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# Comparing the modeling of delay propagation in the US and European air traffic networks

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A B S T R A C T

Complex Systems are those in which a very large number of elements interact, usually in a non-linear fashion, producing emergent behaviors that are typically difficult to predict. Air transportation systems fall in this category, with a large number of aircraft following a pre-scheduled program. It has been shown that it is possible to understand and forecast delays propagation in these systems. The objective of this analysis is to compare the modeling in the US and in the European air traffic networks, analyzing the propagation of delays due to failures in the schedule or to disturbances. We use two different agent based models recently developed to simulate the delays propagation and assess the effect of disruptions in the networks (US and ECAC areas). Our results show that a first-come first-served protocol managing the flights produces larger congestion when compared with an ATFM (Air Traffic Flow Management) slots priority system.



## 1. Introduction

Among all the different means of transport, air transportation is the one that has experienced the fastest growth in the last century (Heppenheimer, 1995). According to the World Bank, in 2014 the number of domestic and international air passengers summed up 3.21 billions worldwide (World Bank, 2015), and it is expected to increase by 6.3% this year (ICAO, 2015). The rapid increase in demand comes at a high price, causing the transport network to become congested (Lan et al., 2006) (see also the evolution of the delays in Europe from the CODA digests of Eurocontrol since 1998 until the present (CODA). It is therefore of great importance to understand the interplay between the various components of the system. Delays are one of these components and have a great economic impact, a study for the US found that the costs imputable directly or indirectly to delays were around 40.7 billion dollars (US Congress, 2008). Delay related direct costs in Europe may look modest in comparison (1.25 billion euros) but still high (Cook and Tanner, 2011; Note).

The intricacy and interaction between the elements that compose the air-traffic system qualifies it as a Complex System. Complexity is not used just to refer to complicated phenomena within Science; it emphasizes the notion of emergent behavior at the system level that surges from the interaction between its components. During the last decade, the scientific community has extensively studied these systems under the light of Network Science. In this context, air-traffic systems can be represented as networks whose vertices represent airports and its edges direct flights during a fixed period of time (Barrat et al., 2004; Li and Cai, 2004; Guimerà et al., 2005; Burghouwt and de Wit, 2005; Balcan et al., 2009; Gautreau et al., 2009). Several aspects of the air traffic network have been studied. The first works (Barrat et al., 2004; Guimerà et al., 2005) were focused on a topological description of the network structure. The results showed a high heterogeneity in the number of connections that bear each node (the so-called degree of a node) and the traffic sustained by each connection, finding a non-linear relation between the node degree and the fluxes of passengers in a given route (Barrat et al., 2004). The Air Transportation Network can also be understood as the backbone where different dynamical processes take place. A story of notable success was the modeling and forecasting of disease spreading using air traffic data (Balcan et al., 2009).

Delay propagation dynamics can be also studied within this framework (Fleurquin et al., 2013, 2013b; 2014, 2014b; Campanelli

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et al., 2014, 2015). Since airlines operate in an interconnected network, they are subject to propagation effects. A disruption in one flight or airport can quickly spread and multiply in cascade affecting other parts of the air transport network (Beatty et al., 1998; Allan et al., 2001; AhmadBeygi et al., 2008; Belobaba et al., 2009). The delay between flights may propagate due to several mechanisms: aircraft rotations, passengers and crew connections, or airport congestion. These factors are at the basis of the models developed to reproduce delay propagation.

Understanding how delays propagate in the airport network starting from primary events is thus of high economic relevance. In the last years, we have introduced two agent-based models to study and forecast delay propagation in the US and European networks (Fleurquin et al., 2013; Campanelli et al., 2014, 2015). The main difference between them is the method to prioritize the flight management in the airports. While in the US model a first-come first-served (FCFS) protocol is used, in Europe an ATFM (Air Traffic Flow Management) slot system is simulated (SM). This applies to the tactical phase of the flights and compresses processes such as slot reallocation and swapping. The purpose of this work is to compare the performance of the networks with each of these management systems. For this and since the models are data-driven, two days with large network congestion not caused by external disturbances have been selected: June 20, 2013, in Europe, and July 13, 2012, in the US. Both models are run in the same conditions and the results compared. Comparisons between the US and European networks have been carried out in the last years (Reynolds-Feighan, 2010; Vilaplana, 2010; Eurocontrol and FAA, 2013). Eurocontrol and the Federal Aviation Administration (FAA) published a joint report on the similarities and differences in ATM performance between the two areas (Eurocontrol and FAA, 2013). These studies take an empirical data analysis perspective, while this work is focused on the comparison of the ATM systems simulating both management systems in standardized conditions.

## 2. Materials and methods

### 2.1. Metrics

The results in this paper are analyzed in terms of two kinds of performance metrics. While the first one is the straightforward total cumulative delay in the system as a function of time, the second is less conventional, and it is intended to assess the level of network delays. We have previously used it in other works concerning network-wide congestion and delay statistics (Fleurquin et al., 2013, 2013b; 2014, 2014b Campanelli et al., 2014, 2015). First, we build a daily (unweighted) airport network using direct flights as edges. Then, for each hour of the day, we extract the subnetwork containing the airports where the average hourly departure delay is above a given threshold, the value of which should be calculated over a long time period (e.g. a year or several months), so that the properties of the network can be analyzed in a stable way. As in all the metrics based on an arbitrary threshold selection, the exact results may depend on the particular value used but the general system trends must be consistent. We refer to the airports where the threshold is exceeded as *congested airports*, and use the size of the largest connected cluster found in the congested subnetwork as an indicator of the presence of network-wide problems. It should be noted that this quantity contains information about correlation, not causation: two airports connected in the same congested cluster may be affected by each other, but the source of the delay is not identified.

### 2.2. FCFS (US) model

We will describe next the elements of the models starting by the simplest: the FCFS model adapted to the US air traffic. A detailed description of the modeling framework is provided at (Fleurquin et al., 2013). This model, as the SM one, needs as inputs the daily schedules of the flights that are typically extracted from flight performance data. A more detailed description of the datasets is provided in Section 2.4, but essentially the inputs needed are the scheduled arrival and departure times, aircraft and airline identification codes, flights' origins and destinations, the airport capacities and the flights primary delays. Cancellations and diverted flights are not used in the model. With the aircraft code and the spatio-temporal information of the flights obtained from the data, we can reconstruct the aircraft rotations and consequently approximate the airline schedules throughout the day.

The model takes as basic units the aircraft and follows them as they complete the daily schedule. The minimum time resolution in the airport operations is 1 min. In the absence of disruption (primary delays) of any kind, daily operations would be carried out exactly as specified in the schedule. The flight operations are generated following three microscopic sub-processes that rule the agents' reaction to each other and the system: aircraft rotation, flight connectivity and airport congestion. The rotation is the itinerary of each aircraft throughout the day, i.e., it goes from airport A to B and then to C following the scheduled arrival and departure times. An aircraft rotation is completed when all the previous legs have been fulfilled sequentially. A flight is not considered finished as far as the aircraft is in the gate-to-gate phase (offblock), which comprehends the taxi-in, taxi-out and airborne time. As a model simplifying assumption, it is not possible to absorb delay offblock.

Once an aircraft is at the gate, in the turn-around phase, it has to comply with a minimum service time ($T_S$) for ground operations. For the sake of simplicity, the value of $T_S$ has been fixed at 30 min. The next model ingredient represents flight connectivity due to crew and passenger connections. It is implemented as a stochastic mechanism due to the lack of information on passenger and crew connections along the day. The fraction of passengers connecting in each airport is estimated from Market Sector Data (DB1B Ticket and T100 Domestic Market repositories of the Bureau of Transportation Statistics (BTS)). Each flight (of the same airline) has a probability of connection proportional, with a factor $\alpha$, to the connectivity levels of each airport. With this in mind, a connection is randomly chosen by considering flights of the same airline within a time window of the scheduled arrival time of 3 h. A flight is able to depart if and only if all its connections have already arrived. Note that the connections are at flight level, they may represent the connections of several passengers or of a single one in first class. The important issue is that once assigned, the flights must wait for their connections. The calibration of $\alpha$ to reproduce the global level of delay in the network provides a way to estimate how many of these flight connections are present in the system. As a simplification, the minimum connecting time for passengers is set to zero. More involved versions of the models (Fleurquin et al., 2013b; Campanelli et al., 2015) have the minimum connecting time into account but this is a feature that can vary from airport to airport and impact differently both models so adding it can render harder the comparison of the models' results.

Airports' capacity is measured as the scheduled airport arrival rate for each hour (SAAR) of the day multiplied by a factor $\beta$. When a perturbation occurs, the demand at the airport may vary and the actual arrival rate can exceed the schedule rate. Whenever this happen the next incoming aircraft will have to wait in order to be served. A queuing protocol based on first-come, first-served (common operating procedure in the US) is implemented in each

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