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Measuring the interactions between air traffic control and flow management using a simulation-based framework

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ABSTRACT

Air traffic in Europe is predicted to increase considerably over the next decades. In this context, we present a study of the interactions between the costs due to ground-holding regulations and the costs due to en-route air traffic control. We dulator that considers the regulation delays, aircraft trajectories, and air conflict resolution. Through intensive simulations based on traffic forecasts extrapolated from French traffic data for 2012, we compute the regulation delays and avoidance maneuvers according to two scenarios: the current regulations and no regulations. The resulting cost analysis highlights the exponential growth in regulation costs that can be expected if the procedures and the airspace capacity do not change. Compared to the delay costs, the costs of the air traffic control are negligible with or without regulation. The analysis reveals the heavy controller workloads when there are no regulations, suggesting the need for regulations that are appropriate for large traffic volumes and an improved ATC system. These observations motivate the design of a third scenario that computes the sector capacities to find a compromise between the increase in the delay costs due to ground-holding regulations and the increase in the controller workload. The results reveal the sensitivity of the delay costs to the sector capacity; this information will be useful for further research into ATM sector capacity and ATC automated tool design. Finally, because of the growing interest in the free flight paradigm, we also perform a traffic and cost analysis for aircraft following direct routes. The results obtained highlight the fuel and time savings and the spatial restrictions that companies use to avoid congested areas.

1. Introduction

The main objectives of air traffic management (ATM) are to ensure flights safety and an efficient organization of traffic flows. Among all the means available to the different actors of ATM, the most commonly used are ground-holding regulations and airborne maneuvers. Both methods are mutually dependent, since a stronger regulation would hopefully induce fewer airborne maneuvers and thus reduce controllers workload. But the costs incurred by the delays due to ground-holding schemes are significantly higher than those of airborne maneuvers, so that reducing those delays seems to be a key target for the actors of air transportation. In this paper, we propose an analysis of these interactions in terms of controllers workload and costs for the airspace users, in the context of increasing air traffic in Europe. The study mainly relies on simulations conducted on various scenarios built upon real traffic data. One important contribution is to justify the need for innovation in ATM practices, and describe a method that sets quantified objectives for future improvement in airspace capacity.

1.1. Context and main concepts

Delays in air traffic can arise from many sources, including the regulations required to avoid congestion on the network. In Europe in 2012, the average delay due to regulations reached 1.15 min per flight (EUROCONTROL, 2012). According to the latest long-term forecast issued by EUROCONTROL (Eurocontrol - STATFOR, 2013), traffic volumes are predicted to increase by 20–80% between 2012 and 2035, resulting in much higher congestion around and

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between airports and increased regulation delays. Joint European projects that are currently underway aim to remodel air traffic management (ATM) in Europe to adapt it to future traffic flow characteristics. Many of these projects are included in the SESAR (Single European Sky ATM Research) program (SESAR Joint Undertaking, 2012).

Currently, the European ATM system is composed of several layers with different time horizons, aiming to safely and efficiently handle the flow of aircraft. A few months in advance, the airspace management filter is triggered. It defines the structure of the route network and the navigation procedures. The airspace is divided into control sectors, which are three-dimensional regions that are each the responsibility of a pair of controllers.

To maintain the workload of the controllers at an acceptable level, each control sector has a *capacity*, defined as the maximum number of aircraft entering the sector in one hour (typically, between 20 and 40 aircraft per hour for a control sector in Europe). Airspace capacity estimation methods have already been developed. A study estimating the airspace capacity in Europe as a combination of different types of air traffic movement in different sectors has been performed (Majumdar, Ochieng, & Polak, 2002). More recently, a simulation-based approach has been designed by Steiner and Krozel (2009). They used ensemble-based weather forecasts to generate probability distributions of airspace capacities. Their model has been extended by Clarke, Solak, Ren, and Vela (2013), who developed a more general model including an air traffic control (ATC) module and capturing traffic-related uncertainties. However, they did not analyze the costs incurred or the impact on the network.

From a few days to a few hours in advance, air traffic flow management (ATFM) regulates the traffic to enforce the sector capacities. This task is assigned to the Central Flow Management Unit (CFMU), whose work relies on traffic predictions based on pilots' flight plans. During peak periods, the CFMU issues ground-holding regulations for flights over congested areas of the airspace by automatically assigning take-off slots via the computer assisted slot allocation (CASA) algorithm, which works in a greedy *first-planned, first-served* fashion. The ground-holding problem (GHP) was defined in 1994 by Vranas, Bertsimas, and Odoni (1994) and has been widely studied since. The techniques in the articles include stochastic models (Mukherjee & Hansen, 2007) and shortest path problems (Vranas, Bertsimas, & Odoni, 1994). Since congestion in the United States is primarily related to important hubs whereas in Europe both airspace and airport capacities can cause congestion issues, most studies focus on European traffic. For instance, the difficulties and potential improvement points of European ATFM have been studied in Lulli and Odoni (2007).

ATC aims to manage air traffic on a short-term horizon. The main tasks of the controllers are to monitor the traffic and to keep the aircraft separated by at least 5 nm horizontally or 1000 ft vertically, as depicted in Fig. 1. To resolve conflict situations, i.e., to avoid predicted losses of separation between two or more aircraft, the controllers issue maneuvers to the pilots. These maneuvers

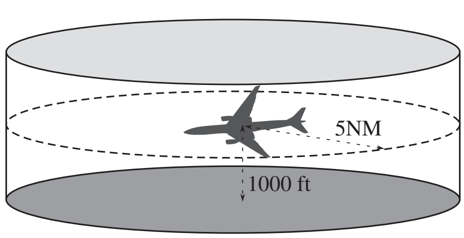

Fig. 1. Vertical and horizontal separation. No other aircraft can be inside the cylinder at the same time.

involve changes in the speed, heading, or flight level, and they induce costs due to fuel consumption and delays.

A study of traffic complexity (Kopardekar, Prevot, & Jastrzebski, 2008) states that if the traffic density should double compared to the current situation, then no controller would be able to monitor and issue maneuvers without an automated tool, which indicates the need for optimization in this domain. Automated ATC has been thoroughly studied, and numerous algorithms have been developed. The literature on aircraft conflict detection and resolution is vast; the techniques applied include mixed integer linear programming (Lehouillier et al., 2016; Omer & Farges, 2013; Vela et al., 2011), nonlinear programming (Alonso-Ayuso, Escudero, & Martin-Campo, 2012; Raghunathan, Gopal, Subramanian, Biegler, & Samad, 2004), metaheuristics (Alonso-Ayuso, Escudero, Martín-Campo, & Mladenović, 2014; Durand, Alliot, & Noailles, 1996), semidefinite programming (Frazzoli, Mao, Oh, & Feron, 1999), and force field models (Hoekstra, Gent, & Ruigrok, 1998). See Martin-Campo (2010) for a comprehensive survey. Research has been conducted to test conflict resolution in a context of growing traffic. For instance, Farley and Erzberger (2007) base their computational tests on future traffic.

1.2. Contribution statement

Our literature review highlights that significant progress has been achieved at all levels of decision of ATM. To push the research further, more bridges between those levels have to be built. In other words, a better understanding of the interactions between the different decision levels would help the improvement of the ATM system as a whole. More specifically, a study focusing on these interactions in a context of extrapolated traffic would be of great value to the field, since it would be fundamental for a better understanding of future situations and their inherent difficulties. To find possible solutions to these upcoming challenges, the knowledge of the aforementioned interactions could highlight key features needed from future optimization tools, and could drive the research towards the main subjects of improvement. Despite the diversity of the literature, we have found few work aiming at filling these gaps.

Our motivation is twofold. We first want to identify the main bottlenecks in terms of costs and security in ATFM and ATC. For this, our approach is to apply a progressive increase in the traffic volume using the reference values of Eurocontrol - STATFOR (2013) and Eurocontrol - STATFOR (2010), and analyze the evolution of the ATFM and ATC costs, and that of the controllers' workload. For ATFM, we focus on the ground-holding and the delay costs, whereas for ATC we study the avoidance maneuver costs and the controller workload. This analysis relies on two extreme scenarios that consist in keeping ground-holding regulation as is, with current airspace capacity, or not performing any ground-holding regulation. Besides their simplicity, the virtue of these extreme scenarios is that they highlight the most pronounced trends in the interactions between ground-holding regulations and ATC. In a second step, we aim at studying how quantified objectives could be set for a continuous improvement of ATM. Our main premise in this study is that the delay costs due to ground holding regulations should not grow faster than linearly with the increase of traffic. For this, we design a scenario controlling the growth in ground-holding costs with an increase in sector capacities. The capacity values computed allow us to determine objectives for research on ATM improvement.

The paper is organized as follows. Section 2 describes the experimental setup of the study, providing details about the automated tools, traffic scenarios and the ground-holding cost model and controller's workload measures we used in our simulations. Section 3 presents the results obtained by simulating traffic with current air-