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# Delay causality network in air transport systems

Wen-Bo Du[a], Ming-Yuan Zhang[a,b], Yu Zhang[c], Xian-Bin Cao[a,*], Jun Zhang[d,*]

[a] School of Electronic and Information Engineering, Beihang University, Beijing 100191, PR China
[b] Shen Yuan Honors College, Beihang University, Beijing 100191, PR China
[c] Department of Civil and Environmental Engineering, University of South Florida, 4202 E. Fowler Avenue, Tampa, FL 33620, USA
[d] Beijing Institute of Technology, Beijing 100081, PR China

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ABSTRACT

To better understand the mechanism of flight delay propagation at the system-level, we built a delay causality network (DCN) based on the Granger causality test. Through topological analysis of DCNs, we found that only about a quarter of airports were involved in delay propagation during the peak travel period and large airports affected by many upstream airports impact fewer downstream airports. Furthermore, temporal analysis of DCNs indicates that the culprits of delay propagation in the air transport system are not a fixed set of airports; instead, they vary daily depending on the operational environment.

## 1. Introduction

With increasing globalization, the world's civil aviation industry has been growing at a fast pace (Barnhart et al., 2009). The flight delay problems that have resulted from the rapid development of the civil aviation industry have become a worldwide challenge (Czerny, 2010). Flight delays have negative impacts on several aspects, such as passengers, airlines, and air transport systems (Ahmadbeygi et al., 2008). Delayed flights throw travel plans into disarray, often making passengers dissatisfied with the airlines (Britto et al., 2012). Airline companies also suffer, not only paying for the resource waste caused by delays but also having to invest more to improve passenger satisfaction (Zou and Hansen, 2014). Due to flight delays, air transport systems are faced with reduced efficiency and increased security risk, leading to economic loss and environmental pollution (JEC report, 2008). A recent study reported that the total direct cost induced by flight delays was nearly $28.9 billion in the United States in 2007 (Ball et al., 2010) (see Table 1).

An initial flight delay can be attributed to several reasons, such as air carrier issues, extreme weather, air traffic control, etc. (BTS report, 2017). However, a propagated delay occurs because of connected resources (Kafle and Zou, 2016). The most common resource is aircraft (Zou and Hansen, 2014). Because the same aircraft flies multiple flight legs, the delay of an earlier flight can affect the subsequent flights of the same aircraft (Lan et al., 2006). If passengers are not free from a previous delayed flight, the next flight will be delayed by waiting for it. Flight crews also switch between different aircraft, causing the delay from one flight to propagate across multiple flights (Beatty et al., 1999; Wang et al., 2017). For these reasons, a small initial delay may lead to larger delays later, inducing much worse situations (Li et al., 2014; Meng and Zhou, 2011). Therefore, research on the mechanism of delay propagation is timely yet challenging.

* Corresponding authors.
*E-mail addresses:* xbcao@buaa.edu.cn (X.-B. Cao), buaazhangjun@vip.sina.com (J. Zhang).

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**Table 1**
The Granger test results.

| Pairwise test | F-statistic | P-value | Hypothesis | GC relationship |
|---|---|---|---|---|
| 1–2 | 2.256 | 0.127 | Accept | Not exist |
| 1–3 | 1.764 | 0.200 | Accept | Not exist |
| 1–4 | 1.139 | 0.368 | Accept | Not exist |
| 2–1 | 0.223 | 0.879 | Accept | Not exist |
| 2–3 | 1.069 | 0.394 | Accept | Not exist |
| 2–4 | 0.368 | 0.777 | Accept | Not exist |
| **3–1** | **4.644** | **0.019** | **Reject** | **Exist** |
| 3–2 | 0.955 | 0.441 | Accept | Not exist |
| 3–4 | 0.558 | 0.651 | Accept | Not exist |
| 4–1 | 0.840 | 0.494 | Accept | Not exist |
| 4–2 | 0.358 | 0.784 | Accept | Not exist |
| 4–3 | 0.829 | 0.500 | Accept | Not exist |

### 1.1. Literature review

The traditional Approximate Network Delays (AND) model was originally conceptualized in a prototype form of three-airport networks (Malone, 1995). Pyrgiotis et al. (2013) enriched the AND model and investigated the delay propagation based on 34 US airports. Their results showed that delay propagation tends to mitigate daily airport demand profiles and push more demands into late evening hours. Zhang and Nayak (2010, 2011) used the multivariate simultaneous equation regression (MSER) model to study the impact of a single airport on the others, and vice versa. Their results revealed that major airports have a higher impact on the average delay. Later, Hao et al. (2014) used the MSER model and the Federal Aviation Administration (FAA) system-wide analysis capability (SWAC) simulation model to quantify the impact of the three airports in the New York area on delays throughout the airport network, finding that the delays within the New York area are lower than expected. Fleurquin et al. (2013) developed the maximum connected subgraph of congested airports for assessing the level of delays across the entire system. They also introduced a model that comprehends aircraft rotation, passenger connectivity, and airport congestion as well as crew rotation to simulate the propagation of delays. This model can simulate the congestion of the system accurately. Then, they proposed a new model involving slot reallocation and swapping to simulate the propagation of reactionary delays in Europe (Campanelli et al., 2014). Afterward, Campanelli et al. (2016) used these two models to simulate flight delay propagation and assessed the effect of disruptions in the US and European aviation networks.

Despite the advances in understanding flight delay propagation, few studies have investigated delay propagation by considering the interdependence relationship of delay time-series. Thus, a systematic framework probing the causal relationship among airports continues to be elusive. Recent years have witnessed a growing interest in the inference of causal interactions (Wahl et al., 2017; Stokes and Purdon, 2017) in complex systems. Thanks to theoretical innovation, the application fields of causality tests have grown to include biology (Stokes and Purdon, 2017), ecology (Sugihara et al., 2012), social sciences (Frank et al., 2018), physics (Martin et al., 2016) and economics (Song et al., 2008). All of these studies have a common theme: the details of the temporal mutual influence of units are difficult to understand, and causality tests are used to detect the interaction patterns in dynamical systems by time series analysis. All of the prior results have shown that causality tests yield new insights into large-scale complex systems.

The air transportation system is also a typical large-scale complex system. Due to its complexity, the mechanisms of delay propagation are not fully understood, especially for the interdependencies of different airports. Causal analysis may provide a new perspective on this problem. In this study, we adopted Granger causality (Granger, 1969) as the main method due to its primary advance on the causation problem (Frank et al., 2018). Then we built a delay causality network (DCN) based on the Granger causality test and investigated the topological and temporal properties of the DCNs, offering insights into the features of specific airports.

### 1.2. Contributions and outline

We apply a theoretical framework of causality test to study the delay propagation of the complex airport system. By considering delay propagation problem from the perspective of delay time-series interdependence, this approach can capture the interaction patterns of delay between different airport pairs. Due to the large number of airports and their complex relationships, the features of delay propagation cannot be understood from information at the individual airport level alone. We construct DCNs to characterize the global structure and dynamics of delay propagation, revealing the direction and range of delay propagation at the network-level. Although air transport system have been abstracted to a directed/undirected, weighted/unweighted network in previous studies (Wang et al., 2016), existing studies have mostly considered static graphs, meaning that the dynamics of the network were could not explicitly be considered explicitly (Ren and Li, 2018). In our research, the edges of DCN are the results of daily temporal interactions, representing the functional connectivity and underlying operational conditions. Theory and application of complex networks are used to further reveal the properties of DCNs. We use the degree, reciprocity, clustering coefficient, community, and other metrics of complex network to describe the situation of delay propagation and find that only about a quarter of airports in China face delay propagation during the peak travel period in China. The results also reveal that large airports affected by many upstream airports actually impact fewer downstream airports. By studying the connected clusters formed by high-degree airports, we find that the