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An aggregate stochastic programming model for air traffic flow management

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ABSTRACT

In this paper, we present an aggregate mathematical model for air traffic flow management (ATFM), a problem of great concern both in Europe and in the United States. The model extends previous approaches by simultaneously taking into account three important issues: (i) the model explicitly incorporates uncertainty in the airport capacities; (ii) it also considers the trade-off between airport arrivals and departures, which is a crucial issue in any hub airport; and (iii) it takes into account the interactions between different hubs.

The level of aggregation proposed for the mathematical model allows us to solve realistic size instances with a commercial solver on a PC. Moreover it allows us to compute solutions which are perfectly consistent with the Collaborative Decision-Making (CDM) procedure in ATFM, widely adopted in the USA and which is currently receiving a lot of attention in Europe. In fact, the proposed model suggests the number of flights that should be delayed, a decision that belongs to the ATFM Authority, rather than assigning delays to individual aircraft.

1. Introduction

The worldwide growth in air traffic during the last several decades has been dramatic. As a result, air traffic management has become increasingly crucial. Air traffic management (ATM) consists of all processes that support the goal of safe, efficient, and expeditious aircraft movement. In addition to the tactical separation services provided by air traffic control, a more "macroscopic" management of traffic flows is used to address system-wide efficiency. Generally speaking, air traffic flow management (ATFM) considers strategic procedures which aim to detect and resolve demand-capacity imbalances by adjusting aggregate traffic flows to match scarce capacity resources. ATFM initiatives can be classified according to their time horizon (see [23]). In this paper, we focus on short-term approaches whose planning horizon is typically less than 24 hour. These operational ATFM initiatives attempt to mitigate the congestion that may arise from unforeseen disruptions as efficiently as possible. Such periods of congestion arise frequently when bad weather causes sudden capacity reductions. The most popular approach, by far, in resolving these short-term periods of congestion, has been the allocation of ground delays. In the US, for instance, the FAA implements approximately 500 ground delay programs (GDPs) per year [10]. Ground delays refer to the idea that flights are delayed prior to their departure; the reason being that it is generally both safer and less costly to delay flights on the ground, rather than flights that are airborne. The ground holding problem considers the development of strategies for allocating ground delays to aircraft. From the seminal paper by Odoni [23], it has received considerable attention, see [17] for a comprehensive survey on the subject.

The mathematical model herein presented addresses the following key issues. A first issue is the stochastic nature of the capacity reductions (e.g. due to bad weather conditions), and the allocation of ground delays in this setting. During September and October 2002, for instance, 111 GDPs were executed in the US Only 17% of these GDPs ran to their completion (that is, according to the initial plans implemented by air traffic managers). This statistic clearly shows that most GDPs are revised during operations, since air traffic managers are generally not able to foresee capacity fluctuations; and flights could *unnecessarily* be assigned the ground delay, see [8]. As such, decision models that explicitly take into consideration uncertainty may improve ATFM operations. For these reasons the proposed model explicitly incorporates uncertainty in the airport capacity through the use of scenarios. In [1,2,7,26,29] modeling and computational aspects on uncertainty have been addressed.

A second important issue is the possible trade-off between arrival and departure capacities, that are absolutely critical in most hub airports. Even though this issue has been raised in many papers on ATFM, only few of them are devoted to this specific issue, e.g. [11,13–15].

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Finally, a third issue is the network impact that results when ground delays are imposed at different, interdependent airports. In the US, for instance, there have been situations during which 10 GDPs were executed simultaneously (see [22]). Clearly the use of GDPs, which only address capacity reductions at a single airport, do not take into account the system-wide effects of these interdependent decisions [4,5,28].

Several papers address one or the other of these three important issues (namely: uncertainty, arrival-departure capacity trade-off and network effects), but none addresses all three of them. To better address these three issues, we build a *macroscopic* model – similar in principle to [25,30] – rather than a microscopic one. The proposed model suggests how many flights should be delayed during each time period under consideration, rather than providing detailed suggestions on how much delay should be imposed on each single flight. With respect to previous work on ATFM, e.g. [3,4], which addressed the problem at a more microscopic level of detail, the model we propose is consistent with the Collaborative Decision-Making (CDM) procedure [10] in ATFM, which is widely adopted in the USA and is currently receiving a lot of attention in Europe. Microscopic models, which are also able to capture connections between departures and arrivals at a specific airport, assume that the decision maker has the Authority to decide which specific flight should be delayed, and therefore are not well suited to the CDM procedure. Due to the focus on aggregate capacities, as opposed to the consideration of individual flights, the approach we propose concur with the CDM paradigm in ATFM. Indeed, given the aggregate capacity profiles, CDM procedures could be used to distribute the slots among individual flights. Notice that in the extreme case where all operations are run by a single airline, our model will find how many flights should be delayed (and this is a decision that belongs to the ATFM Authority) while the airline will decide which individual flights should be delayed (this is a decision that belongs to the airline). In the more realistic case where more than one airline is using the airport, then there will also be the need of an intermediate decision, i.e., how many flights of each company should be delayed. This again could be resolved through CDM measures.

The paper is organized as follows: In Section 2, we formally describe the capacity allocation problem. In Section 2.1, we present a formulation for the tactical capacity allocation problem. Computational experiments and analyses of these models are given in Section 3. Finally, Section 4 contains conclusions and indications for future research.

2. Problem description

In this paper, we propose a multi-airport capacity allocation problem to manage congestion phenomena in ATFM. Generally speaking, our objective is to compute an optimal mix of arrivals and departures for a given network of airports that minimizes the total delay over all the airports during the periods of congestion.

To be more precise, we consider a given set of airports $\mathcal{K}$ and, for each airport, a given demand for both arrivals and departures during a time horizon $[0,T]$ for which we expect congestion. The time horizon is discretized into time periods. The resulting cumulative demand of departures from airport h to airport k at time period τ is denoted by $D_\tau^{h,k}$. If $FT^{h,k}$ denotes the flight time between airports h and k, $D_\tau^{h,k}$ implies a cumulative a demand of arrivals at airport k from airport h at time period $\tau + FT^{h,k}$. We represent the airport capacity by a so-called airport capacity envelope, which incorporates all the feasible combinations of arrivals and departures capacities, see Fig. 1. An obvious example involves cases in which the same runway is used for both arrivals and departures during a particular time period: the more arrivals are assigned to the runway, the fewer the departures that can be served – and vice versa. At multi-runway airports, arrival and departure capacities will vary according to the "mix" of operations (arrivals only, departures only, or a combination) which is assigned to each of the active runways. For instance, in the case of the Rome Fiumicino airport (see Fig. 1) with good weather conditions, if all the capacity is allocated to arrivals then 56 flights could arrive, and if all the capacity is allocated to departures then 44 flights could depart within 1 hour. In the case of mixed operations, we may have for instance, 34 arrivals and 32 departures or any other point of the capacity envelope. The reduction of capacity from its maximum nominal level, for both arrivals and departures, is to assure the spatial separations between flights. Therefore, for each airport $k \in \mathcal{K}$ and time period $t \in \{1,\ldots,T\}$ the airport capacity envelope $\mathcal{E}(k,t)$ denotes the feasible combinations of arrivals and departures at airport k during time period t.

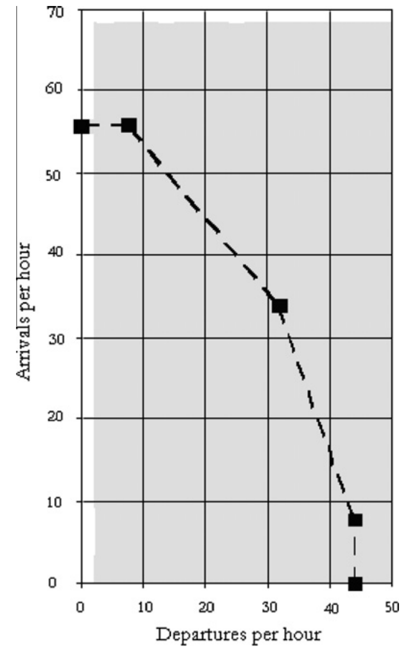

Fig. 1. The capacity envelope (Rome Fiumicino).

We note that a pair of airports is connected if there exists a nonzero air traffic flow between the two airports. To summarize, the resulting problem can now be stated as follows. Given the parameters described above, compute for any time period t and for any airport of the network k the delay-optimal flow of in-bound and out-bound flights while satisfying the capacity constraints on the mix of arrivals and departures at each airport of the network during each time period. The resulting model can incorporate both deterministic and stochastic problem data.

Herein, we consider situations where airport capacity is uncertain. As a result, the airport capacity envelopes $\mathcal{E}(k,t)$ are represented as random variables. In most stochastic programming applications, however, a complete and accurate description of a complex stochastic process may be difficult to obtain. As such, it is common to consider a finite set of scenarios, where each scenario describes a possible trajectory of the random variables over time. This assumption implies that we are assuming random variables with finite support (see [9]).

It is important to note that in the stochastic framework, the assignment of both ground and airborne holding delays are used as control decisions to define the appropriate mix of departures and arrivals. In fact, using exclusively ground delays may lead to