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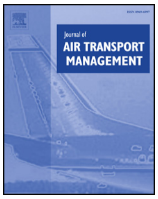

Characterization and prediction of the airport operational saturation

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ABSTRACT

This paper develops a functional analysis of the aircraft flow through the airport operational framework, focusing on the airspace-airside integrated system. In this analysis, we use a dynamic spatial boundary associated with the Extended Terminal Maneuvering Area (E-TMA) concept, so inbound and outbound timestamps can be considered. Aircraft operations are characterized by several temporal milestones, which arise from the combination of a Business Process Model (BPM) for the aircraft flow and the Airport Collaborative Decision Making (A-CDM) methodology. This timestamp approach allows us to study the successive hierarchical tasks. The objective is to establish a taxonomy that classifies the system's capacity to “receive and transmit” aircraft streams with adherence to the expected schedule. By considering the accumulated delay across the different processes and its evolution, several indicators are proposed to evaluate the system's level of saturation and its ability to ensure an appropriate aircraft flow in terms of time-efficiency. Finally, the relationships between the factors that influence the aircraft flow are evaluated to create a probabilistic graphical model, using a Bayesian Network (BN) approach. This model predicts outbound delays given the probability of having different values at the causal control variables. The methodology is developed and validated through a case study at Adolfo Suárez Madrid-Barajas Airport (LEMD): a collection of nearly 34,000 turnaround operations (registered at the peak traffic months of 2016) is used to statistically determine the aircraft path characteristics. The contribution of the paper is twofold: it presents a novel methodological approach to evaluate and predict the system's state at the rotation stage and it also provides insights on the interdependencies between factors influencing performance.

1. Problem statement and motivation

Air transport functionality depends on a complex network architecture, where several facilities, processes and agents are interrelated and interact with each other (Goedeking, 2010). In this large-scale and dynamic system, airports represent the interconnection nodes that help aircraft distribution through the network, enable crew and passenger connectivity and ease transport modal changes (Belobaba et al., 2015).

Potential incidents, failures and delays (due to service disruptions, unexpected events or capacity constraints) may propagate throughout the different nodes of the network, making it vulnerable (Beatty et al., 1999). This situation has led to system-wide congestion problems and has worsened due to the strong growth in the number of airport operations during the last decades (Pyrgiotis et al., 2013).

The economic cost of congestion in this interconnected and sometimes overscheduled network of airports and aircraft is enormous: direct costs due to flight delays in Europe reached €1.25 billion during 2010, according to Cook and Tanner (2014). In the United States, during 2007, the directly or indirectly costs originated by delays were around $32.9 billion (Ball et al., 2010). Furthermore, delays have also a substantial impact on the schedule adherence of airports and airlines, passenger experience, customer satisfaction and system reliability (Bazargan, 2010; Campanelli et al., 2016; Cook et al., 2012b; Deshpande and Arıkan, 2012; Jetzki, 2009).

A significant portion of delay generation occurs at airports, where aircraft connectivity acts as a key driver for delay propagation (Gopalakrishnan et al., 2016). During 2015, in the EUROCONTROL Statistical Reference Area, the share of reactionary delay (due to the late arrival of the aircraft on its previous leg) was 45% of total delay minutes (5.1 min of the 11.3 min average delay per flight) and airline related delays (a category that includes crew connections) accounted for another 28% of delay minutes (EUROCONTROL, 2017). Moreover, 33% of all delayed flights in the United States in 2016 were due to reactionary delays (39% of total delay minutes), while airline delay was

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the cause for another 27% of delayed flights and 33% of total delay minutes (United States Department of Transportation, 2017). "Rotation" (flight cycle through the airport and its surrounding airspace, from inbound to outbound processes) is therefore the stage that has the greatest influence on punctuality within the entire air transport network, and accumulates its impact over the day (Beatty et al., 1999). Hence, this paper focuses on the rotation stage and analyzes the aircraft flow through the airport operational environment, which is the dominant mechanism by which delays propagate through the air transport network (Rebollo and Balakrishnan, 2014).

The evolution of a flight can be described as a sequential flow of events or processes (Katsaros et al., 2013; Schaefer and Noam, 2003; Wu and Caves, 2004a). Each of these events occurs consecutively, and if any of them gets delayed, this may result in subsequent processes also being delayed (unless certain buffers or "slacks" are added into the times allocated to the completion of certain events) (Cook, 2007; Hirst, 2008). In order to analyze the evolution of the aircraft flow and the potential delays in the successive phases, this paper follows a "milestone approach" by assigning completion times to each event. This view, in line with the Airport Collaborative Decision Making (A-CDM) method (EUROCONTROL et al., 2012), allows us to understand the operational performance and the potential saturation of the system. Saturation is here understood as the lack of capacity at the airport-airspace system to "receive and transmit" aircraft flows on time (schedule adherence).

In this analysis we use a dynamic spatial boundary associated with the Extended Terminal Maneuvering Area (E-TMA) concept, which allows us to consider inbound and outbound timestamps. This management boundary (airport centric limit of 200–500 NM) has already been implemented at multiple airports, with a horizon that ranges from around 190 NM for Stockholm to 250 NM for Rome and 350 NM for Heathrow (Bagieu, 2015). The E-TMA (and not just the basic on-ground turnaround path at the airport that connects inbound and outbound flights) is selected in order to integrate delay propagation in the airport system with global delays in the air traffic network. This approach reflects the interaction between airport and airspace processes. The analysis is focused on the aircraft flow-airside operations (Fig. 1).

In time, we restrict actions to a tactical phase (day of operations) in order to consider the primary and initial inefficiencies of the system.

The main objectives of the study are: (a) to analyze the aircraft's flow of processes, in order to define metrics and indicators that enable airport operators and policy makers to assess the system's state (in terms of time-saturation); and (b) to generate a practical probabilistic model that predicts the outbound delay given different explanatory variables.

2. Background and contribution

This paper revises three main topics: the airport-airspace integrated flow of an aircraft, the propagation of delays through the E-TMA processes and the evaluation of the system's efficiency in terms of time-saturation.

A review of the literature about airport-airspace integration illustrates that several prior studies have dealt with the importance of connectivity at airports (Dobruszkes et al., 2017; Fageda and Flores-Fillol, 2016; Redondi and Gudmundsson, 2016; Suau-Sanchez et al., 2016). This paper revises the linkage between inbound and outbound flights by assessing the aircraft operational flow (turnaround integration in the air transport network). This approach is in line with past analyses (Fricke and Schultz, 2009; Katsaros et al., 2013; Oreschko et al., 2014) and with the SESAR's "Airport Transit View" concept (SESAR, 2014a). Our main contribution in this field is the construction of a business process model (BPM) that shapes the airport-airspace integration, by extending the spatial scope to the E-TMA boundaries. Besides, the statistical characterization of the different processes enables us to understand the particularities of the rotation stage.

Regarding delay propagation through the air transport system, a large number of studies showed the complexity of the network (Ciruelos et al., 2015; Cook et al., 2015a; Pyrgiotis et al., 2013) and the potential impact of delays on the system's reliability (Abdelghany et al., 2008, 2004; Delgado and Prats, 2014; Nash, 2008; Prats and Hansen, 2011). Delay propagation is a global process fostered by relationships inside the network: disruptions in one part of the system can disseminate to many others (Gopalakrishnan et al., 2016; Jetzki, 2009). Therefore, network analysis provides a global view of the transmission process (Cook et al., 2015b). Nevertheless, a significant portion of these propagations (45% in 2016 according to EUROCONTROL (2017)) occurs at airports (i.e. the nodes of the system): "rotation" (delayed flight cycles)

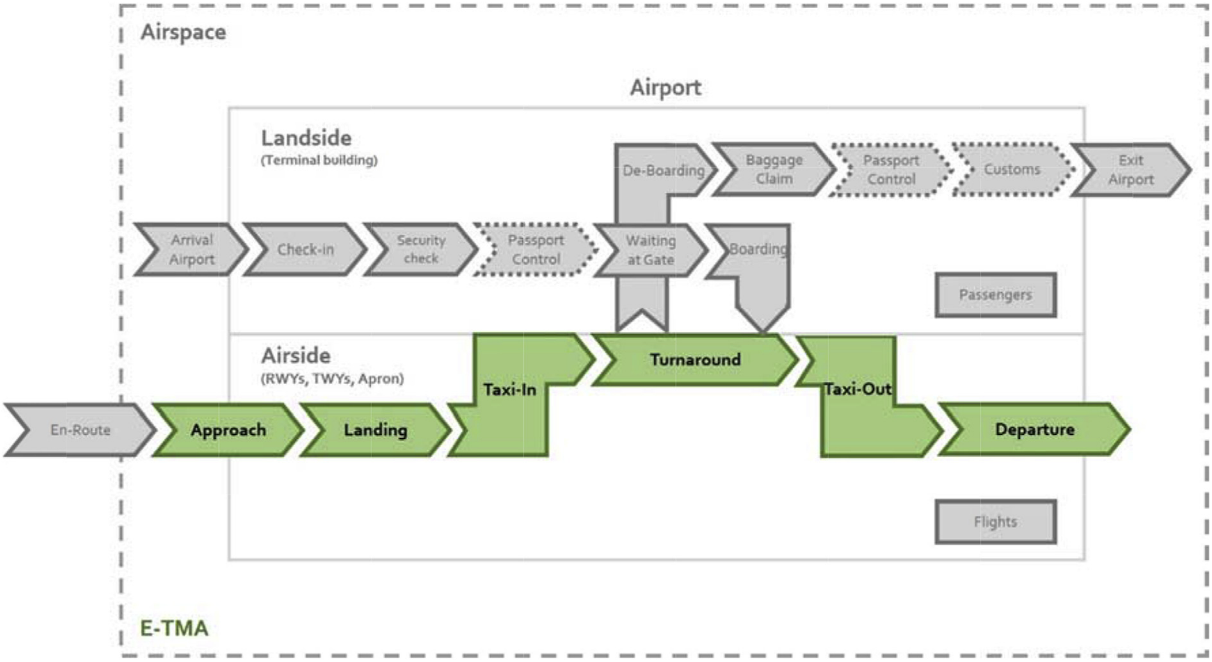

Fig. 1. Spatial scope of the problem.