

Price-Setting Auctions for Airport Slot Allocation: a Multi-Airport Case Study

An Agent-Based Computational Economics Approach to Strategic Slot Allocation

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Abstract—ACCESS (www.access-sesar.eu) is a SESAR WPE research project that addresses the study of market-based mechanisms for airport slot allocation from the perspective of agent-based computational economics. In this paper, we present the airport slot allocation simulation model developed by ACCESS and we apply it to the evaluation of primary slot auctioning in a multi-airport scenario. We show how combinatorial price-setting auctions can be used to balance capacity and demand in a decentralized manner, without the need for airlines to disclose sensitive information, so that the available capacity is used by those airlines able to make best economic use of it. The end prices of the auction reveal the economic value of each slot.

Keywords—airport slot allocation; combinatorial auctions; auction engineering; agent-based computational economics.

I. INTRODUCTION

The continuous growth in air transport along the last decades has put increased pressure on airport capacity. The construction of new airports or new runways has a look-ahead time of 5 to 10 years, and it can often be complicated or even impossible, due to cost, environmental impact, land availability, or political reasons. Consequently, improvements in the management of capacity and demand have lately been the subject of much attention. The ACCESS project focuses on demand management policies for the allocation of airport capacity.

Even though several studies carried out along the last decade have concluded that administrative slot controls may hinder competition and create entry barriers ([1], [2], [3], [4]), slot control and schedule coordination have so far been the dominant approach in most of the busiest airports in the world outside the US. Slot allocation at EU airports is governed by Regulation 95/93 [5] and its respective amendments, which retain and develop the principles of the IATA slot allocation process [6]. The European Commission has recently acknowledged the need to revise the Slot Regulation to favor more efficient use of airport capacity, opening the door to the introduction of market-based approaches [7].

Market mechanisms, such as primary slot auctioning and secondary slot trading, have been proposed as a means to ensure that scarce capacity is used by those airlines making best economic use of it, but they also raise a number of concerns, from the negative impact on airline operating costs to market failures. There is therefore a need for a comprehensive assessment of different market designs [8]. The main goal of ACCESS is to develop a modelling and simulation framework for the evaluation of slot allocation mechanisms, allowing the assessment of their impact on network performance and the costs and benefits for the involved stakeholders.

Different authors have investigated primary slot auctioning and secondary slot trading relying on analytical models ([9], [10], [11], [12]). ACCESS adopts a different approach, based on auction theory and agent-based modelling. Auction theory is an applied branch of economics which deals with how agents act in auction markets and investigates the properties of those markets to inform the design of real-world auctions [13]. An agent-based model is a computer model consisting of a set of software objects, the agents, interacting within a virtual environment. The agents, often with a one-to-one correspondence with the real world actors, react to and act on their environment and on other agents trying to achieve their goals [14]. An overview of the applications of agent-based modelling to other markets can be found in [15]. Due to the complexity of the combinatorial assignment problems underlying primary slot auctioning and secondary slot trading, agent-based computational economics provides a particularly suitable framework to study different alternatives for market design, allowing the exploration of features (such as bounded rationality, evolutionary behavior or anti-competitive practices) that are difficult to capture by classical approaches from economics and operations research.

In this paper, we present the ACCESS simulation model and its application to primary slot auctioning in a multi-airport scenario. Section II describes the general logic of the simulation and the main modelling assumptions. Section III describes the proposed case study. Section IV presents and

discusses the main results of the simulation. Section V concludes and discusses future research directions.

II. THE ACCESS SIMULATION MODEL

A. Overall Model Structure

The overall structure of the ACCESS simulation platform is shown in Fig. 1.

- The inputs of the simulation environment are the particular combinations of primary and secondary slot allocation mechanisms to be studied: these are the policies under testing, and it is in the hand of the regulator to modify them.
- A set of exogenous variables are considered to take into account different elements that affect the model without being affected by it, such as the evolution of fuel prices or passenger demand between different origin-destination pairs.
- The core of the simulation model is composed by an agent-based model (ABM) comprising four types of agents: (i) the slot allocation coordinator, (ii) airports, (iii) airlines, and (iv) passengers. Agents interact according to the decision sequence depicted in Fig. 2.
- The output data are a set of indicators influenced by the slot allocation mechanisms, intended to facilitate the evaluation and comparison of different mechanisms.

Different combinations of the inputs can be simulated across a set of pre-established scenarios representing different

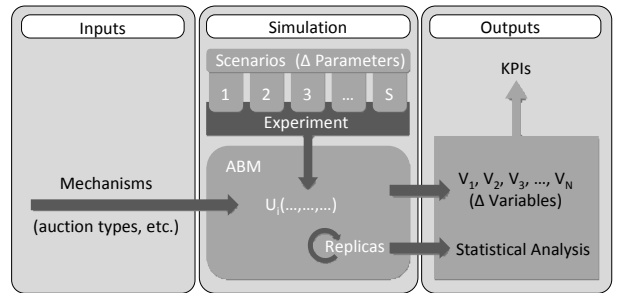


Figure 1. Overall structure of the ACCESS simulation platform

situations involving aspects not under the control of the regulator/policy maker. A scenario is composed by a set of airports, a set of airlines in the market, and a pre-defined evolution of air travel demand and fuel costs. Additionally, the simulation platform allows the selection of the simulation time step (e.g., one month) and the temporal horizon of the simulation (one or several consecutive seasons).

In the remaining of this section, we describe briefly each element of the model. The simulation platform specification and the functional and technical design (including the algorithmic implementation of the model) can be found in [16] and [17], respectively.

B. Model Inputs: Slot Allocation Mechanisms

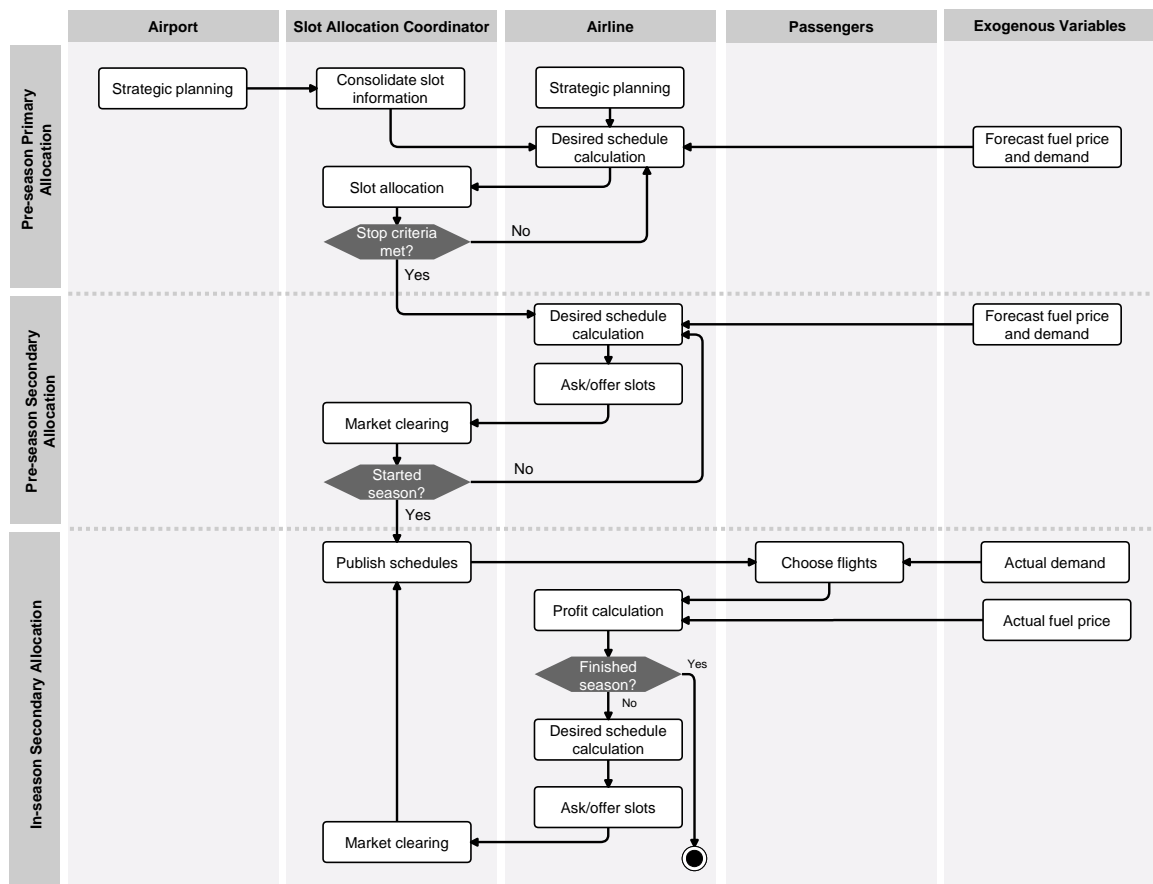


Figure 2. General logic of the simulation model

The platform allows the simulation of different primary slot allocation mechanisms, including: (i) administrative slot allocation based on EU Regulation 95/93; (ii) combinatorial auctions with different types of price-update mechanisms: ascending, descending, and Walrasian. In Walrasian auctions, the prices are raised if the demand is greater than the capacity and lowered if the capacity is greater than the demand. This process can be adaptive, with prices varying as a function of the excess of demand or supply, or non-adaptive, where prices vary by a constant quantity; and (iii) hybrid mechanisms, e.g., grandfather rights + auctioning of the slot pool.

The secondary slot allocation mechanisms include: (i) trading in a decentralized, over-the-counter market; and (iii) trading in a centralized, organised market.

The system allows the simulation of only a single phase, as well as the combination of one primary and one secondary slot allocation mechanism over one or several seasons.

C. Exogenous Variables

Exogenous variables are used for setting arbitrary external conditions that affect the model but are not affected by it. The current version of the ACCESS simulation model considers two exogenous variables: air travel demand and fuel prices.

Passenger demand is modelled as a number of business passengers and leisure passengers, each with a certain utility curve and a value of time, at each simulation step and for each origin-destination pair. Forecasted passenger demand is known by the airline agents, which use it to decide their preferred schedule. Actual passenger demand is calculated by the model as a deviation from the forecasted demand, by adding a stochastic noise at each simulation step. As a result, actual demand may differ from the forecast, and the forecast values for the subsequent simulation steps are revised accordingly.

Similarly, there is a forecasted fuel price profile (which could be generalized to other factors influencing airline operating costs) known by the airlines. As for travel demand, the actual fuel price is calculated as a deviation from the forecast, by adding a stochastic noise to the forecasted value at each simulation step and revising the forecast values for the subsequent simulation steps.

The purpose of including air travel demand and fuel prices as exogenous variables with a stochastic component is to test the ability of different slot allocation mechanisms to adapt to changing circumstances in the presence of uncertainty.

D. Agents' Behavior

The slot allocation coordinator has the role of applying the selected slot allocation mechanism. If administrative slot allocation based on EU Regulation 95/93 is chosen, the slot allocation coordinator plays the role of real-world airport coordinators, allocating slots according to the administrative rules. In the case of slot auctioning, the slot allocation coordinator agent acts as the auctioneer, announcing the available slots, gathering the airlines' requests, updating slot

prices according to the selected auction type, adjusting the result of the allocation (if needed) to ensure full compatibility with capacity constraints, and announcing the final slot allocation and the final prices.

Airport agents take two actions at the beginning of each season: they communicate their capacity and landing fees, and they decide whether or not to expand their capacity. Airport may be non-coordinated, schedules facilitated, or coordinated. For coordinated airports, two sets of capacity constraints are defined: (i) maximum number of arrival, departure and total slots per coordination time interval along the day, and (ii) maximum number of arrival, departure and total slots during several consecutive coordination time intervals (rolling capacity). The coordination time interval is the valid period of time for a slot to be used at a certain airport. Several slots may be allocated within the same coordination interval. The coordination interval has different duration at each airport.

The airline agent is the most complex one. At each simulation step, airline agents take the following actions: (i) calculate their desired schedule, i.e. set of routes that airline would like to fly, the aircraft types on these routes, flight frequencies and departure times. For iterative slot allocation processes, such as auctions, the desired schedule is recalculated at each iteration; (ii) define the fares for such desired schedule; (iii) estimate the market share they will capture and therefore the expected profit, based on the forecast travel demand and a number of assumptions about the behavior of their competitors; (iv) decide which slots they will request (or offer, in the case of being able to sell slots in the secondary market) and at what maximum (resp. minimum) price; (v) pay for the slots they get as a result of the slot allocation process or the secondary market / be paid for the slots they sell in the secondary market; (vi) publish their final schedule and their final fares; and (vii) calculate their actual profit, based on the actual behavior of demand as well as on their operating costs.

Finally, each passenger represents a group of real life passengers (business or leisure) constituting the potential demand for a certain origin-destination pair. The goal is to simulate the behavior of demand as a response to the flights offered by the airline agents. At the end of each simulation step, the passenger agents determine the actual number of passengers in each flight as a function of the passenger utility curve and value of time, and the schedule and price of the flights offered by airlines for each origin-destination pair. The number of passengers that choose each flight is then used to compute the profit obtained by each airline.

E. Model Outputs: Performance Indicators

The output of the model is a set of indicators aimed to evaluate the performance of the slot allocation mechanisms along the performance areas defined in [8], including data on available slots, slot requests, slot prices, slot allocation and slot use, as well as the utilities (i.e., the value of their objective functions) obtained by the airlines, the airports and the passengers for each particular scenario.

III. CASE STUDY: PRIMARY SLOT AUCTIONING IN A MULTI-AIRPORT SCENARIO

A. Objectives and Methodology

The proposed case study simulates the outcome of a combinatorial price-setting auction for primary slot allocation, extending the results reported in [18] to a multi-airport scenario. The simulation scenario encompasses a reduced set of airports and airlines, with the aim to represent in a realistic yet simplified manner the dynamics of the principal airport and airlines types. The goal is to allow a detailed analysis of the performance of the proposed auction mechanism in terms of its ability to match capacity and demand, as well as its impact on different types of airlines with different business models and cost structures. Only a single season is simulated, and it is assumed that all available capacity is simultaneously auctioned for all the coordinated airports in the network.

The scenario includes two types of airspace users: network carriers and low cost operators. The set of airports has been defined so as to be consistent with the airlines included in the scenario, intending to represent a mix of hubs and secondary airports with different coordination levels. Airline and airport attributes are based on data from real-world airlines and airports.

The behavior of the airline agents included in the case study is a simplification of the airline behavioral model described in Section II. We use an approach similar to the one described in [18]. Each airline intends to operate a pre-defined set of flights. Each of these flights provides a utility that is a function of the time at which the flight is scheduled. If the price of all the slots is 0, airlines will request those slots allowing them to operate their preferred schedule, i.e., the one that maximizes the utility obtained from the flights. If, as a result of the auction, the price of certain slots increases, airlines may decide to shift the departure/arrival times of certain flights, so as to maximize the net utility, i.e., the utility obtained from the flight minus the cost of the slots required to operate such flight. In a scenario with a high level of congestion, airlines could eventually decide to cancel certain flights, if the net utility for all possible options were negative.

B. Description of the Combinatorial Price-Setting Auction

The proposed combinatorial price-setting auction has the following characteristics:

- As a price-setting auction, the auctioneer (in this case, the so-called “slot allocation coordinator”) varies the prices depending on the difference between supply and demand. The supply is determined by the capacity constraints of the airports involved in the auction.
- As a price-setting auction, several slots can be combined in one request, allowing an airline to bid at the same time for all its preferred slots. This prevents the risk that a bidder cannot obtain the complementary items of other assets already acquired, thus not being able to extract the expected utility of such assets.

The auction follows an iterative process:

- Slot prices are communicated to the participants for arrival and departure slots in each coordination interval. In our case study, the initial price of all the slots in the first iteration is 0.
- At each iteration, airlines make their requests for their preferred slots depending on the current prices and their internal objective functions. For example, if some of the originally preferred slots are too expensive, they may shift some of their requests to other coordination time intervals. The airlines only know the prices at each round, but not the bids of the other airlines.
- The auctioneer compares the number of requested slots with the different capacity constraints and increases or decreases the slot prices in each coordination interval according to a pre-defined price update algorithm. These new prices are announced and used to repeat the process in the next iteration.

The process is repeated until the auction stop criterion is met. In our case study, the stop criterion used comprises the two following conditions: (i) all capacity constraints are respected; and (ii) prices reach a state of equilibrium

A more detailed description of the proposed iterative combinatorial auction for the case of a single airport, including the price evolution along the auction, can be found in [18].

C. Scenario Description

The scenario is composed by two network carriers, NW1 and NW2, and two low cost carriers, LC1 and LC2. Network carriers schedule their flights to/from their hub, connecting their hub with a number of regional airports as well as with other hubs. Low cost operators are characterized by their spoke-to-spoke network.

Two types of airports have been represented: one hub for each network carrier (HUB1 and HUB2) and two regional airports (REG1 and REG2), considered as feeders for the hubs. HUB1 and HUB2 are coordinated airports with a 10 min coordination interval, REG1 is also coordinated and has a coordination interval of 20 min, and REG2 is non-coordinated. Hub airports also have rolling capacity constraints defined for 60 min intervals.

Each airline intends to schedule a set of flights according to the connections shown in Fig. 3.

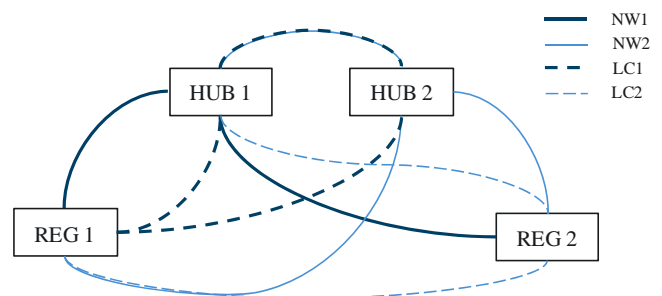


Figure 3. Airport and airline connections

Flight duration is considered to be fixed. For each flight, there is a preferred departure (and consequently arrival) time for which the utility obtained by the airline is maximized. The utility obtained by each airline from each flight as a function of the scheduled departure/arrival time is assumed to have the shape shown in Fig. 4.

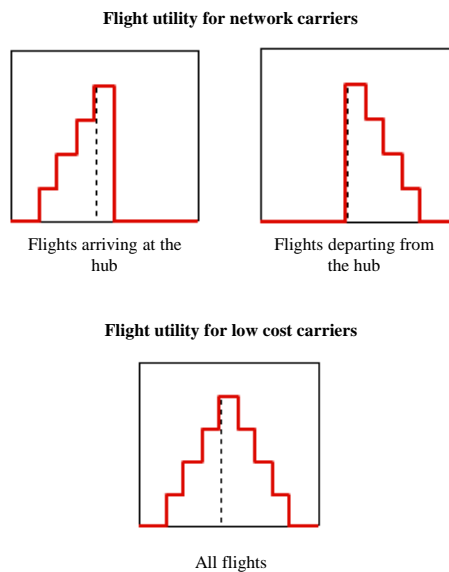


Figure 4. Flight utility for network carriers and low cost carriers. The dotted line indicates the ideal departure/arrival time

The utility curves in Fig. 4 are based on the assumption that network carriers schedule their flights in the form of waves of arrivals and departures to/from their hub, and therefore utility falls abruptly if an arriving (resp. departing) flight is scheduled too late (resp. too early) to allow passengers connection at the hub. Low cost operators operate according to a point-to-point network, and therefore the utility curve is assumed to be symmetric. It is also assumed that the peak utility is higher for network carriers (20 and 18 monetary units (m.u.) per flight for NW1 and NW2, respectively) than for low cost carriers (16 and 14 m.u. per flight for LC1 and LC2, respectively), and that time sensitivity is higher in the case of network carriers, i.e., the utility of a flight drops faster when the flight is shifted from its optimal departure/arrival time following a staircase function with jumps of equal length, until it is 0. For NW1, the utility is 0 when the flight is scheduled 110 minutes or more before (resp. after) the ideal time for flights arriving at (resp. departing from) HUB1. For NW2, the utility is 0 when the flight is scheduled 130 minutes or more before (resp. after) the ideal time for flights arriving at (resp. departing from) HUB2. For LC1, the utility is 0 when the flight is scheduled 230 minutes or more away from the ideal time. For LC1, the utility is 0 when the flight is scheduled 250 minutes or more away from the ideal time.

The preferred schedule of each airline (i.e., the one that maximizes the utility of all the flights) is shown in Table I.

TABLE I. AIRLINES PREFERRED SCHEDULE

Flight ID	Airline	Departure Airport	Preferred TOD	Arrival Airport	Preferred TOA
1	NW1	REG2	7:20	HUB1	8:37
2	NW1	HUB1	10:00	REG2	11:17
3	NW1	REG2	12:10	HUB1	13:27
4	NW1	HUB1	15:55	REG2	17:12
5	NW1	REG2	18:35	HUB1	19:52
6	NW1	HUB1	20:30	REG2	21:47
7	NW1	REG1	7:55	HUB1	8:51
8	NW1	HUB1	10:55	REG1	11:51
9	NW1	REG1	12:55	HUB1	13:51
10	NW1	HUB1	15:45	REG1	16:41
11	NW1	REG1	18:05	HUB1	19:01
12	NW1	HUB1	20:00	REG1	20:56
13	NW1	REG1	21:40	HUB1	22:36
14	NW1	HUB1	22:40	REG1	23:36
15	NW2	REG1	7:25	HUB2	9:29
16	NW2	HUB1	7:15	HUB2	8:51
17	NW2	REG2	7:30	HUB2	8:36
18	NW2	REG2	8:45	HUB2	9:51
19	NW2	HUB1	8:25	HUB2	10:01
20	NW2	HUB2	10:00	HUB1	11:36
21	NW2	HUB2	10:15	REG2	11:21
22	NW2	HUB2	11:10	REG1	13:14
23	NW2	HUB2	11:00	HUB1	12:36
24	NW2	HUB2	12:00	REG2	13:06
25	NW2	REG2	13:05	HUB2	14:11
26	NW2	HUB1	12:50	HUB2	14:26
27	NW2	REG1	13:35	HUB2	15:39
28	NW2	HUB1	14:15	HUB2	15:51
29	NW2	REG2	14:20	HUB2	15:26
30	NW2	REG1	14:35	HUB2	16:39
31	NW2	REG2	15:20	HUB2	16:26
32	NW2	HUB2	16:00	HUB1	17:36
33	NW2	HUB2	16:10	REG2	17:16
34	NW2	HUB2	17:20	REG1	19:24
35	NW2	HUB2	17:00	HUB1	18:36
36	NW2	HUB2	17:15	REG2	18:21
37	NW2	HUB2	17:30	REG1	19:34
38	NW2	HUB2	18:00	HUB1	19:36
39	NW2	REG1	18:50	HUB2	20:54
40	NW2	HUB1	19:00	HUB2	20:36
41	NW2	REG2	19:40	HUB2	20:46
42	NW2	HUB1	20:15	HUB2	21:51
43	NW2	HUB2	21:00	REG2	22:06
44	NW2	HUB2	21:30	HUB1	23:06
45	NW2	HUB2	21:40	REG1	23:44
46	NW2	HUB2	21:50	REG2	22:56
47	LC1	HUB2	6:35	REG1	8:39
48	LC1	HUB2	7:15	HUB1	8:51
49	LC1	REG1	7:50	HUB1	8:46
50	LC1	HUB1	9:30	HUB2	11:06
51	LC1	HUB1	9:55	REG1	10:51
52	LC1	REG1	13:00	HUB2	15:04
53	LC1	HUB2	14:05	HUB1	15:41
54	LC1	REG1	16:25	HUB1	17:21
55	LC1	HUB1	16:20	HUB2	17:56
56	LC1	HUB2	17:20	REG1	19:24
57	LC1	HUB1	18:00	REG1	18:56
58	LC1	HUB2	17:55	HUB1	19:31
59	LC1	REG1	19:50	HUB2	21:54
60	LC1	HUB1	20:15	HUB2	21:51
61	LC2	REG2	6:45	HUB1	8:02
62	LC2	HUB1	8:40	REG2	9:57
63	LC2	REG1	12:10	REG2	13:27
64	LC2	REG2	15:40	REG1	16:57
65	LC2	REG2	18:30	HUB1	19:47
66	LC2	HUB1	20:25	REG2	21:42

TOD = Time of Departure; TOA = Time of Arrival

The capacity constraints of the three coordinated airports included in the case study are shown in Table II.

TABLE II. AIRPORT CAPACITY

HUB1	Coord time interval		REG1	Coord time interval	
	10min	60min		60min	
ARR	1	4	ARR	3	
DEP	1	4	DEP	3	
TOTAL	1	6	TOTAL	4	

HUB2	Coordination Time Interval					
	10 min			1 hour		
	ARR	DEP	TOTAL	ARR	DEP	TOTAL
0:00	0	0	1	2	2	3
1:00	0	0	1	1	2	3
2:00	0	0	1	1	1	2
3:00	0	0	1	1	1	2
4:00	0	0	1	1	1	2
5:00	0	0	1	2	2	3
6:00	1	0	1	2	2	5
7:00	1	1	1	3	4	7
8:00	1	1	1	4	4	7
9:00	1	1	1	4	4	7
10:00	1	1	1	4	4	8
11:00	1	1	1	4	4	7
12:00	1	1	1	3	4	7
13:00	1	1	1	3	4	7
14:00	1	1	1	4	4	7
15:00	1	1	1	3	4	7
16:00	1	1	1	3	4	7
17:00	1	1	1	4	4	7
18:00	1	1	1	4	4	7
19:00	1	1	1	4	4	7
20:00	1	1	1	3	4	7
21:00	1	1	1	3	3	6
22:00	1	1	1	3	2	5
23:00	0	1	1	2	2	4

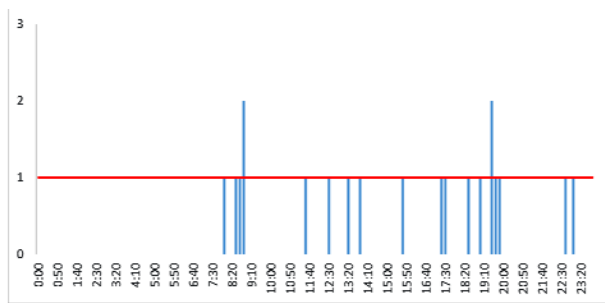


Figure 5. Arrivals in HUB1: capacity (red) vs total slot requests (blue)

For HUB1 and REG1, capacity is constant, while for HUB2 it varies along the day. Accumulated airline requests violate capacity constraints. Fig. 5 shows arrival capacity for HUB1 vs the requested slots. Similar figures can be built for the rest of capacity constraints in the three coordinated airports, showing that the desired schedule violates several of such constraints, especially at peak times around 7-8 am and 7-8 pm.

IV. SIMULATION RESULTS

A. Requested Schedule vs Final Schedule

The auction runs for 496 iterations until all capacity constraints are respected and prices reach an equilibrium state. The results of the auction are presented in Table III. The last column shows the net utility of each flight, i.e., the utility obtained from the flight as finally scheduled, minus the price(s) of the slot(s). For example, Flight #1 obtains its preferred slot, and thus a utility of 20 m.u.; the price of the arrival slot in

HUB1 is 1.20 m.u., so the net utility is 18.80 m.u. In REG2 there are no slots because the airport is non-coordinated and it is assumed to have enough capacity for all the flights.

TABLE III. SLOT ALLOCATION RESULTING FROM THE AUCTION

Flight ID	Airline	Departure Airport	Obtained Departure Slot	Arrival Airport	Obtained Arrival Slot	Net Flight Utility
1	NW1	REG2	-	HUB1	8:30	18.80
2	NW1	HUB1	10:00	REG2	-	20.00
3	NW1	REG2	-	HUB1	13:20	20.00
4	NW1	HUB1	15:50	REG2	-	20.00
5	NW1	REG2	-	HUB1	19:50	17.10
6	NW1	HUB1	20:30	REG2	-	17.60
7	NW1	REG1	7:40	HUB1	8:50	18.20
8	NW1	HUB1	10:50	REG1	11:40	20.00
9	NW1	REG1	12:40	HUB1	13:50	20.00
10	NW1	HUB1	15:40	REG1	16:40	19.20
11	NW1	REG1	18:00	HUB1	19:00	16.90
12	NW1	HUB1	20:00	REG1	20:40	15.80
13	NW1	REG1	21:40	HUB1	22:30	20.00
14	NW1	HUB1	22:40	REG1	23:20	20.00
15	NW2	REG1	7:20	HUB2	9:20	18.00
16	NW2	HUB1	7:10	HUB2	8:50	18.00
17	NW2	REG2	-	HUB2	8:30	18.00
18	NW2	REG2	-	HUB2	9:40	16.62
19	NW2	HUB1	8:10	HUB2	9:50	14.92
20	NW2	HUB2	10:00	HUB1	11:30	15.40
21	NW2	HUB2	10:10	REG2	-	16.70
22	NW2	HUB2	11:10	REG1	13:00	18.00
23	NW2	HUB2	11:00	HUB1	12:30	17.20
24	NW2	HUB2	12:00	REG2	-	18.00
25	NW2	REG2	-	HUB2	14:10	18.00
26	NW2	HUB1	12:50	HUB2	14:20	18.00
27	NW2	REG1	13:20	HUB2	15:30	17.20
28	NW2	HUB1	14:10	HUB2	15:50	17.20
29	NW2	REG2	-	HUB2	15:20	17.20
30	NW2	REG1	14:20	HUB2	16:30	17.20
31	NW2	REG2	-	HUB2	16:20	17.80
32	NW2	HUB2	16:00	HUB1	17:30	18.00
33	NW2	HUB2	16:10	REG2	-	18.00
34	NW2	HUB2	17:20	REG1	19:20	11.45
35	NW2	HUB2	17:00	HUB1	18:30	14.20
36	NW2	HUB2	17:10	REG2	-	12.30
37	NW2	HUB2	17:30	REG1	19:20	12.25
38	NW2	HUB2	18:00	HUB1	19:30	14.75
39	NW2	REG1	18:40	HUB2	20:50	17.65
40	NW2	HUB1	18:40	HUB2	20:10	15.03
41	NW2	REG2	-	HUB2	20:40	17.65
42	NW2	HUB1	20:10	HUB2	21:50	13.40
43	NW2	HUB2	21:00	REG2	-	16.60
44	NW2	HUB2	21:30	HUB1	23:00	16.20
45	NW2	HUB2	21:40	REG1	23:40	16.00
46	NW2	HUB2	22:00	REG2	-	15.62
47	LC1	HUB2	7:00	REG1	9:00	13.91
48	LC1	HUB2	7:20	HUB1	9:00	14.75
49	LC1	REG1	7:40	HUB1	8:40	14.30
50	LC1	HUB1	9:20	HUB2	10:50	15.30
51	LC1	HUB1	9:50	REG1	10:40	16.00
52	LC1	REG1	12:40	HUB2	14:50	15.30
53	LC1	HUB2	13:50	HUB1	15:30	15.30
54	LC1	REG1	16:20	HUB1	17:20	16.00
55	LC1	HUB1	16:20	HUB2	17:50	15.35
56	LC1	HUB2	18:10	REG1	20:00	12.07
57	LC1	HUB1	18:00	REG1	18:40	16.00
58	LC1	HUB2	18:40	HUB1	20:20	11.37
59	LC1	REG1	20:00	HUB2	22:10	14.61
60	LC1	HUB1	20:40	HUB2	22:20	12.61
61	LC2	REG2	-	HUB1	8:00	13.60
62	LC2	HUB1	8:20	REG2	-	12.33
63	LC2	REG1	12:00	REG2	-	14.00
64	LC2	REG2	-	REG1	17:20	14.00
65	LC2	REG2	-	HUB1	19:20	12.58
66	LC2	HUB1	21:00	REG2	-	11.76

Slots are expressed as the start time of the coordination interval

B. Demand and Capacity Balancing

Fig. 6 shows how the cumulative number of arrival slots allocated to airlines in HUB1 (blue) does not exceed nominal arrival capacity (red). Similar figures could be built for the rest of capacity constraints in the three coordinated airports, showing that the final schedule resulting from the auction respects all such constraints.

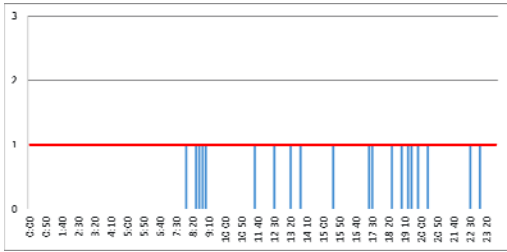


Figure 6. Arrivals in HUB1: capacity (red) vs total allocated slots (blue)

C. Analysis of Slot Prices

Prices rise in the most congested intervals due to higher demand. Consequently, net flight utility in such congested intervals drops, and some airlines shift their requests to less congested intervals, where slots are cheaper and net utility is higher. Fig. 7 shows the final slot prices in HUB2. The highest prices are concentrated in the most congested intervals.

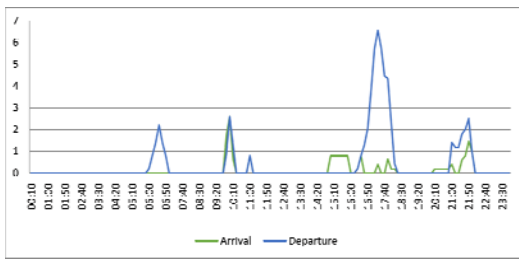


Figure 7. Final prices of HUB2 arrival (green) and departure (blue) slots

Fig. 8 shows the evolution of the departure slot prices along the different auction rounds.

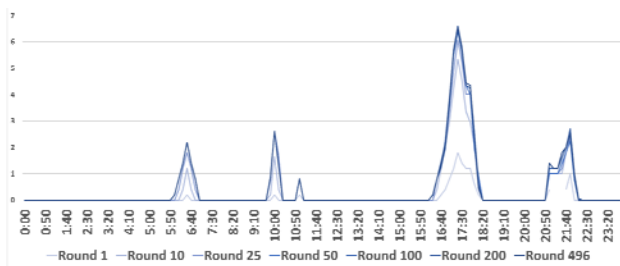


Figure 8. Evolution of HUB2 departure slot prices along the auction

Tests performed for the same scenario have shown that the convergence speed to equilibrium prices strongly depends on the initial prices, the price update mechanism and its parameterization. It can be expected that the optimization of

these factors will lead to a significant reduction of the number of iterations required to achieve similar results.

D. Impact on Network and Low Cost Airlines

Once a feasible schedule is obtained, the impact of the slot allocation process on the different types of airlines, as a function of their preferences and flight patterns, can be analyzed. Tables IV and V show the total price and the average price per slot paid by network and low cost airlines.

TABLE IV. TOTAL PRICE PAID FOR THE SLOTS

Airline		Total Price Paid (m.u.)	
Network carriers	NW1	16.10	62.25
	NW2	46.15	
Low cost carriers	LC1	5.70	6.95
	LC2	1.25	

TABLE V. AVERAGE PRICE PAID PER SLOT

Airline		Total Price Paid (m.u.)	
Network carriers	NW1	1.15	1.35
	NW2	1.44	
Low cost carriers	LC1	0.41	0.35
	LC2	0.21	

As one of the assumptions for this case study was that the flight utility obtained by network carriers from their optimal schedule is higher than that of low cost carriers, network carriers are willing to pay higher sums to get slots as close as possible to their preferences, while low cost carriers, for which flight utility falls more slowly as they depart from their optimal schedule, are willing to accept slots further away from their preferred ones as long as prices stay low. Therefore network carriers pay higher amounts of money and have a small amount of shifted flights, while low cost carriers get cheaper slots at the expense of a greater amount of shifted flights.

TABLE VI. PERCENTAGE OF SHIFTED FLIGHTS

Airline		Percentage of Total Flights Shifted from Preferred Schedule	
Network carriers	NW1	7.14%	13.04%
	NW2	15.63%	
Low cost carriers	LC1	62.29%	65%
	LC2	66.67%	

TABLE VII. AVERAGE SHIFT PER FLIGHT

Airline		Average Shift per Flight (Number of Coordination Intervals)	
Network carriers	NW1	0.07	0.54
	NW2	0.75	
Low cost carriers	LC1	1.57	1.60
	LC2	1.67	

Finally, Table VIII shows the maximum achievable utility and the final utility obtained by network and low cost airlines.

TABLE VIII. MAXIMUM UTILITY VS FINAL UTILITY

Airline		Maximum Utility (m.u.)	Final Utility (m.u.)	Difference
Network carriers	NW1	280	158.8	600.5
	NW2	576	441.7	
Low cost carriers	LC1	224	202.9	281.1
	LC2	84	78.3	

V. CONCLUSIONS AND FUTURE DIRECTIONS

In this paper, we have presented an agent-based model aimed to investigate the effects of different airport slot allocation mechanisms. The model simulates the behavior of a set of airlines competing over a congested airport network, allowing the prediction of the resulting schedule and the utilities obtained by the airlines. We have applied this model to evaluate the impact of primary slot allocation through a combinatorial price-setting auction in a simplified scenario. The simulation illustrates how the auctioning mechanism allows the balancing of capacity and demand in a decentralized manner, without the need for airlines to disclose sensitive information. Different airlines are affected in different ways, depending on their business model. The available capacity is allocated to those airlines able to make best economic use of it, and the economic value of each slot emerges from the auction.

Several model extensions are being implemented and will be used for future studies, in particular a more complex airline behavioral model. Instead of using a set of pre-defined flights, each airline will determine its preferred schedule as a function of the forecasted travel demand and the expected profit. Airline agents will be endowed with learning capabilities, so that they are able to improve their estimation of future profits from the observed behavior of their competitors in previous seasons. Behaviors other than utility maximization will also be explored, e.g., anticompetitive practices. Additional experiments will be conducted to optimize the design of the auctions (e.g., testing different price update mechanisms) and explore how the presence of more airports and airlines affects the results and the convergence time. The outcome of slot auctioning will be compared with the current administrative system, as well as with that obtained by solving the equivalent optimization problem, in order to evaluate the ability of different types of auctions to yield an optimal (or nearly optimal) solution according to different optimization criteria (e.g., maximization of social welfare). Finally, simulations will be conducted to evaluate different combinations of primary and secondary slot allocation mechanisms along several seasons in more complex and realistic scenarios, as well as to validate the model, as a necessary step prior to applying the proposed approach to inform decision making in the real world. The developed framework and the proposed computational experiments are expected to advance the state of the art in the strategic management of airport demand, allowing a more comprehensive understanding of the benefits and risks of market mechanisms and informing future policy developments.

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REFERENCES

- [1] Dot Econ Ltd., "Auctioning airport slots: a report for HM treasury and the department of the environment, transport and the regions", London, UK, 2001.
- [2] NERA, "Study to Assess the Effects of Different Slot Allocation Schemes", Technical Report prepared for the European Commission (DG TREN), London, UK, 2004.
- [3] Mott MacDonald, "Study on the Impact of the Introduction of Secondary Trading at Community Airports", Technical Report prepared for the European Commission (DG TREN), London, UK, 2006.
- [4] Steer Davies Gleave, "Impact assessment of revisions to Regulation 95/93", Final report prepared for the European Commission (DG MOVE), London, UK, 2011.
- [5] Council of the European Communities, European Council Regulation (EEC) No. 95/93 of January 1993 on Common Rules for the Allocation of Slots at Community Airports. Official Journal of the European Union, L 14, 22.01.1993, p.1. Brussels, Belgium, 1993.
- [6] IATA, "Worldwide Slot Guidelines", 7th Ed.. Montreal, Canada, 2015.
- [7] European Commission, "Airport package. Proposal for a Regulation of the European Parliament and the Council on common rules for the allocation of slots at European Union airports", COM(2011) 827 final. Brussels, Belgium, 2011.
- [8] A. Ranieri, N. Alsina, L. Castelli, T. Bolic, and R. Herranz, "Airport slot allocation: performance of the current system and options for reform", Proceedings of the 3rd SESAR Innovation Days, Stockholm, Sweden, November 2013.
- [9] K.G. Zografos, Y. Salouras, and M.A. Madas, "Dealing with the efficient allocation of scarce resources at congested airports", Transportation Research Part C Vol. 21, pp. 244–256, 2012.
- [10] L. Castelli, L., P. Pellegrini, and R. Pesenti, "Airport slot allocation in Europe: economic efficiency and fairness", International Journal of Revenue Management, Vol. 6, No. 1-2, pp. 28-44, 2012.
- [11] P. Pellegrini, L. Castelli, and R. Pesenti, "Secondary trading of airport slots as a combinatorial exchange", Transportation Research Part E 48, pp. 1009-1022, 2012.
- [12] P. Pellegrini, P., L. Castelli, and R. Pesenti, "Metaheuristic algorithms for the simultaneous slot allocation problem", IET Intelligent Transport Systems, Vol. 6, Iss. 4, pp. 453–462, 2012.
- [13] P. Klemperer, The economic theory of auctions, Edward Elgar, 1999.
- [14] S. Moss, "Relevance, Realism and Rigour: A Third Way for Social and Economic Research", Report No. 99-56, Centre for Policy Modelling, Manchester Metropolitan University. Manchester, UK, 1999.
- [15] ACCESS Consortium, "Position Paper: Application of Agent-Based Computational Economics to Strategic Slot Allocation. State-of-the-art and Future Challenges", April 2013.
- [16] SESAR WPE ACCESS Project (E.02.29), Deliverable D3.1 "Simulation framework specification", October 2014.
- [17] SESAR WPE ACCESS Project (E.02.29), Deliverable D3.2 "Simulation and analysis toolset", July 2015.
- [18] M. Ramírez, F.A. Villafañez, A. Araúzo, A. López-Paredes, "Agent-Based Pilot Model for Alternative Primary Airport Slot Allocation with Price-setting Auctions", Proceedings of the 4th SESAR Innovation Days, Madrid, Spain, November 2014.