Mitigating Airport Congestion: Market Mechanisms and Airline Response Models

(Extended Abstract of PhD Dissertation)

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The National Air Transportation System (NATS) is a core part of the national economy, generating revenue of about \$150 billion, transporting over 750 million people annually. In addition to being one of the largest US industries, it is a catalyst for economic growth and international competitiveness.

Air traffic is at its record high and is projected to grow at close to 3% annually. The Federal Aviation Administration (FAA) predicts that the US commercial aviation is on track to carry one billion passengers by 2016 with load factors well above 80% [AF07]. This sheer volume and sustained growth of the aviation sector is putting an enormous strain on the air transportation system. For 2007, the Air Transport Association (ATA) reported a total of 134M system delay minutes (up by 15% from 2006) that resulted in \$8.1B in direct operating cost and the estimated total cost to passengers was \$4.2B [ATA08].

All the components of an airline – passengers, crews and planes – operate as a network, interweaving into one another so closely that airline delays have strong network effects. A disruption in one operation can propagate into several other downstream operations creating havoc and propagating disproportionately through the entire network. The primary cause of disruptions is the mismatch between the increasing demand for access to airports and the limited operational capacity restricting the number of landings and take-offs at airports. The limited capacity is due to the constraints on runway (spacing between the planes for safety), gate availability and air-traffic control either due to unforeseen circumstances, like bad-weather or due to over-scheduling of the flights during peak demands.

Congestion mitigation procedures are critical to the nation's air system and the economy to ensure that delays and congestion costs do not increase excessively with the projected increasing growth in air traffic. The role of the Air Traffic Flow Management (ATFM) is to match the capacity of the air transportation system with the demand so as to mitigate congestion and ensure that aircraft can flow through the airspace safely and efficiently. They adopt *capacity enhancement measures* and *demand-management techniques* to mitigate congestion. Demand management involves policies that influence the demand side with the FAA restricting the number of operations (i.e., capacity) to tolerable delay levels and allocate the limited capacity to the airlines.

In this thesis, we focus on demand-management policies to mitigate congestion.

1 Demand-Management Techniques

According to the US code, a *slot* is a reservation for an instrument flight rule takeoff or landing of an aircraft by an air carrier in air transportation [USC05]. ATFM estimates the available capacity at an airport based on the number of operations, i.e., number of landing and take-off slots, per hour for every 15 minutes based on constraints on the runway, gate availability and other safety constraints and simply allocated them to the airlines. Demand-management techniques can be classified into two types based on the time-frame over which the landing slots are allocated to the airlines:

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1. *Strategic (medium-term) initiatives*: With these initiatives, slots are allocated to the airlines over a medium-term horizon (usually on the order of a few years). The airlines are allowed to schedule planes only in the slots allocated to them. This approach is called a strategic demand-management technique as airlines can establish their priorities, anticipate issues and plan for the long-term. These initiatives are applied to airports that have prolonged periods of congestion everyday, even on a day with good weather.

2. *Operational (real-time or short term) initiatives*: These initiatives are applied just for the day of operation when there is an unforeseen circumstance, like bad weather, causing a sudden drop in capacity on the day of operation. On these days, 50% capacity drops over a period of 4-5 hours are not uncommon. Once ATFM receives an update about the capacity estimate, it allocates the available arrival slots to all airlines scheduled to land. The times of the slots allocated often tend to be later than the scheduled arrival times (due to the capacity drop) and the planes are delayed in the departure cities accordingly. Because the capacity estimate typically is both stochastic and dynamic due to the stochastic nature of weather and frequent updates, a new set of allocations are performed, each time a new capacity value is obtained. This approach is called operational or real-time demand-management technique because allocations are made in real-time and the airlines also have to respond to such allocations in real-time.

In this thesis, we study both these approaches to demand-management as well as the airline response to the same but our primary focus will be on strategic approaches.

2 Strategic Approaches to Mitigate Airport Congestion

Congestion at airports has led to the formation of slot-controlled airports where there is an administrative limit on the number of landings, and hence take-offs, at an airport. The guiding principles of the current procedures of allocating landing slots in the US include grand-fathering, lotteries and setting of landing fees independent of demand levels (peak vs. non-peak hours). Such allocation schemes not only are inefficient methods of utilizing a scarce resource but also act as barriers for new entrants. Market mechanisms such as congestion pricing and slot auctions have been proposed (in fact, since the 1980's) as an alternative method to current schemes to achieve efficient allocations [GIP79, GIP89, DoE01, BDH06, BAB+07]. These schemes provide transparent demand-based pricing techniques to attain efficiency.

Our work focuses on slot auctions as a strategic demand-management approach. In the design of an auction, it is important to understand how the bidders (here, airlines) value slots. Airlines rely on passenger connections between different fleets and aircraft, and profitability is a function of the markets served and the frequency of service in these markets. It is, thus, evident that airlines have a non-linear valuation over the slots at an airport. In the auction literature, it is well-known that when valuations have complementary and substitutable effects, *iterative combinatorial auctions*, where the auction is conducted in rounds and the bidders bid on packages of goods, are best suited [CSS06, Par06].

Budget-constrained bidders: Airlines are *budget-constrained*, i.e., have valuations that are greater than their ability to pay (for instance, due to liquidity or credit problems). Airlines typically carry large amounts of debt, have low profit margins compared to an average US business and are especially vulnerable to fuel spikes, recession or economic shocks. In the past, for the sake of simplicity this budget-constrainedness of the participating bidders has been generally ignored. In this thesis, we argue that this overlooking leads to wrong allocations and hence, it is essential that the fact that airlines are budget-constrained is accounted for in slot auction design.

In our work, we focus on two aspects in the design of iterative slot auctions - *airline valuations* and *activity rules*.

3 Airline Response to Airport Slot Auctions:

Preference elicitation, the problem of finding the best bundle of goods in which to bid (landing slots in the case of airlines), is a hard problem in combinatorial auctions. It is even harder for airlines because they have to solve large scheduling, fleeting and revenue management problems which often take several hours to solve to find the value of one bundle of slots.

We propose the *Aggregated Integrated Airline Scheduling and Fleet Assignment Model* that can estimate the profitability of a bundle of slots by considering the network as a whole and performing both scheduling and fleeting decisions with airlines treated as budget-constrained bidders. To the best of our knowledge, no previous work has studied this aspect of airline behavior. We refer to the model as an aggregate model because it uses different levels of discretizations of the time space network at different airports; a finer discretization in more congested airports with slot controls and a coarse one in less congested airports. This modeling approach allows us to dramatically improve the computational time needed to solve the model without losing information needed to build an accurate representation of the problem. This is particularly relevant in an iterative auction setting where computations are performed after each round of the auction. This computational advantage comes at the cost of counting the number of planes in the network approximately. However, this approximate counting is not an issue since the valuation model is only a planning tool for bidding purposes that is used several months before the implementation of the actual schedule wherein exact counting is required. This modeling approach is useful whenever large-scale problems that can pose tractability issues need to be solved and higher levels of granularity are required for some of the decisions than for others.

We first propose a simple leg-based valuation model with demand on each leg independent of frequency of the number of operations on that leg. We then provide several ways of enhancing this model to include non-linear variation of demand with frequency, itinerary-based pricing and demand and alternate ways of strengthening the plane count. We present experimental results using the leg-based valuation model with increasing prices (as in an auction), on real data from a carrier. We observe the changing trends in the airline network as prices increase which include the airline eliminating markets that are no longer profitable, reducing frequency into the airport with the auction, up-gauging in the profitable markets, moving into newer markets and potentially, creating newer hubs. We also observe that the model is computationally efficient and that the bids in the auction are robust to uncertain demand data in the network. The latter is especially interesting because of the uncertainity in demand information several months before the actual season.

4 Activity Rules for Iterative Combinatorial Auctions:

We focus on the design of activity rules for a slot auction. Activity rules are checks made by the auctioneer at the end of every round of an iterative auction to suppress strategic behavior by bidders and to promote consistent, continual preference elicitation. They are used in several real-world settings including the spectrum auction, procurement auctions and have been considered in the airline landing slot [BAB+07]. It is well known that good iterative auction design should promote straightforward, demand-revealing behavior on the part of bidders [AC04, Par06]. We show that the commonly used activity rules in iterative auctions, *Revealed Preference Activity Rule* (RPAR), prevents straightforward bidding strategies of a budget-constrained bidder. In fact, we also observe that they do not guarantee consistent bidding for bidders without budget constraints. The former is a critical issue in the context of slot auctions as airlines are, in fact, budget-constrained bidders.

Informally speaking, we define a *strong activity rule* as the best possible activity rule that prevents all preventable strategic behavior without precluding consistent (and thus, straightforward) behavior. More formally, we do so by formulating the set of necessary and sufficient conditions for an activity rule to exactly characterize the set of straightforward bidding strategies. Strong rules still allow for price discovery because a bidder is still guided in terms of the packages on which to bid by the price trajectory in the auction. For this reason, iterative auctions with strong rules continue to have the advantage over sealed-bid auctions of facilitating preference elicitation in complex problem domains as they allow for pure demand revelations.

We design strong rules, which we refer to as Strong Revealed Preference Activity Rules (SRPAR), for a general iterative combinatorial auction for both budget-constrained bidders and quasi-linear bidders. We express them as simple linear feasibility problems. In practice, we observe that one cannot have a rule that is simultaneously strong for both budget-constrained bidders and quasi-linear bidders, and the choice of rule depends, to some extent, on the bid taker's beliefs about participants in the auction. We also propose simple relaxations to SRPAR that could be of interest in practical auction implementations to provide some leeway to the bidders in the bidding process. This work on activity rules complements the current literature on iterative auction design, and slot auctions, in particular. These strong rules can be used in other iterative auction settings as well.

In our experimental simulations we compare SRPAR and RPAR for the *clock-proxy auction*, an iterative combinatorial auction proposed for practical settings like the spectrum auctions, when populated with straightforward bidders. SRPAR outperforms RPAR with respect to efficiency and revenue by 3.8% and 9.4% respectively (on average across the different distributions) at low budgets, with benefits falling off as budgets are increased.

5 Real-Time Approaches to Mitigate Airport Congestion

In this section, we study real-time demand-management techniques, where we propose a system design to evaluate different real-time allocations schemes based on different metrics.

Due to unforseen circumstances like bad weather, capacity of the runway in terms of the number of landings per unit time, can drop suddenly. In such an event, FAA adopts real-time procedures to assign airlines to the different landing slots. There are three different stages that are closely linked to obtain the final allocation of slots. The three stages are: (1) a primary allocation of slots; (2) airline recovery; and (3) inter-airline exchanges. As the names suggest, in the first stage the FAA allocates airlines to slots. In the second stage, airlines repair their schedules to accommodate the disruptions (that is, landing slots allocated are different from the slots in which the flights were scheduled to arrive). In the third stage, the airlines trade slots between each other based on their private objectives. Because it is impractical and impossible for the FAA to provide all the airlines with their most preferred slots, a trading scheme is essential for airlines to achieve their private objectives. Also, trading reduces the wastage of slots resulting from flight cancellations during recovery. After the first allocation of the slots, the three systems run in parallel for the duration of the bad weather as updates of the runway capacity enable new allocations and trades.

We provide a survey of the current allocation procedures that are considered 'fair' but might not be system optimal, and alternate procedures proposed in the literature, many of which are system optimal with regard to different metrics but are not considered 'fair'. One can also divide the allocation procedures based on single-airport decentralized models and multi-airport simultaneous allocation models that ensure connectivity of aircrafts. Because the FAA is allocating the slots, these approaches do not consider flight cancellations which the airline recovery would do. So, we ask the question if connectivity really matters at the initial allocation stage when cancellations cannot be performed.

To answer this question, in our opinion, it is important to study the system as a whole, as the three stages are closely interrelated. The thesis provides a review of airline recovery procedures and models. These procedures can be treated as airline preferences, like an airline response behavior to an allocation. We suggest using a network-based recovery model that estimates the true cost of a recovery considering the network operated by the airline. The literature in the context of real-time demand-management tend to use local recovery models, that do not consider network effects of the airline, over network-based ones for experimentation.

We then review inter-airline exchange mechanisms. We observe that in the mechanisms currently used, airlines cannot completely express their preferences and expose themselves to the risk of giving up something without the guarantee of getting something back in return (also known as the exposure problem in mechanism design). On the other hand, a fully expressive exchange might be overly sophisticated leading to the problem of information overload, wherein airline controllers are unable to react due to the complexity. So, understanding airline preferences and designing an exchange that has the appropriate tradeoff between expressiveness and efficiency, is a problem open for future research.

To answer the questions on connectivity and fairness, we suggest a system design with all the three components – initial allocation, a network-based recovery model that accurately captures recovery costs and the currently used exchange mechanism. For different allocation schemes, we can compute different metrics, proposed in the thesis, to analyze if certain airline network structures (that can again be categorized with respect to some metrics that we suggest) tend to be more preferred over others. We also present data sources that we will need to run such experiments. These ideas can be used as a basis for future work in real-time slot allocation.

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