight (link failure) randomly, while targeted attacks correspond to the closure of an airport or the cancellation of a flight based on certain criteria. For instance, Beijing Capital International Airport (PEK) has the largest number of passengers (77,531,486) in 2013 in the whole world (Data source: http://www.airdi.net). Such hub nodes are critical for the structure of air transportation and they are inherently priorities for targeted attacks. One might think that airline routes are impermanent and links come and go all the time, and therefore robustness analysis is less important for this type of network than for other types of network with a more static structure, e.g., electricity or road networks. However, it is a long process to establish a new route for an airline. Before setting up a new route, the airline network planning department needs to spend considerable amount of time to analyze the profitability of the new route.[17] Several factors need to be considered, for instance, market demand forecasting[18,19], competitor analysis[20,21], aircraft capacity planning, and passenger spill model.[22,23] Ultimately, the reason for studying the resilience of the system resides in the time frame associated with an attack to an airport. It is true that, if a route is closed (for instance because of adverse weather), alternative solutions can be found fast. Nevertheless, an attack to an airport may have long-term important consequences as in the recent case of 2016 Brussels bombings. It is thus important to prevent such attacks. In this research, we perform a systematic robustness analysis for the worldwide airport network against random failures and targeted attacks, with focus on several attacking strategies and robustness measures.

Several research on the robustness of the worldwide airport network has been conducted in the past years. Lordan et al. presented a methodology for the detection of critical airports in the worldwide airport network, and the network robustness was measured by the size of giant component.[24] The airports are isolated based on several node selection criteria, and especially a novel criterion, Bonacich power centrality, has been tested. Wei et al. introduced the flight route addition/deletion problem and compared three different methods to optimize the robustness of the airport network, with algebraic connectivity as the robustness measure; the Virgin America network was used as a case study with the link failure probability as weight.[25] Wang et al. compared the behavior of two real networks and two synthetic networks under degree based attacks using the size of giant component.[26] Louzada et al. proposed to reroute a series of flights within certain distances of original destination airports in order to improve the robustness of the worldwide airport network under degree targeted attacks, where robustness is measured by an estimation of the number of stranded passengers in the giant component.[27] Verma et al. analyzed the resilience of the worldwide airport network and revealed that it is a redundant and resilient network for long distance air travel, otherwise it breaks down completely due to removal of short insignificant connections.[28] Woolley-Meza et al. investigated the eruption of Eyjafjallajoekull volcano, September 11th terrorist attacks, and geographical disruptions in the worldwide airport network; effective distance was used to quantify the impact of disasters on the network.[29] Wuellner et al. analyzed the individual structures of seven US largest passenger airline networks and examined the networks' resilience to random/degree/betweenness targeted node deletion.[30] Lordan et al. also analyzed the robustness of three major airline/alliances route networks.[31,32] Wei et al. also studied the optimization of the robustness of the airport network, with algebraic connectivity as the robustness measure.[33,34] The effective distance is based on the idea that a small fraction of traffic is effectively equivalent to a large distance, and vice versa.[35] The size of giant component and travel cost in the giant component were used to quantify the network performance under various deletion processes. Moreover, the design of a robust hub network has also been studied.[36] Kotegawa et al. measured the robustness of airline service route network topology under random and targeted disruptions.[37] Closely related works are summarized in terms of robustness measures, attacking strategies, and network weights in Table 1.

In this research, which was motivated by the work of Ref. 38, we extract data from the Sabre Airport Data Intelligence (ADI) (http://www.airdi.net) to build the worldwide airport network, and an excerpt is shown in Fig. 1. Each node is one airport, and the size of a node is proportional to its degree, which is weighted by the number of passengers. In this figure, we only show the links which have more than 100,000 passengers travelling per year. Note that spherical links are not always drawn as the shortest connection, but go through the center of the projected map. We consider the network as directed and weighted; two different weights are used for this study: geographical distances and the number of passengers travelling between two airports. Given a consistent view on the worldwide airport network, the goal of this research is to make clear, through comparison, which attacking strategy harms the network most and which robustness measure is more appropriate for the network under disruptions.

We are interested in the robustness of air transportation systems under disruption from the function point of view[38–41]: transferring passengers from their origins to destinations. We use unaffected passengers with rerouting as a baseline measure from the passenger stakeholder's perspective: if an airport is closed due to convective weather or intentional human disruptions, how many passengers can still make their journeys? We compare our baseline metric to three other robustness measures: the size of giant component, algebraic

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