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An optimization model to fit airspace demand considering a spatio-temporal analysis of airspace capacity

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ABSTRACT

The European and U.S. airspace systems are highly congested at certain peak time intervals. Controllers' workloads have reached generally accepted limits; therefore, many highly demanded sectors are subject to traffic regulations and restrictions during many hours of each day. A lack of a spatio-temporal analysis of the airside capacity management tools generates airside delays at the destination airport in the form of holding or path-stretching in terminal manoeuvring areas, or even during the cruise by re-routing. These emergent dynamics are demonstrated every day by the urgent need for new and better tools for analyzing and making strategic and tactical decisions that neither induce delays nor negatively impact daily operations. This paper presents an optimization model for airspace capacity–demand management that performs an efficient departure time bounded adjustment configuration for trajectory based operations. This optimization model is supported by the *4D* trajectories paradigm, in which a discrete event model has been developed to formalize the trajectories' spatio-temporal interdependencies. Based on the elements and parameters declared on the validated *coloured Petri net* model, a set of constraints is obtained. By means of constraint programming, feasible solutions for demand–capacity imbalances are proposed for a case study scenario, while the original departure slots are preserved in addition to the airspace users' preferences. The results obtained show the advantages in terms of capacity and robustness that can be achieved by applying an efficient departure time bounded adjustment configuration.

1. Introduction

Growing air traffic trends necessitate the identification of operational and managing policies for better performance of existing airside capacity (Farhadi et al., 2014). The current method of organizing airspace and balancing demand and capacity is to partition airspace into sectors. This fragmentation of airspace configurations into several *air traffic control* (ATC) boundaries for *air traffic management* (ATM) directly influences the airside capacity utilization, among other impact factors (European Commission Memo, 2013).

Presently, the demand–capacity airside (i.e., ATC sectors) problem is detected by a simple aircraft counter for a time interval. Each sector has a capacity threshold in the form of the maximum number of aircraft at a given time slot. This threshold

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serves as a controller workload limit indicator for each sector without taking into account the traffic complexity (Kopardekar et al., 2008).

At a tactical level, when the lack of airspace capacity is predicted in a certain sector, regulations are applied by holding flights on the ground prior to departure (Helme, 1992). Currently, there are two main ground-delay based tools to tackle the demand–capacity problems:

- *Airspace flow program* (AFP), which applies delays to a subset of flights predicted to fly through a designated flow-constrained area (including one or several sectors) (Business Aviation Association, 2015).
- *Ground delay program* (GDP), in which delays are applied only to a set of flights destined for a single airport (Manley and Sherry, 2010).

A detailed survey of ground-holding policy models for the *air traffic flow management* (ATFM) problem can be consulted in Agustín et al. (2010) and the current European slot allocation system in Castelli et al. (2011). By delaying departures in present GDPs, new problems can be induced:

- *At Airport*: Usually, in congested airports, runways are considered to be one of the main bottlenecks to preserve the programmed landing and departure operations (Idris et al., 1999; Mori, Mar. 2013; Montoya et al., Feb. 2014). Therefore, delaying a certain number of flights due to airspace congestion will generate extra delays once regulations are cancelled, by trying to schedule the departure of the programmed flights along with the previously delayed flights (Delgado and Prats, 2011).
- *At Airspace*: Congestion in sectors depends mainly on the programmed traffic, in terms of spatial and temporal distribution. Thus, a sector B that was properly balanced considering the programmed traffic could become congested when the delayed trajectories expected in the interval [Ts_1 .. Te_1] fly through sector B in the interval [Ts_2 .. Te_2]. (Here, *Ts* and *Te* refer to start and end time stamps, respectively.)

Under existing GDPs, the airlines' operations are often disrupted, which results in a state of 'irregular operations' or route failure (Wei et al., 2014). These may be characterized by significant delays, many cancellations and a large number of disrupted passengers, which are recognized to be highly detrimental to airline profit and passenger welfare (Xiong and Hansen, 2013). Thus, more stringent scheduling procedures may be necessary (Deschinkel et al., 2002), including some form of resources management (i.e., intelligent decision support tools (D'Ariano et al., 2012) to adapt the demand to the available capacity with bounded collateral effects on the airline's operation or narrow passenger disruptions.

In presence of highly demanded airspace spots (Nosedal et al., 2014) (i.e., regions with demand consisting of several trajectories that coexist during the same time frame), the air traffic controllers' intervention (i.e., holding and heading manoeuvres) to handle potential conflicts easily propagates and increases induced ATC workload. The high degree of connectivity in air traffic networks could affect overall network performance with leading to higher operational and fuel consumption costs for the airlines.

To achieve needed capacity, it is necessary to improve ATM procedures to ensure a better synchronization of all air traffic flow (Ruiz et al., 2013; Rodionova et al., 2014). Considerable research efforts have been undertaken, and several operational systems have been developed around the world to address airspace *demand–capacity* imbalances. The underlying principle in each is that *demand–capacity* imbalances should be addressed before the affected flights depart from their originating airports (Churchill and Lovell, 2012).

The technology modernization of *communication*, *navigation and surveillance* (CNS) through international programs, such as SESAR (SESAR, 2015) and NextGen (NEXTGEN, 2015; Brooker, 2008), has enabled a key change in ATFM to a *trajectory based operations* (TBO) approach. Under this approach, airspace users will fly precise *4-dimensional trajectories* (4DTs), involving 3 spatial dimensions plus time, previously agreed upon with the network manager (Wandelt and Sun, 2015). A 4DT, otherwise known as a *business trajectory* (BT), represents a contract between the airline and the network manager such that the aircraft should fly the trajectory, preserving the time stamps specified in the BT (Berechet et al., 2009; Castelli et al., 2011; Enea and Porretta, 2012).

With respect to the airspace, the TBO paradigm (Prevot et al., 2003) enhances the design of new tools to evaluate the demand–capacity balance by the amount of potential controller interventions that can be required in each particular traffic scenario. Thus, the demand–capacity balance of a region – e.g., en route European airspace or the *National Airspace System* (NAS) of the U.S. – can be estimated by considering the amount of potential proximate events (such as loss of safety distances between trajectories with time stamp concurrency) that could emerge due to all the programmed traffic (based on airspace users' preferences). The proximate event zone can be represented by a square cell of 6 NM (0.1 latitude $\times$ 0.1 longitude degrees) and height 1000 feet, values in which aircraft are perceived to pass far enough away from each other to ensure a safe distance (otherwise referred to as 'protected zones' (Huang et al., 2014).

At the airport, the surface traffic automation systems (Mori, 2013; Roling and Visser, 2008) enhance the management of airport surface operations to provide shared situational awareness and to control taxi times through the use of 'virtual queues'. This approach has become an important component of ATM research and development in both Europe and the U.S. (Bhadra et al., 2012; Brinton and Lent, 2012).