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A network based dynamic air traffic flow model for en route airspace system traffic flow optimization

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ABSTRACT

This study proposes a mesoscopic dynamic air traffic model based on a dynamic network for en route airspaces by characterizing the dynamics and distribution of traffic speed. Based on this model, we solve a flow optimization problem for enforcing capacity constraints with the minimum operational cost using a dual decomposition method. A case study of an en route airspace in Shanghai demonstrates the accuracy of the proposed model in successfully capturing the flow dynamics, as well as the effectiveness of the proposed optimization framework to reduce en route delays by balancing the dynamic traffic demand and airspace capacity.

1. Introduction

Global air traffic has grown dramatically during the last few decades, and a recent study from Eurocontrol shows that en route traffic is expected to grow with an annual average rate of 2.5% in the next 7 years (Eurocontrol, 2017). The rapid growth in air traffic with limited airspace resource results in demand-capacity imbalances and flight delays, which may cause potential safety and inefficiency issues in the air traffic control system. To mitigate the imbalance of demand and capacity in air traffic, various automation tools are designed to assist air traffic controllers with decision-making in air traffic flow management (ATFM), with the goal of safe, efficient and cost-effective flow of air traffic. However, most current ATFM tools mainly focus on local regions, e.g. a single airport or sector, while the system-wide decision-making, which takes into account the network effect of those independent decisions, heavily relies on human intuition and past experience of experts (Sun et al., 2011).

To address the system-wide demand-capacity imbalance in ATFM, this paper presents a novel dynamic network air traffic flow model, based on which an efficient en route optimization method is proposed for air traffic on a particular route and in a network of such routes. Unlike most existing air traffic flow models, the proposed model takes into account the dynamic feature of traffic flow speed, and provides a more practical and flexible mechanism to control air traffic flow at both air route and en route network levels.

The controlled airspaces in China are categorized into (1) tower controlled airspace; (2) approach controlled airspace; and (3) en route controlled airspace, where the aircraft are, respectively, in the landing/take-off phase, the approach phase, and the cruise phase. The en route controlled airspace is further partitioned into area sectors, and controllers guide the aircraft in their assigned sectors along the specified air route according to the flight plan. Aircraft in the en route airspace are all in the

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cruise phase, which takes up the longest part of most flights. In addition, delay in en route airspace is likely to accumulate and propagate to its upper stream regions and airports (i.e., the regions and airports where aircraft traverse before they fly into the delayed airspace), and therefore responsible for network impact of local delays. A recent study from Eurocontrol shows that capacity, weather, activity and operation of the en route airspace account for 51.18% of the total flight delays in Europe, which means en route airspace (rather than airport terminal area, surprisingly) is the main reason for ATFM delay in Europe (Eurocontrol, 2015). Advanced and effective ATFM in the en route airspace is thus important to ensure a safe and efficient air transportation system. Motivated by this observation, this paper aims to address the short-term air traffic flow optimization in the en route airspace, by enforcing capacity constraints at the minimum achievable cost. The optimization framework proposed in this paper can be applied to assist air traffic controllers in managing en route traffic flow by providing reliable short-term traffic flow prediction and optimization with the goal of safe, efficient and cost-effective flow of air traffic. Furthermore, the method proposed in this paper can be also used to evaluate airspace performance from the perspective of optimal air traffic operation.

The past few decades have witnessed increased interest in developing ATFM models and tools, which aim to identify and resolve the demand-capacity imbalances through the prediction and optimization of air traffic (ETMS, 2000; Erzberger et al., 1993; Bilimoria et al., 2001; Gong and McNally, 2004; Lymperopoulos et al., 2006; Bertsimas and Patterson, 1998; Corolli et al., 2010; Kopardekar and Green, 2005; Bayen et al., 2002; Ichoua, 2013; Corolli et al., 2014). Trajectory-based models are widely used in the US air traffic control (ATC) system (ETMS, 2000; Erzberger et al., 1993), as well as the Future Air Traffic Management Concepts Evaluation Tool (FACET, a simulation and analysis tool developed at the NASA Ames Research Center) (Bilimoria et al., 2001). The trajectory-based models, which keep track of each individual aircraft, are also known as aircraft-level models. Air traffic demand prediction based on these models is carried out by calculating the total number of aircraft in an airspace by propagating the trajectories of the proposed flights forward in time (Gong and McNally, 2004; Lymperopoulos et al., 2006). The aircraft-level models are also adopted for the optimization of traffic to address the imbalanced demand and capacity. The most well-known aircraft-level optimization model is proposed by Bertsimas and Patterson (Bertsimas and Patterson, 1998). This model introduces binary variables to characterize whether or not a certain flight enters at a certain sector by a certain time. The objective is to minimize the total operational cost of flights under the capacity constraints of sectors in the en route airspace. Corolli et al. introduce time windows for flight operations such that the minimum delay is achieved under capacity constraints (Corolli et al., 2010). Kopardekar et al. compared several control strategies for air traffic optimization, including the trade-offs of implementing altitude capping, local rerouting, ground holding, time-based metering, and miles-in-trail restrictions (Kopardekar and Green, 2005). To predict the corresponding delay with sector capacity constraints, a sector-based traffic flow model using hybrid automata theory is proposed by characterizing the detail of aircraft dynamics under air traffic control commands, such as speed change, heading, and holding patterns (Bayen et al., 2002). More recently, the previous model is further explored by taking into account the dynamic capacity, which is effected by weather conditions, other flights' status, equipment status, etc., to facilitate the optimal operations in various scenarios (Ichoua, 2013; Corolli et al., 2014).

However, the scales of these models, as well as their computational difficulties, depend on the number of aircraft under consideration. This leads to high computational burdens when modeling or attempting to optimize air traffic flow management problems of large but realistic sizes. Furthermore, recent research reveals that the errors of the aircraft-based flow prediction increase sharply when the forecast time horizon exceeds certain threshold, which is caused by model sensitivity to various uncertain factors related to individual aircraft, such as weather, departure management and human factors (Lymperopoulos et al., 2006). Thus, in practice it is difficult to implement a sound on-line ATFM strategy based on the aircraft-level models for large regions or long planning horizons due to the expensive computational cost and limited forecast horizon.

Efficient air traffic flow management requires reasonable prediction and optimum control of flows of aircraft rather than individual aircraft. Therefore, aggregate air traffic flow models, which focus on the overall distribution of the air traffic flow, are introduced recently. Aircrafts are spatially aggregated to airspace volumes according to their geographical location, which means that the scale of the aggregate model depends solely on the number of airspace volumes rather than the number of aircrafts in the airspace. This aggregate method will, thereby, reduce the computational cost significantly when modeling a large but realistic number of flights. In addition, since the microscopic behavior of the individual aircraft is not explicitly considered in the aggregate models, the prediction results tend to be more robust against the aforementioned uncertain factors related to individual aircraft. Thus, a longer forecast time horizon with less prediction errors can be achieved by the aggregate traffic flow models compared to the aircraft-level ones. The aggregate air traffic flow models support a more macroscopic ATFM management and perform more consistent with the Collaborative Decision-Making (CDM) procedure in ATM (Air Traffic Management), which aims to identify and resolve the demand-capacity imbalances by adjusting the aggregate traffic flow to match the capacity resources of the airspace system (Andreatta et al., 2011). Therefore, the aggregate models are suitable to be used to conduct en route traffic flow management at a system-wide level.

The aggregate models are widely discussed in the recent literatures (Sridhar et al., 2004, 2006, 2009; Gilbo et al., 2007; Bloem and Sridhar, 2008; Grabbe and Sridhar, 2005; Andreatta et al., 2011; Sridhar et al., 2008). A stochastic framework with linear dynamic system model is developed by Sridhar et al., where aircraft are aggregated according to their geographic location, e.g., control center. So the scale of this model depends on the number of control centers. Poisson distributions and split parameters, which are estimated from historical traffic data, are introduced to characterize the inflow quantity and the traffic transmission ratio between neighboring control centers, respectively. The established time-invariant model further