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An efficient algorithm for smoothing airspace congestion by fine-tuning take-off times

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A B S T R A C T

Current technological advances in communications and navigation have improved air traffic management (ATM) with new decision support tools to balance airspace capacity with user demands. Despite agreements achieved in flying reference business trajectories (RBTs) among different stakeholders, tight spatio-temporal connectivity between trajectories in dense sectors can cause perturbations that might introduce time or space deviations into the original RBTs, thus potentially affecting other 4D trajectories. In this paper, several challenging results are presented by properly tuning the Calculated Take-Off Times (CTOTs) as a tool for mitigating the propagation of perturbations between trajectories that can readily appear in dense sectors. Based on the identification of "collective microregions", a tool for predicting potential spatio-temporal concurrence events between trajectories over the European airspace was developed, together with a CTOT algorithm to sequence the departures that preserve the scheduled slots while relaxing tight trajectory interactions. The algorithm was tested by considering a realistic scenario (designed and analyzed in the STREAM project (Stream, 2013)) to evaluate relevant ATM KPIs that provide aggregated information about the sensitivity of the system to trajectory interactions, taking into account the system dynamics at a network level. The proposed approach contributes to enhancing the ATM capacity of airports to mitigate network perturbations.

1. Introduction

The level of saturation at different periods in some air traffic sectors in the European airspace, together with the predicted growth in air traffic demand, requires a new design for decision support systems (DSSs) to improve certain procedures of air traffic management (ATM).

One of the most important challenges of the SESAR (Sesar program, 2013) and Next Gen (Next Gen program, 2013) programs regarding current ATM is the introduction of trajectory-based operations (TBO), which involve the use of 4D trajectories (defined by consecutive waypoints in three spatial dimensions and their corresponding time-stamps), also known as business trajectories (BTs) according to SESAR's terminology for civil flights. It is expected that the use of 4D trajectories and the underlying new ATM procedures will improve the synchronization and predictability of the air transportation system (Korn et al., 2006).

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Currently, if an imbalance is predicted on the day of operations between the traffic demand and the available airspace capacity, the ATM authority (i.e., the ATFCM) issues a *regulation* to maximize the rate of flights entering the ATM sectors at a given time. When the *regulation* delays flight departures (Castelli et al., 2011), the delays are often known as *green delays* (Piera et al., 2014).

As alternatives to the ATM *regulations*, air traffic controllers (ATCOs) frequently issue maneuvers at a tactical level consisting of holding stacks, headings or speed variations (ATFCM Services, 2013); unfortunately, such maneuvers are often not considered desirable measures by AUs due to high operational and fuel consumption costs (i.e., airborne delays, when incurred, dominate ground delay costs (Ferguson et al., 2013). *Green delays* are therefore deemed more acceptable alternatives (Carlier et al., 2007).

The purpose of this ground-holding scheme is to respect the en route capacity constraints provided by each ATC center (ATCC) as the number of aircraft that can coexist in the same sector within a given time frame, based on their daily schedule. The number of aircraft in a sector is the air traffic characteristic that has been most cited, studied and evaluated in terms of its influence on workload (Prandini et al., 2011). However, a limitation of this *regulation* model is that the definition of the sector's capacity (the hourly rate of aircraft entering a sector) is poorly related to traffic complexity (Barnier et al., 2001). To capture ATC complexity more accurately, it is necessary to consider the flight characteristics of each individual aircraft and interactions between aircraft pairs. (Djokic et al., 2010)

Air traffic complexity can be measured by the control activity required to accept an additional aircraft entering a sector (Lee et al., 2007) (i.e., local complexity). From a network perspective, global complexity is related to the interactions between trajectories (i.e., all en route potential conflicts).

Due to the high degree of connectivity in air traffic networks (Lu and Shi, 2007), it is expected that only if global traffic complexity is considered can all potential interactions be identified.

Domino effects (Ruiz et al., 2014), together with a lack of complete understanding and a suitable formalism for modeling these interactions, are key elements that often lead to the introduction of negative network effects (i.e., ground holding based solely on local complexity information) and the impossibility of taking advantage of positive network effects (i.e., ground holding to improve the network's robustness).Thus, even small delays can easily propagate through trajectories (Pyrgiotis et al., 2013), leading to regulations that could be avoided (e.g., the application of unnecessary delays and/or airborne holding procedures) and the underuse of sectors (European Commission, 2013).

In this paper, by identifying "collective microregions" (square cells of six NM used by two or more flights at the same Flight Level (FL), independent of occupancy time window) and the analysis of occupancy time windows (i.e., temporal-longitudinal looseness (Ruiz et al., 2012), the volume of potential concurrence events that could require controller intervention is determined. Furthermore, an algorithm that can mitigate the effect of potential spatio-temporal concurrence events (i.e., congestion) between any two interacting trajectories is proposed. This algorithm preserves all pre-assigned slots by computing and applying "fine-tuning" (i.e., time offsets of [0, 15] minutes) on the Calculated Take-Off Times (CTOTs).

The proposed algorithm allows for the analysis of the interactions among en route trajectories (i.e., loss of due safety distance between the geometric description of flight paths) to calculate "clearance" and "overlapping" time windows along the complete flight paths, thus predicting potential "concurrence events" (i.e., conflicts) and/or the longitudinal looseness for each trajectory (assuming TBO). With this approach, the proposed algorithm seeks to help ATM incorporate new strategies based on complete interaction-causal analysis to improve decision-making processes.

The paper is organized as follows. Section 2 provides a literature review. Section 3 describes the algorithm. Experimental results for a realistic scenario are reported in Section 4, and conclusions and opportunities for further work are discussed in Section 5.

2. Literature review

Traffic assignment techniques have been developed to reduce congestion in transportation networks by distributing traffic demand across time and space (Delahaye et al., 2005). Because congestion indicates that aircraft are occupying the same space at the same time, it can be reduced by shifting flight trajectories in time (slot re-allocation) or in space (route re-allocation). The following approaches have been developed to solve this general route-time allocation problem: space–time network (Zenios, 1991); variational inequality (Nagurney, 1998); optimal control (Janson et al., 1993); simulation (Cascetta, 1987); integer and dynamic programming (ground-holding problem) (Glover and et al., 2013; Maugis, 1996); and more recently, the collaborative en route resource allocation model (Combined Trajectory Options Program) (Kim et al., 2013) and airspace planning and design based on conflict risk assessment (Netjasov et al., 2013) have been investigated.

Slot allocation problems focused on controllers' workload using constraint programming (CP) technology are discussed in Barnier et al. (2001). Multi-sector complexity planning resolution using CP technology is presented in Flener et al. (2007). In Peeta and Ziliaskopoulos (2001), some of the most relevant dynamic traffic assignment (DTA) methods are analyzed, and path processing modeling approaches are addressed as the core of future DTA development. In Delahaye et al. (2005), the application of multi-objective stochastic methods (i.e., genetic algorithms) on real traffic data, not by using the flow network concept but by simulating the flight of each aircraft, for one day over the French airspace is presented. In Margellos (2012), Monte Carlo simulations and reachability analysis are applied to assess the 4D trajectory concept. Theoretical and