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# Complementary strengths of airlines under network disruptions

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ABSTRACT

Disruptions of air transportation systems, caused by events such as, extreme weather conditions or human-intended attacks, can lead to huge economic losses. Existing studies have modeled and estimated the robustness of air transportation networks under node/link failures, and found that networks disintegrate quickly under targeted attacks. The robustness of airline networks, however, has been largely neglected in the past, with investigating strongly spatially constrained regions and few airlines only.

In this study, we first investigate the robustness of more than 200 global airline networks, which cover almost 95% of worldwide air passenger transportation. We find that the robustness depends largely on the structure of the airline network. Second, we estimate how much these disruptions can be absorbed by other airlines using the notion of static complementary strength. In addition, with passenger data and rerouting considerations, we analyze how much of an airline disruption can be compensated by other airlines in reality. Results show that the traditional complementary strength clearly overestimates the robustness of the network; according to our more realistic model, many airlines are indeed easy to fail and the consequences of failures are not readily compensated by other airlines. Our work contributes towards improving air transportation systems, by understanding the hidden threats of airline disruptions.

## 1. Introduction

Air transport systems can be studied from a complex network point of view, where airports are modeled as nodes and links exist between two airports if there is at least one direct flight connection (Zanin and Lillo, 2013; Sun et al., 2015). Due to convective weather conditions or human-intended interruptions (such as terrorist attacks, air traffic controller strikes or pilots strikes) or unexpected mechanical failures (such as aircraft component breakdown or runway systems failures), air transport systems can become vulnerable (Wandelt et al., 2015). Such disruptions often lead to huge economic and social costs (Janić, 2015; Rosenthal et al., 2013). The eruption of Eyjafjallajoekull volcano in 2010, for instance, caused airlines losing approximately 1.7 billion US dollars and more than 10 million passengers were affected (Wilkinson et al., 2012). In order to avoid such high socio-economic costs, it is critical to assess the robustness of air transportation systems against disruptions (Skorupski, 2016; Clothier et al., 2015; Wang and Gong, 2014). Accordingly, understanding and improving the resilience of air transportation systems is a major challenge to ensure safe and efficient global transportation (Oldham et al., 2017).

Related studies have analyzed air transportation network robustness mainly against node/link failures (Wang et al., 2014; Woolley-Meza et al., 2013; Wuellner et al., 2010), where node failure refers to airport closure and link failure refers to the cancellation of a flight. Most of these techniques perform either random attacks or they attack nodes in the network using some type of node ranking as a guiding strategy, following traditional complex network-based view (Fang et al., 2014). Examples for such rankings are degree (the number of incoming/outgoing links) or betweenness (the centrality of a node according to how many shortest paths it is located on). Other works also consider the closure of airports based on spatial distance from a given epicenter (Woolley-Meza et al., 2013); and link attacking strategies (Wuellner et al., 2010). Moreover, all these studies focus on the negative effects of airport network disruptions, with a strong emphasis on airports. Finally, there is a large body of literature on other cyber-physical systems, e.g., power-grids (Wang and Rong, 2009, 2011; Ouyang and Dueñas-Osorio, 2014; Ouyang et al., 2014; Zhang et al., 2015) and ground transportation networks (Jenelius et al., 2006; Ouyang et al., 2014; Yang et al., 2015; Hong et al., 2015, 2017) (see Ouyang, 2014 for a recent review), or other transportation infrastructure elements (qi Tong et al., 2017; Hickey and Collins, 2017; Goerlandt et al., 2017; Wang et al., 2013).

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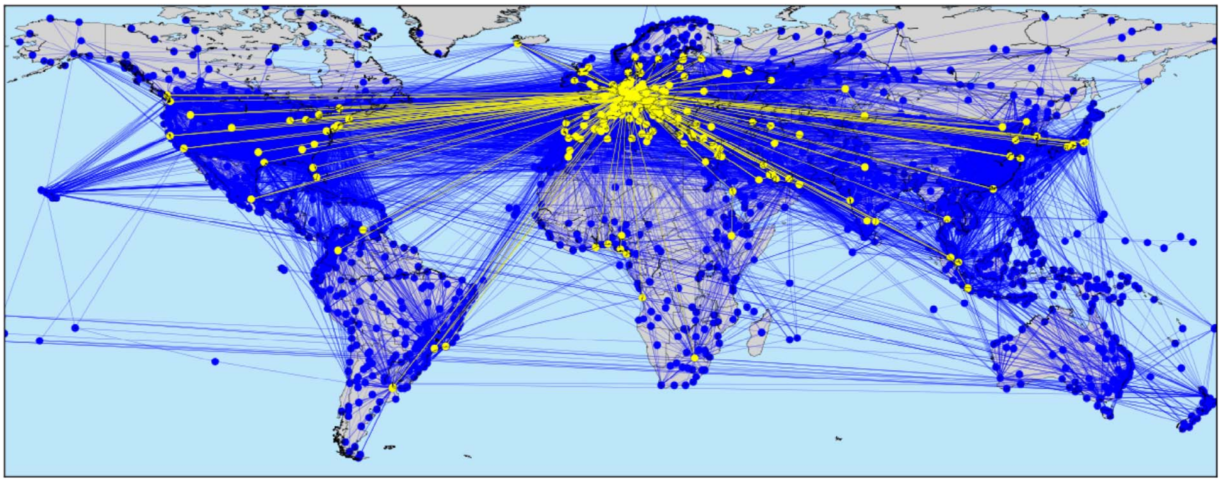

**Fig. 1.** An overview on the worldwide airport network for August 2015. Airports are represented by blue circles and direct flight connections by blue lines. The airline network for Lufthansa is highlighted in yellow color. Many of the connections for Lufthansa originate from the European airspace, particularly from the two Airports Frankfurt and Munich. (Data source: Sabre Airport Data Intelligence, ADI). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In this study, we investigate the robustness of individual airlines and the complementary strengths of airlines to compensate for airline network disruptions. We define a topology-induced notion of static complementary strength to evaluate the pairwise ability of airlines to help each other during disruptions. Extending this view towards a more realistic model, we take into account passengers and rerouting under disruptions. Based on worldwide airline data for August 2015, we show how the top 250 airlines are interconnected and how their complementary strength can be possibly exploited to prevent large-scale disasters. Our work contributes towards improving air transportation systems, by taking a novel view of airline disruptions and their complementary effects (see Fig. 1).

This paper is organized as follows. Section 2 summarizes the literature on resilience analysis of air transport networks. Individual airline networks and their robustness against disruptions is studied in Section 3. Section 4 assesses the complementary robustness of airline networks in a global context. Finally, conclusions are discussed in Section 5.

## 2. Literature review

The robustness of worldwide air transport network as a single layer, i.e., ignoring airlines, was analyzed with comparison of several different robustness measures and attacking strategies (Sun et al., 2017). It was found that degree and Bonacich based attacks harm passenger weighted network most; with a new notation of robustness metric originating from the function of air transport: Unaffected passengers with rerouting. The robustness of US air transport network was studied (Yang et al., 2015), using attacking strategies based on degree, betweenness, closeness, and HITS (Hyperlink Induced Topic Search), with the size of giant component as the robustness measure. A new exploration/exploitation search technique for a computationally efficient attacking model was proposed in Wandelt et al. (2015); four real-world domestic air transport networks were presented to analyze the scalability of the proposed techniques. With an estimated number of stranded passengers in the giant component as a robustness metric, Louzada et al. proposed reroute of flights within certain distances of original destination airports in order to improve the resilience of worldwide air transport system under targeted node attacks (Louzada et al., 2015). Robustness of Australian air transport network was investigated under random attacks and degree/betweenness/strength targeted attacks, with the size of giant component and network reachability as robustness measures (Hossain et al., 2013). The worldwide air transport network was studied under random attacks as well as degree and betweenness-based attacks; with shortest average path length and the size of giant component as robustness measures (Frohn, 2012). The flight routes addition/deletion problem was introduced and algebraic connectivity was used as the robustness measure to optimize the network robustness; with the Virgin America network as a case study (Wei et al., 2014,; Wei and Sun, 2011). Essentially, all these measures investigate node/link failures and largely ignore the multi-layer structure.

Individual structures of seven US largest passenger airline networks were analyzed (Wuellner et al., 2010); the networks' resilience to random node/edge deletion and targeted node deletion based on degree/betweenness were examined as well. The size of giant component and a relative global travel cost were used to quantify the network performance under various deletion processes. Cardillo et al. analyzed the resilience of European air transport network against random edge failures (flight cancellation), with each airline as an interdependent network (Cardillo et al., 2013). The re-scheduling of the passengers who are affected by random edge failures has been considered; rescheduled passengers are divided into three groups: those who cannot fly, those who can fly via an alternative path with the same airline, the ones who have to switch airlines. It was shown that the multi-layer structure strongly reduces the system's resilience under disruptions. Note that this paper focused on the effects of layered structures on the resilience of the European air transport. Zhao et al. evaluated the robustness of multiplex networks under layer node-based random and targeted attacks (Zhao et al., 2016), with the size of giant component as the robustness measure. It was found that layer node-based attack makes the multiplex networks less robust. These works are most similar to ours, yet, none of them focuses on the complementary effects at the world-wide scale.

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, but otherwise breaks down completely due to removal of short insignificant connections (Verma et al., 2014). The eruption of volcano Eyjafjallajoekull, the September 11th terrorist attacks, and geographical disruptions in the worldwide air transport system were investigated; effective distance (Brockmann et al., 2013) was used to quantify the impact of these disruptions on the network (Woolley-Meza et al., 2013).

## 3. Individual airline networks and their robustness

We present an overview of the airlines used in our study in Table 1; the names of all 250 airlines and their IATA codes are summarized in Table 3 in the Appendix. In total, we analyze the top 250 airlines,