

# PROPOSAL FOR DEMAND MANAGEMENT USING AUCTION-BASED ARRIVAL SLOT ALLOCATION

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## Abstract

This paper discusses a new approach to demand management of overscheduled US Hub airports. The approach attempts to assure safe aircraft separation, optimize passenger enplanement opportunities and equitably allocate a limited supply of landing opportunities. Arrival timeslot auctions are explored as a promising market-based approach to balance demand and supply at slot-constrained airports. The proposed auction model, which is an adapted combination of simultaneous multiple round and package auctions, balances conflicting objective functions of the stakeholders – or agents – involved in the process – airlines and airports. The determining factor is not simply the bid price, as it is in most auctions, but includes other factors related to the performance of the overall system. The presented work constitutes part of an ongoing effort to model the national airspace system using agents, as well as to simulate a more synchronized air traffic network.

## 1. Introduction

The current practice of air transportation in the US does not regulate airline scheduling of flights to and from most airports (except LaGuardia, Washington National, Kennedy International, and O'Hare International) [1][2]. These slot-controlled airports are scheduled to change their slot control agreements in 2007. Even at these airports, airlines are free to set up their own schedules and ATC follows a first-come first-served acceptance rule. Airline schedules are market-driven to accommodate travel time preferences of passengers (airlines operate on a profit maximizing principle). Many business passengers would prefer morning and evening departures, thus producing non-uniform flight schedules. Also, as a result of hub schedule banking and a desire for hub airport market dominance, strongly periodic and highly peaked flight schedules are generated that exceed runway supply. At the same time, other airports with excess infrastructure are underutilized, as observed in the FAA's Airport Capacity Benchmark report [3].

The unbalance between traffic demand and airport capacity induces many problems. Not only does it create delay and increased operational cost for the airlines, it also compromises system safety since air traffic controllers attempt to accommodate as many aircraft as are scheduled and frequently are unable to maintain minimum separation standards for landing aircraft [4] under peak arrival rates in excess of 30 arrivals per runway per hour. In addition, the asynchronous operation of the current system leads to queuing delays that are not allowing the air transportation system to make the most of the limited airport resources.

The recent US commission on the future of the Aerospace Industry [5] recognizes that technology alone will not solve the modernization and capacity limitation problem. Goetz [1] describes one of the serious and unexpected consequences of the 1978 deregulation of the US air transportation system. Over 20 major US airports have an Herfindahl-Hirschmann Index over 1800<sup>i</sup> producing what is sometimes referred to as fortress hubs with little price competition or incentives to improve service quality. Policies may be changed to make better use of scarce capacity at major airports to increase competition and optimize airport utilization when demand exceeds available capacity.

Congestion Pricing may be a powerful network demand management tool [2]. Promoting the use of larger aircraft, where it is economically justified, could also help increase enplanement capacity. There is an emerging interest in the auctioning of airport time slots, which could improve the efficiency with which slots are utilized at slot-constrained airports. Slot auctioning would increase the costs of slots until demand equals supply by limiting the number of arrival metering fix time slots to the level of safe airport capacity and only allocating individual slots to those airlines flights for which the demand (willingness to pay) is greatest.

Slot auctioning can be undertaken for landing or take-off slots, and although the principle of slot auctioning may appear simple, there are many issues involved in allocating airport runway slots. As for

optimization purpose, the solution in order to resolve the network problem as a whole should not be limited to evaluating financial gains from airline bids with detriment to the performance of the overall system. As for feasibility, since an airline's demand for a take-off slot at a flight's originating airport is not independent of its demand for a landing slot at the flight's destination airport, the auctioning will have to deal with contingency bidding. Moreover, flexibility in the allocation system is essential and has to be taken into account, as airlines' operating programs change from time to time and airlines need to have matching slots at airports around the world if those plans are to be realized. This relates to the need for designs of secondary market in addition to primary market.

Attempts to synchronize air traffic using market-driven mechanisms such as auctioning date back to 1979 with the work of Grether, Issac, and Plot [6]. Their procedure is based upon the competitive (uniform-price) sealed-bid auctions for primary market, complemented by the oral double auction for the secondary market. Rassenti and Smith's research [7] explores the use of combinatorial sealed-bid auctions to serve as the primary market for allocating airport runway slots in flight-compatible packages for which individual airlines would submit package bids. These are mainly based upon maximizing financial gain to the seller as the criterion to choose the winning carriers. They fail to deal with the more subtle issues such as network performance, safety and equity to ensure competitiveness among air carriers, however. A similar study in the UK [8] promotes simultaneous multiple round auctions while taking into account terminal, stand and runway capacity as a bid unit. The report presented substantial work investigating many design issues and options, including efficiency and equity. However, a concrete solution to this optimization problem is still missing.

Our approach constitutes another attempt to solve this allocation problem. From the systems engineering point of view, the auction involves two main kinds of stakeholders: airlines and airport coordinators/regulators (i.e. DOT/FAA). Designing a system made up of a large number of entities such as airlines that interact in specific ways calls for an agent-based modeling approach. Due to the dynamic nature of air transportation, agent-based models are especially useful to model the emergent behavior of interacting entities, which is not explicit in any individual actor. The network model of MITRE [9] introduces the use of this promising simulation paradigm in modeling airline behavior using agents.

Our work also promotes agent-based modeling and is specifically focused on agent behavior in an arrival slot auctioning context. The auction mechanism is built on top of a network simulation model, which is being developed in parallel, to evaluate the performance of the system given airlines' modification of schedules as output of the auctioning model.

From the optimization point of view, each agent has an objective function that is to be achieved. Airlines aim to maximize profits whereas airport coordinators (DOT/FAA) are concerned with optimizing the use of their scarce resources while insuring safety. Airlines need to maintain a stable schedule and leverage their investment at hub airports, but equity issues require airports to provide fair market access opportunity for every airline. In order to solve the allocation problem one must find a common solution for these conflicting objective functions. Five criteria are taken into account to formulate the optimization model: 1) number of seats; 2) flight OD pair; 3) prior airline infrastructure investments to insure financial investment equity; 4) historic slot occupancy rates to insure schedule stability; and 5) price bids to evaluate airlines-assigned slot values.

This is research in-progress and we limit ourselves to arrival slot auctions at US airports. Much more work in this area needs to be done. Section 2 provides more insights about current practice of slot allocation and auction forms we utilized for our model. Section 3 introduces our modeling approach illustrated by a sample scenario presented in section 4. The paper concludes with observations on future research needed to improve the model.

## 2. Background

The United States employs a hybrid system in which airlines are sometimes permitted to own or control terminals and gates and thus effectively control market access. Since many congested US airports are dominated by only a few airlines [1], it is effectively the dominant one or two airlines that manage access to the airport from its control of the gates. The FAA ensures that aircraft do not take off unless an arrival is assured and the en-route airspace can cope. This suggests a justification for choosing arrival slots to be auctioned in order to leave a certain degree of freedom to airlines to adjust flexibly their schedules.

At the four airports for which slot allocation is mandated, only two (New York-Kennedy and Chicago-O'Hare) cater for international traffic. At

these international airports priority is given to international flights over domestic and operators of domestic rights can ultimately be required to surrender slots needed for international services. This reflects the US Government's position that countries have an obligation to provide slots to meet the capacity needs of airlines operating under government agreements.

Airport slots are essential for the provision of airline services to and from congested airports. A slot is defined as the concession or the entitlement to use runway capacity of a certain airport on a specific date and at a specific time. Runway slots are allocated to airlines on a seasonal basis.

The supply of airport slots is limited by available runway and gate capacity. Demand for air travel is growing rapidly. Investment in new airport capacity is limited by environmental concerns. Even if capacity could be extended to meet overall demand, optimal allocation would require that those carriers most able to switch to off-peak slots, leaving peak capacity to those for whom switching would be difficult and costly, i.e. to try to spread out the air carriers in order to decrease queuing delay at peak periods and/or switch to low-traffic airports to increase the utilization of the existing resources.

Efficient allocation requires that a resource should be assigned to whoever values it most. Auctions serve as an effective way to balance demand and supply when the former exceeds the latter. Auctions come in many forms [10] and have been successfully used for radio spectrum allocation with large numbers of interrelated regional licenses. Here we introduce two auction formats that are reused in our model design.

Simultaneous Multiple-Round (SMR) auctions: have discrete, successive rounds, with length of each round announced in advance. After each round closes, round results are processed and made public.

In a SMR auction, there is no preset number of rounds. Bidding continues, round after round, until a round occurs in which all bidder activity ceases. That round becomes the closing round of the auction.

This design relates to the open ascending (English) auction on the ground that it furnishes bidders with valuable information. This reduces the winner's curse, which contributes to more aggressive bidding, to the benefit of the seller. However, the exchange of information in the course of an English auction also has a drawback: It may invite preemptive or jump bidding, and it may be misused by bidders to communicate and enforce collusion.

Moreover, in this design, bidders could wait as late as possible to make their bids in order not to give away any information about their intentions to other bidders. For this reason, activity rules are defined to force bidders to make bids at each round in order to keep their options open for later in the auction:

Package bidding (aka. combinational bidding): under this system, bidders submit bids for multiple combinations of lots rather than just individual lots. Package bidding is either accepted or rejected in its entirety. The US Federal Communications Commission has recently been experimenting with the use of package bidding and has decided to move to this system for allocating regional spectrum licenses as of 2001.

### **3. Auction Model**

#### ***3.1 Design Issues***

There are two main interests to be taken into account.

The first is the interest of airports in having the most efficient use made of available infrastructure. Given optimum airport arrival rate in good weather condition, airports should chose an optimum fleet mix in such a way as to increase the throughput while maintaining safety standards. Throughput relates to the number of arriving aircraft and to the number of passenger enplanement opportunities. The former is inherently constrained by airport capacity and separation standards. Previous work of Hansen [11] shows that separation time varies for a particular pair of aircraft types: a trailing aircraft of small type should be separated farther from a leading aircraft of large or heavy type than a trailing aircraft of the same type would be. Another concern is the market segment of the flight; international flights should have more priority over domestic ones.

The second is the aviation industry - charter and scheduled airlines and operators of business aircraft - which needs the security to support investment in route development, aircraft and airport infrastructure which would be denied by threats of arbitrary slot confiscation. At the same time, there is a potential conflict between airlines, which wish to grow, and new entrants wanting to enter the marketplace. To compromise these conflicting interests, the auction model should take into consideration the prior investments of airlines at particular airports as a criterion in determining slot winners. Besides, it may be possible for a carrier to restrict competition and attain market power by purchasing a large number of slots, for example by establishing a strong position at

a hub or frustrating expansion by existing competitors on a specific point-to-point route. Increased concentration of slots holding has been observed at US airports that have introduced market mechanisms. An auction system should not be introduced without safeguards against market power. Grandfather rights used in Europe mandate that only if air carriers can demonstrate to the satisfaction of the coordinator that they have operated their slots, as cleared by the coordinator for at least 80% of the time during the period for which they have been allocated, shall be entitled to the same series of slots in the next equivalent period. The continuation of slot allocation based on a certain historical precedence in the usage is justified from both the passenger and the air carrier side. From the passenger side, because they will benefit from certain stability, continuity and increasing quality of services resulting from business investments of air carriers. From the operators' side because they have an incentive to use their slots according to the slot allocation rules so as to guarantee that the networks they are developing will not be unduly affected by forced and unpredictable reallocations of slots [4]. Therefore historic slot occupancy rate should figure among determining factors of the auction mechanism.

The last determining factor of the auction model is the bids that airlines offer as a measure of market value they assign to arrival slots.

The importance of the factors mentioned above varies depending on current practice and priority preference at each individual airport. Taken all together, they provide a "score" to determine the winners as an optimum solution to respective (and conflicting) objective functions of different agents. This is rather a subjective choice, for an exploratory work, our model proposes a simple way to evaluate eligible airline candidates.

### ***3.2 Auction Model***

The auction mechanism is an iterative and interactive process that involves airlines – bidders – and airport coordinators – auctioneers. The model makes use of Simultaneous Multiple-Round auction and package bidding models with some simplifying adaptations.

Airport regulators select airports with an aggregate capacity ratio in excess of 0.6 and propose a number of slots to be auctioned. This number should correspond to airport capacity to assure safety standards. A typical one for a particular period would

be equal to optimum airport arrival rate during that period.

The auction process begins with a required minimum bid for each slot. Activity rules are defined as the required continual participation of any airline: if an airline does not submit a bid for a slot for a round, she will not be eligible to continue in the auction process for that slot. The auction process proceeds through many discrete, successive rounds until the closing round or a specified deadline whichever comes first.

Auction rules determining the winners for each round are made public. The amount of bid is only one of the six factors that constitute the scores of airlines for each round, the other five are 1) number of seats; 2) flight OD pair; 3) prior airline infrastructure investments to insure financial investment equity; and 4) historic slot occupancy rates to insure schedule stability. Depending on its own operational practice, each airport can provide different weights for those factors as well as different score computing formula. For illustration purpose, our model proposes hypothetical weights and a linear combination of those factors to calculate the scores for each bid.

Based on statistical data and the scoring made publicly, airlines are aware about their respective scores and therefore are able to adjust their bids to obtain a better deal. Airport coordinators inform the airlines about the result of each round, airlines propose bids after having run their optimization models and the auction proceeds in this manner through multiple rounds.

For the time being, our model only deals with the primary auction market and airport coordinators are totally in charge of allocating arrival slots. Monitoring airlines' performance in utilizing acquired slots should be part of the future design improvement work must also be developed to allow airlines schedule adjustment on a monthly or daily basis.

### ***3.3 Airport Optimization Model***

During the period of auctioning process, for each round, the airport regulators calculate the scores of each airline and use their optimization models to determine the leading bidders for that round. As stated above, the expected optimal solution should satisfy many conflicting criteria: good utilization of resources, safety and equity. The airport regulators could calculate the scores of each bid in a simplistic way as follows:

$$\tau_{ij} = \sum_k w_k * v_{kij}$$

Where:

$k = 1, \dots, 5$  subscripts a determining factor,

$w_k$ : weight of factor  $k$ .

$v_{kij}$ : normalized value of factor  $k$  for airline  $j$  that bids for slot  $i$ .

The airport regulators formulate the problem as a BIP (binary integer problem) model:

*Optimization model:*

$$\left\{ \begin{array}{l} \text{Maximize } \sum_i \sum_j \tau_{ij} * x_{ij} \\ \text{Subject to:} \\ \sum_j x_{ij} \leq 1 \quad \forall i \\ B_{0i} * x_{ij} \leq B_{lij} \quad \forall i, j \\ \sum_i x_{ij} * f(AT(i, j), AT(i+1, k)) \leq TW \\ \text{Airlines' logical constraints} \\ x_{ij} \in \{0, 1\} \end{array} \right.$$

Where:

TW denotes the time window (in minutes) containing peak period slots to be auctioned,

$i = 1 \dots AAR * TW / 60$  subscripts a slot,

$j, k = 1 \dots m$  subscripts an airline,

$l \geq 1$  subscripts a round.

The binary variables  $x_{ij}$  are such that:

$$x_{ij} = \begin{cases} 1 & \text{if airline } j \text{ wins the slot } i \\ 0 & \text{otherwise} \end{cases}$$

If an airline  $j$  doesn't request slot  $i$   $x_{ij} = 0$ .

$\tau_{ij}$  : The score of the airline  $j$  for the slot  $i$ .

$B_{0i}$  : minimum bid for slot  $i$ .

$B_{lij}$  : Bid offered by airline  $j$  for slot  $i$  in the round  $l$ .

The first set of constraints concern the capacity constraints, the second one assure that the minimum bid requirements are satisfied, the third reflects separation constraints in allocating slots:  $AT(i, j)$  provides aircraft type of the flight that airline  $j$  schedules for slot  $i$ ,  $f(AT, AT)$  gives the separation time (in minutes) between a particular pair of aircraft in final approach mandated by FAA. Following is a summary of these values based upon wake vortex separation rules, Hansen [11].

Leading	Trailing				
	Small	Large	Heavy	B757	Unknown
Small	1.33	1.13	1.07	1.1	1.16
Large	2.74	1.21	1.07	1.1	1.53
Heavy	3.91	2.467	1.73	2.26	2.59
B757	3.35	1.92	1.69	1.7	2.17
Unknown	2.836	1.68	1.39	1.54	1.87

**Table 1: Mean of the calculated inter-arrival times by aircraft weight categories (minutes).**

Airlines' logical constraints are discussed further in the optimization model of airlines.

### 3.4 Airline Optimization Model

The application of arrival slot auctioning will not only effect the airline cost models, since the airlines will have to pay extra fee, but also create changes of airline schedules. Scheduling is one of the most important tasks in a well-functioning, efficient air transportation network. The two major categories of scheduling are scheduling by revenue requirements and scheduling by the operational needs and constraints of the airlines. These two, sometimes with opposite requirements, have to be reconciled and optimized.

When proposed to offer bids for a set of slots, airlines would tend to bid for those slots that include their regular arrival times. For example airline A has a flight F scheduled to arrive in slot  $i$ . Statistics show that F arrives at  $\dots, i-2, i-1, i, i+1, i+2, \dots$  with respective probabilities  $\dots, P_{i-2}, P_{i-1}, P_i, P_{i+1}, P_{i+2}, \dots$ . Airline A would bid for the slot having the maximum probability, e.g. slot  $i$  if  $P_i$  is substantially greater than the others. This choice makes sense if A is more concerned about schedule stability and it also corresponds to the priority order established by the airport auction coordinator. In case of many similar probabilities, airline A would bid for the most productive slot, i.e. the one with the greatest mean profit,  $\max(Pf_i)$ . In a simplistic way, airline A could specify her preferences of operational policy for this particular flight F by a weight vector  $C(c_1, c_2)$  with  $c_1$

relates to operational needs and  $c_2$  relates to revenue requirements, and the slot to bid for would be determined by the one giving  $\max(c1*[Pf_k | P_k = \max(P_i)], c2*\max(Pf_i))$ .

$Pf_i$  refers to the mean profit generated by those instances of flight F that actually arrived in slot  $i$ , airlines typically can calculate this metric from financial records.  $Pf_i$  could also refer to simulated profit generated by F should airlines have to shift F's arrival time (and maybe F's departure time) from the current slot to  $i$ . Each airline has its own sophisticated system of traffic demand forecasting, schedule simulation, complex cost structure and model. We assume that  $Pf_i$  are readily available from other models.

After determining the slot to bid for, airlines offer bids. Bids should be greater than the starting amount originally specified by the auction coordinator,  $B_i \geq B_{i0}$ , and of course the bid should not exceed a certain level to secure airlines' operational profitability. The level can be specified as a percentage of  $Pf_i$ .

Given the publicly known rules of determining the winner, airline A can calculate its own score  $Sc_{A,i}$  and know its current rank among the bidders. Comparing that to the maximum score  $\max(Sc_i)$  and using the score function, airline A would know how much more she should offer to get to the first rank. Let  $B_i$  be the bid airline A has offered in the previous round (or the starting bid), with our simple score function, A would have to offer  $\frac{\max(Sc_i) - Sc_{A,i}}{w_5}$

more to get slot  $i$ .

Airlines could also have logical constraints like "both slot  $k$  and  $j$  or neither", or "either slot  $m$  or  $n$  but not both", or "accept no more than  $n$  slots of the following  $m \geq n$  slots requested" or "accept slot  $i$  only if slot  $j$  is accepted". These can be easily expressed using integer variables. The logical constraint "Either slot  $m$  or  $n$  but not both" can be formulated as:

$$\begin{cases} B_n \leq Mx_j \\ B_m \leq M(1-x_j), x_j \text{ is binary, } M \text{ is large} \end{cases}$$

Following is our simple optimization model from airlines standpoint for slot auctioning problem:

*Optimization model:*

$$\left\{ \begin{array}{l} \text{Maximize } \sum_i (Pf_i - B_i) \\ \text{Subject to:} \\ B_i \leq My_i \\ -B_i \leq -B_{i0} + M(1-y_i) \\ B_i \leq \alpha Pf_i + M(1-y_i) \\ (B_i + \frac{\max(Sc_i) - Sc_{A,i}}{w_5} * B_{i0}) * y_i \leq \alpha Pf_i * y_i \\ -B_i + \frac{\max(Sc_i) - Sc_{A,i}}{w_5} * B_{i0} \leq -B_{i0} + M(1-y_i) \\ \text{Logical constraints} \\ B_i \geq 0, i = 1..n, y_i \text{ is binary, } M \text{ is a large} \end{array} \right.$$

#### 4. Illustration scenario and results

We have considered a simple example to run the auctioning process among 7 airlines that compete for 8 slots at a single airport. The example has been chosen for illustration purpose in order to validate the model, more complicated scenarios covering complete sets of slots and contingency bids across airports should be tested in the future.

The airport regulator informed the airlines about the auctioning process, minimum bid for each slot, and the weight of the five considered factors as well as the scoring method.

Factors	Weight
Number of seats	0,32
Previous Airline infrastructure investment	0,25
Historic slot occupancy frequency	0,19
OD-Pair	0,13
Bid	0,11

**Table 2: weight of the five determining factors.**

The airlines inform the airport regulator about their choices among the available slots and the information concerning their scheduled flights for those requested slots.

Table 3 below regroups all the information concerning the airlines choices and values of the determining factors:

Slots	1	2	3	4	5	6	7	8
Minimum Bid	5000	7500	8600	10000	12000	8300	6600	5200
AC1 (0.25)	S 30 0 0.4			H 205 1 0.25			L 128 0 0.35	
AC2 (0.19)		L 147 0 0.5		H 283 1 0.4				L 291 1 0.35
AC3 (0.15)			S 18 0 0.25		H 392 1 0.3		S 18 0 0.2	
AC4 (0.13)		S 30 0 0.35		S 30 0 0.15		L 150 0 0.35		
AC5 (0)		S 18 0 0.15	S 30 0 0.06		S 18 0 0.1			S 30 0 0.4
AC6 (0.21)	S 30 0 0.35		L 120 0 0.5	L 85 0 0.2		S 30 0 0.45		
AC7 (0.11)	S 18 0 0.2				H 202 10.3		S 30 0 0.4	

**Table 3 Sample of Airline bid packages relating to the determining factors required for the bids.**

Slots	1	2	3	4	5	6	7	8
Minimum Bid	5000	7500	8600	10000	12000	8300	6600	5200
AC1	1.67 0 1.42			6.83 1 1.25			7.11 0 1.21	
AC2		8.17 0 1.5		9.43 1 1.33				9.7 1 1.06
AC3			1 0 1.42		21.78 1 1.07		1 0 1	
AC4		1.67 0 1.25		1 0 1.25		5 0 1		
AC5		1 0 1	1.67 0 1		1 0 1			1 0 1
AC6	1.67 0 1.17		6.67 0 1.25	2.83 0 1		1 0 1.06		
AC7	1 0 1				11.22 1 1.13		1.67 0 1.07	

**Table 4 Airlines' normalized values of the five determining factors.**

Slots	1	2	3	4	5	6	7	8
Minimum Bid	5000	7500	8600	10000	12000	8300	6600	5200
AC1	1.48			3.23			3.18	
AC2		3.44		3.94				3.98
AC3			1.04		7.75		0.96	
AC4		1.18		0.96		2.20		
AC5		0.62	0.83		0.62			0.62
AC6	1.34		2.96	1.68		1.11		
AC7	0.87				4.30		1.10	

**Table 5 Airlines' scores.**

Slots	1	2	3	4	5	6	7	8
Minimum Bid	5000	7500	8600	10000	12000	8300	6600	5200
AC1	5000			64109			6600	
AC2		7500		8600.00				5200
AC3			149482		9200		139800	
AC4		161590		0.00		8300		
AC5		199773	164945		0.00			164036
AC6	11364		8100.00	185291		90545		
AC7	32727				297745		131400	

**Table 6 Airlines' bids.**

**Round 1**

Slots	1	2	3	4	5	6	7	8
<b>Minimum Bid</b>	<b>5000</b>	<b>7500</b>	<b>8600</b>	<b>10000</b>	<b>12000</b>	<b>8300</b>	<b>6600</b>	<b>5200</b>
AC1	1.48			3.94			3.18	
AC2		3.44		3.94				3.98
AC3			2.96		7.75		3.18	
AC4		3.44				2.20		
AC5		3.44	2.96					3.98
AC6	1.48		2.96	3.94		2.20		
AC7	1.48				7.75		3.18	

**Table 7 Airlines' scores for Round 1.**

**Round 12**

Slots	1	2	3	4	5	6	7	8
<b>Minimum Bid</b>	<b>5000</b>	<b>7500</b>	<b>8600</b>	<b>10000</b>	<b>12000</b>	<b>8300</b>	<b>6600</b>	<b>5200</b>
AC1	187500.00						48000.00	
AC2		58620.00		609800.00				15440.00
AC3					201040.00			
AC4						103340.00		
AC5								
AC6			48900.00					
AC7								

**Table 8 Airlines' bids in Round 12.**

**Round 12**

Slots	1	2	3	4	5	6	7	8
<b>Minimum Bid</b>	<b>5000</b>	<b>7500</b>	<b>8600</b>	<b>10000</b>	<b>12000</b>	<b>8300</b>	<b>6600</b>	<b>5200</b>
AC1	5.50						3.87	
AC2		4.19		11.63				4.19
AC3					10.05			
AC4						3.45		
AC5								
AC6			3.51					
AC7								

**Table 9 Airlines' scores for Round 12.**

The first column reports the value of airline investment factor (percentage). For each requested slot  $i$ , airlines present the information concerning the type of aircraft, number of seats and the type of flight, e.g. airline 2 (AC2) has requested slots 2, 4 and 8, the data entry [H 283 1 0.4] means that AC2 has scheduled a heavy aircraft with 283 seats and the OD-Pair of this flight gives it priority to land, 0.4 is the average slot occupancy rate. S and L denote small and large aircraft.

Airport regulators normalize airlines-provided data to calculate the scores, as shown in Table 4: number of seats, OD-Pair and average slot occupancy

rate are four component terms of the score formula. Values of initial bids for each slot complete the scores of the airlines, which are presented in Table 5; the shaded cells represent the highest scores. The normalization method used by airport regulators consists of dividing the values by the smallest positive value for each factor.

Airlines determine the bids using their own optimization models; the results of Round 1 are shown in table 6, the value 0 means that airlines withdraw from bidding for a particular slot as its price exceeds the expected profit.

Table 7 shows the scores of the airlines, they are equal in each column, reflecting the fact that airlines' optimization models solve the problem in a monolithic way: maximize profits. The model recommends the smallest bid that guarantees low-ranking airlines to keep up with the leading bidder of the previous round, assuming that the latter does not change her bid. The solution serves therefore as a reference for airlines to make rational decisions. If the solution is zero, the bidding value for that slot exceeds airlines' estimated values, otherwise, airlines can bid as much as the optimal solution, or they can consider a trade-off: Bidding more will increase the probability of winning, but will decrease the surplus. A game-playing factor that is airline-specific should be introduced here, due to incomplete information in the auction process, that reflects airlines' risk attitude. In our scenario, we assume that airlines uniformly add 10% of their expected profits to get ahead when there are ties in the auction process. This reaction is certainly a random feature and needs to be calibrated after more study in simulating airlines' behavior.

The auctioning process continues until the closing round or the deadline. Table 8 shows the bids of the last round, with corresponding scores shown in Table 9. For each slot, a unique winner is determined, black-shaded cells depict revealed airlines that could have offered bids for adjacent slots or others as well. The auction outcome results in the traffic mix (S, L, L, H, H, L, L, L) with also the largest sum of seats. Based on the auction outcome, a particular airport coordinator could calibrate the coefficient values to reflect the airport's current practice and operational preferences.

## 5. Observations

Market-based mechanisms (such as auctions) may promise to provide better synchronization and maximization of air traffic operations. The properly designed auction's role in solving the slot allocation problem is four-fold: 1) better balancing of operational supply and demand; 2) decreasing queuing delay's at high capacity fractions; 3) decreasing potential hazardous risks due to loss of separation at high arrival rates between heavy and small aircraft; and 4) better utilization of scarce runway resources by spreading out flight schedules. Since auctions involve many stakeholders with different (and conflicting) interests. The model must consider many relevant factors, including financial

gains from price bids, aircraft size decisions to optimize the overall enplanement performance of the whole system, aircraft separation safety assurance, prior investment equity and fair and open access to airport markets.

More work on auction design and evaluation is needed:

- More realistic model inputs such as score parameter weights, airline historic performance data and scoring formula;
- More realistic modeling in terms of airlines' behavior to reflect the possibility of preemptive or jump bidding.
- Evaluation of scenarios that involve departure and arrival slots at different airports to illustrate package-bidding reality
- Secondary spot market designs for dynamic and optimal slot utilization;
- The network simulation model used to evaluate these auction models needs to be improved and validated.

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<sup>i</sup> The Herfindel-Hirschmann Index (HHI) is a market concentration index used by the US DOJ and FTC to estimate monopolistic trends. The HHI is the sum of the squares of a activities industrial market share and ranges from 100 (perfect competition) to 10,000 (a perfect monopoly). In practice, <1000 is considered to be an un-concentrated market and > 1800 is considered to be a highly concentrated market.

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