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Collaborative air traffic flow management: Incorporating airline preferences in rerouting decisions

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ABSTRACT

This paper discusses the air traffic flow management problem under the new operating paradigm of collaborative rerouting. A route and slot allocation model that incorporates flight operator's disutility cost of rerouting to avoid an impacted airspace is proposed to optimally schedule flights into multiple flow constrained areas. In order to evaluate the benefits of a combined rerouting/ground holding control mechanism and assess the impacts of accounting for airline preferences on individual and aggregate system delays, the model is applied to a realistic case of flow management into LaGuardia Airport under capacity constraints caused by convective weather conditions in the transition airspace. The results show that incorporating rerouting as a control action has the potential to reduce flight delays considerably if compared to traditional ground holding based mechanisms. Moreover, the specific flight operators' inputs regarding route preference and cost of rerouting and the route network characteristics have major contributions to individual and system level efficiency. Finally, efficiency-fairness trade-offs are discussed for the multi-resource allocation process based on different fairness schemes.

1. Introduction

The Air Traffic Management (ATM) system manages a complex network of airport and airspace resources in order to serve thousands of flights daily in a safe and efficient way. Despite the planning efforts for smooth and predictable operations, the dynamic and uncertain behavior of air traffic demand and system capacity often lead to demand-capacity mismatches, imposing significant delays for passengers and costs for the airline industry and the economy as a whole. For instance, system capacity shortfalls caused by inclement weather conditions accounted for 54.06% of the U.S. National Airspace System (NAS) delays in 2016, while 35.17% were attributed to high volume of operations (Bureau of Transportation Statistics of the U.S. Department of Transportation, 2017). In order to correct demand-capacity imbalances and mitigate delays, adjustment of traffic flows is performed on a national or regional basis through different types of Air Traffic Flow Management (ATFM) strategies at strategic (i.e., planning horizons of 2–8 h) and tactical (i.e., real-time to planning horizons of 2 h) time frames. In the U.S., these ATFM strategies are referred to as Traffic Management Initiatives (TMI). Typical strategic TMI include delaying aircraft on the ground at the origin airport via a Ground Delay Program (GDP) when capacity at the destination airport is reduced or via an Airspace Flow Program (AFP) when the aircraft is planned to traverse a Flow Constrained Area (FCA), i.e., an airspace region that is capacity constrained (primarily because of inclement weather). Still at strategic time frame, flights can be rerouted pre-departure to avoid congested or weather impacted areas.

It is a consensus that increased collaboration between flight operators and Air Navigation Service Providers (ANSP) can contribute to generate better ATFM solutions from both individual and system level perspectives. Indeed, Collaborative Decision Making (CDM) arose as a new operating paradigm, characterized by improved information exchange among various parts in the aviation community and improved tools and procedures to enable their participation in ATFM decisions, and became an integral part of the current programs for ATM modernization around the world (e.g., NextGen, SESAR). Currently, CDM is already incorporated in some TMIs. For example, airlines can exchange assigned arrival slots internally or with others, at their own will and according to their priorities, during GDPs. However, flight operators still have low level of control over their trajectories while in the air, especially when they traverse congested or weather impacted areas.

With the aim of increasing the opportunities for CDM practice in ATFM, the Federal Aviation Administration (FAA) has recently launched the Collaborative Trajectory Options Program (CTOP) (Federal Aviation Administration, 2017a). It is a new type of TMI in which not only ground delays but also reroutes are collaboratively assigned to flights pre-departure in order to balance demand with capacity in a FCA. An innovative collaborative approach is proposed as flight

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operators can submit a list of desired routes (Trajectory Options Set – TOS) and indicate an associated cost for each route (Relative Trajectory Cost – RTC) that explicitly incorporates their preferences about the ground delay/rerouting combination to meet a constraint in the system.

In order to best leverage the capabilities of this new program, it is important to better understand their interactions and impacts within the air traffic flow management problem and to develop resource allocation mechanisms that can provide effective solutions. This paper contributes to this goal by presenting an optimization-based approach for the route and slot assignment problem in a CTOP framework with multiple FCAs. The model optimally schedules flights to FCA slots in order to meet capacity constraints and minimize delays and flight operators' disutility costs of rerouting. In order to demonstrate the proposed resource allocation mechanism and investigate the impacts of this new CDM paradigm on traffic flow management, the model is applied to a realistic case of arrival traffic regulation into LaGuardia Airport (LGA) to meet capacity constraints caused by convective weather impacts in the transition airspace. Specifically, we analyze the benefits of CTOP over traditional GDP and AFP programs, provided by the introduction of a rerouting control option, and discuss how incorporating specific flight operators' preferences impact individual and system level efficiency.

2. Literature review and state of the practice

2.1. Air traffic flow management

The problem of adjusting air traffic flows in real time in order to balance demand with capacity has been historically discussed in the literature under the topic of ATFM and was first introduced by Odoni (1987). Because of the complex decision-making nature of this problem, Operations Research techniques have been widely used to develop models that can optimize ATFM decisions. Several analytical models have been conceptualized for the flow management problem at different scales and considering various types of capacitated resources and control mechanisms.

At the national and strategic level, ATFM is typically concerned about regulating flights destined for a capacity constrained airport or planned to traverse a capacity constrained airspace region. The Single Airport Ground Holding Problem (SAGHP) introduced a ground holding control mechanism to manage flows to an airport with degraded capacity. Its underlying motivation is that delaying aircraft on the ground prior departure instead of imposing airborne delays tends to be a better solution in terms of costs and safety. The first formulations of the problem were deterministic and static, in other words, capacity was assumed to be known with certainty and decisions were made once for the entire planning horizon. Stochastic-static models were proposed by Richetta and Odoni (1993) and by Ball et al. (2003) in recognition that uncertainty in airport capacity profiles should be accounted for during the optimization process. In order to also incorporate the ability to revise decisions as updated information becomes available during the planning horizon, dynamic models were proposed by Richetta and Odoni (1994), Mukherjee and Hansen (2007) and Liu and Hansen (2007). The Multi-Airport Ground Holding Problem extended this traffic flow management strategy to a network of airports that can be simultaneously capacity-constrained (Vranas et al., 1994). The Air Traffic Flow Management Problem (TFMP) further extended the ground holding problem by considering that not only the airport but also the airspace can be capacity constrained (Bertsimas and Patterson, 1998). Departure times and traversing times throughout the airspace were deterministically controlled from origin to destination for each individual flight. The TFMP implicitly assumes airborne delays can be accomplished through speed adjustments, but it can also be adapted to incorporate rerouting of flights as a control option. The Air Traffic Flow Management Rerouting Problem (TFMRP) has also been explored as a multi-commodity network flow problem (Bertsimas and Patterson, 2000; Mukherjee and Hansen, 2009).

At the regional and tactical level, ATFM also plays an important role in the regulation of the local traffic at individual airports or terminal areas. Many approaches have been derived for more efficient coordination of airport arrival and departure flows, with the objectives of minimizing delays and maximizing resource throughput while maintaining fairness among airspace users. Runway sequencing and scheduling models have been developed to determine the optimal sequence and schedule of runway usage by arrival and departure aircraft based on the safety requirements between specific aircraft types and their wake turbulence categories (Beasley et al., 2000; Balakrishnan and Chandran, 2010; Solveling et al., 2011; Sama et al., 2014; Murça and Müller, 2015; Samà et al., 2017a,b,c). Runway configuration selection models have been developed to optimally schedule airport runway configuration changes based on expected demand and meteorological conditions in order to best balance capacity with the demand of arrivals and departures (Bertsimas et al., 2011a). Taxiway scheduling models have been designed to schedule taxi operations and determine the optimal routing in the taxiway system in order to prevent "stop-and-go" situations and minimize taxi times (Rathinam et al., 2008). Finally, departure metering models have been developed to manage the demand of departures by holding aircraft at the gate, with engines off, until the right time for its release (i.e., the optimal time to leave the gate and reach the runway at its assigned slot for takeoff) towards minimizing taxi and runway delays and mitigating airport surface congestion (Malik et al., 2010; Burgain et al., 2012; Simaiakis et al., 2013).

Research in ATFM has produced useful models to optimize the traffic flows at multiple scales, showing efficient computational times on practical size instances and significant potential towards improving the efficiency of air traffic operations. Yet, it is still observed a large gap between theory and practical implementation. A couple of reasons for this gap are associated with the characteristics of the ATM operating environment. Many analytical models make assumptions that do not hold under the high levels of dynamism and uncertainty in air traffic operations, or do not fully adapt to current operating procedures. For instance, national-level ATFM models typically allocate flights to resources by modeling capacity as the maximum number of flights simultaneously using a resource during a given time period, and by assuming complete control over aircraft traversing times throughout the airspace. Besides, they do not take into account specific airspace users inputs regarding their personal priorities. By contrast, strategic national-level ATFM programs such as GDP and AFP allocate flights to resources using slots and incentivize information exchange and collaboration among stakeholders through CDM.

Towards increasing the participation of flight operators in ATFM decisions, the FAA first introduced the CDM paradigm in Ground Delay Programs in 1998 (Federal Aviation Administration, 2017b). Under CDM, the ANSP has no complete control over ground delays assigned to individual flights as flight operators can internally change the amount of delay that will be imposed to their own flights. In the current practice, it is implemented as follows. The ANSP is responsible for determining planned arrival rates and arrival slots at a capacitated airport. Slots are then assigned to individual flights using a "First Come, First Served" strategy with respect to original scheduled arrival times, which is known as "Ration-by-Schedule" (RBS). RBS is followed by a procedure called "Compression", a second round of slot allocation that takes advantage of reported cancellations and delays from flight operators. Finally, flight operators can internally exchange arrival slots among their own flights or even exchange slots with others.

With the goal of providing more efficient resource allocations in GDPs, Vossen and Ball (2006) proposed an optimization-based approach for the slot allocation and compression procedures under CDM based on an assignment model called OPTIFLOW. The OPTIFLOW model determines the optimal assignment of flights to slots in order to minimize overall delay costs. They showed that the model fully reproduces the RBS policy if the costs of ground delays are equal for all