ACCESS

APPLICATION OF AGENT-BASED COMPUTATIONAL ECONOMICS TO STRATEGIC SLOT ALLOCATION

Working Paper 6

Agent-Based Simulation of Airport Slot Allocation Mechanisms: Analysis of Results

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Authors

Nommon Solutions and Technologies

Ricardo Herranz

David Toribio

Advanced Logistics Group, Indra-Europraxis

Núria Alsina

Laia Garrigó

University of Valladolid

David Poza

Università degli Studi di Trieste

Raffaele Pessenti

Lorenzo Castelli

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Executive summary

ACCESS has developed an agent-based simulation platform that allows the assessment of various airport slot allocation mechanisms in different scenarios. The present document provides an overall view of the ACCESS simulation platform and describes the simulation experiments conducted in the frame of the project.

The first set of simulation experiments explores the use of combinatorial price-setting auctions for primary slot allocation. The experiments show the ability of the proposed auction to balance capacity and demand, and allow us to analyse the impact of different parameterisations on the dynamics of the auction, in particular on the auction convergence times, helping us derive some guidelines for optimising the auction design.

Then we present a second set of experiments aimed to compare the auction-based slot allocation and the current administrative slot allocation mechanism based on grandfather rights. These experiments show that the auction allows the allocation of scarce airport capacity to those airlines able to make best economic use of it and increases the total social welfare with respect to the current administrative system. At the same time, these experiments demonstrate the ability of the ACCESS simulation platform to capture the distribution of costs and benefits of different slot allocation mechanisms among different stakeholders. The obtained results show that a proper evaluation of different slot allocation mechanisms requires not only an analysis of total surplus (social welfare), but also of the way this surplus is distributed among stakeholders, as a necessary step to understand the conditions for stakeholders' buy-in of any potential regulatory changes.

Finally, we conclude by discussing future lines of research for increasing the realism of the ACCESS simulation model, with aim of taking it to the point where it can be used for a comprehensive evaluation of the benefits and risks of market mechanisms and inform future policy developments.

1. Introduction

1.1 Scope and objectives

The aim of this document is to describe the ACCESS simulation platform and present the results of the simulation experiments conducted in the frame of the project.

1.2 Structure of the document

The document is structured as follows:

- Section 1 defines the main concepts and terms used throughout the document.
- Section 2 provides an overview of the ACCESS simulation platform.
- Section 3 describes and discusses the results of the simulation experiments, including a detailed analysis of primary slot allocation by means of combinatorial price-setting auctions and a comparison of the auction mechanism with the current administrative slot allocation system based on EU Regulation 95/93.
- Section 4 summarises the main conclusions of the experiments and discusses future research directions.

1.3 Glossary of terms

Concept or term	Definition
Active Agent	A particular agent set with capability to initiate an interaction with other agents pursuing a certain goal, therefore influencing them. (See also *Agent* and *Passive Agent*).
Actor	See *Stakeholder.*
Administrative Slot Allocation	Slot allocation mechanism based on administrative rules, not including market or other types of mechanisms. The current slot allocation process, based on the EU regulation and IATA slot guidelines, is a particular case of administrative slot assignment.
Agent	An autonomous discrete entity with its own goals and behaviour, generally used to represent a certain stakeholder in a model. Autonomy means that the agent is able to adapt and modify its own behaviour, which is guided by an objective function and a set of decision rules or algorithms of different complexity.
Agent-Based Model	A class of computational model for simulating the actions and interactions of autonomous agents (including both individual and collective entities such as organisations or groups) with a view to assessing their effects on the system as a whole. It consists of a set of agents, a set of agent relationships, and a framework for simulating their behaviours and interactions.

Concept or term	Definition
Agent-Based Modelling and Simulation	A class of computational simulation to run agent-based models. It is based on local interaction between agents, with no central authority that operates the system or controls its evolution or change of state.
Auction Market	A market where products, services or rights are bought and sold through a formal bidding process.
Combinatorial Auction	An auction where participants can place bids on combinations of discrete items, or "packages", rather than individual items or continuous quantities.
Congestion Pricing	Capacity demand management mechanism consisting in surcharging users for the use of scarce capacity to regulate demand, by establishing different prices along the day based on marginal congestion costs.
Coordination Interval (or Coordination Time Interval)	Period of time comprising the valid time for a slot to be used at certain airport. It is given different names across the literature, such as 'coordination interval', 'time interval' or 'slot width'. Several slots may be allocated within the same coordination interval. The coordination interval has different duration at each airport (constant along the whole day), usually between 5 and 20 minutes (and up to 60 minutes in some cases).
Coordination Parameters	Set of parameters encompassing capacity, connecting times, night curfews, etc. They are specified for each airport before the season starts.
Endogenous Variable	Variables whose value is determined by the functional relationships in a model. They vary as a result of the execution of the simulation. (See also *Variable* and *Exogenous Variable*)
Event	A situation during simulation where some action is triggered. Examples are: a communication attempt, an attribute change, a decision process, etc.
Exogenous Variable	Variables that affect a model without being affected by it. They are used for setting arbitrary external conditions. Useful models require strict delineation regarding what is included and excluded from the model, as typically not all relevant subsystems can be represented. We therefore define parts of the system that are unaffected by other parts within the system. These components, which are relevant but unaffected by the model, are taken into account as exogenous variables. (See also *Variable* and *Endogenous Variable*)
Experiment	A set of scenarios representing several interrelated case studies (e.g., simulation of a certain slot allocation mechanism for a variety of scenarios).

Concept or term	Definition
Forward Market	An over-the-counter market where the items traded are usually contracts for specific quantities at a specified price with delivery set at a specified time in the future.
Futures Market	An organised market where the items traded are usually standardised contracts for specific quantities at a specified price with delivery set at a specified time in the future.
Global Indicator	Indicator measured at network level. (See also *Local Indicator*)
Grandfather Rights	Historical precedence for a series of slots an airline earns if it operates the said series of slots for a minimum percentage of the time in a previous equivalent season.
Intermediate Indicators (or Process Indicators, or Surrogate Indicators)	Indicators that provide useful information about the system (e.g., they may serve as a proxy for outcome indicators or have an influence on their evolution), but are not an objective per se. Expressing policy objectives in terms of intermediate indicators often leads to well-intentioned but ill-targeted policies. (See also *Outcome Indicator*)
Local Indicator	Indicator measured at airport level. (See also *Global Indicator*)
Market	Systems, institutions, procedures, social relations and infrastructures whereby parties engage in exchange.
Market Equilibrium	A condition where a market price is established through competition such that the amount of goods or services sought by buyers is equal to the amount of goods or services produced by sellers. The equilibrium price is often called the competitive price or market clearing price and will tend not to change unless demand and/or supply change.
Model	A simplified description of a complex entity or process, often in mathematical terms, that helps to conceptualise and analyse the problem.
Non-Monetary Slot Exchanges	Slot exchanges between airlines where no money is involved.
Objective Function	A function that defines the goals of an agent. Agents will try to maximise or minimise this function with its behaviour, and may even adapt/vary it to better accomplish this purpose.

Concept or term	Definition
Optimisation	Mathematically formulated problem whose solution is used to select a best option from a set of available alternatives.
Outcome Indicator	Indicator that measures progress towards policy objectives (i.e., the variables one wants to optimise in the system). (See also *Intermediate Indicator*)
Parameter	A variable that is assigned with a value and kept constant along a simulation. (See also *Variable*)
Passive Agent	A particular Agent not set with capability to initiate an interaction with other agents. Passive agents are included in the Agent-Based Model as they can still interact with others if they are asked, hence influencing or being influenced by the process. Stakeholders can be modelled as active or passive agents, or even both, depending on the purpose of the model. Passive agents are still agents, since they keep their autonomy and goals despite they do not influence others with them. For instance, passengers may be modelled as passive agents to analyse how they benefit from certain allocation mechanism, or active agents if they choose the airline they fly with, therefore influencing the slot demand. (See also *Agent* and *Active Agent*)
Performance Area	Broad focus area encompassing one or several goals or objectives.
Performance Framework	Set of performance areas and indicators that guide the evaluation of a particular slot allocation mechanism. (See also *Performance Area* and *Performance Indicator*)
Performance Indicator	Means of summarising the current position and the direction and rate of change of progress towards a particular goal. The use of indicators for the control and monitoring of processes helps evaluating and monitoring developments; focuses the discussion with stakeholders; promotes the idea of integrated action; demonstrates progress towards goals and objectives; and ultimately supports decision making.
Price-Setting Auction	A combinatorial iterative auction where the auctioneer sets and modifies the prices of the items as a function of demand and supply. (See also *Auction Market* and *Combinatorial Auction*)
Primary Slot Allocation (or Primary Slot Assignment)	First stage of the slot allocation process, during which most of the slots for the scheduled operations are allocated. Currently it is usually based on IATA's World Slot Guidance. (See also *Secondary Slot Allocation*)

Concept or term	Definition
Processing Time	Measure of time related to the real-life time which is needed to run a simulation. It depends on the ABM software implementation and the hardware used to run it. (See also *Simulated Time*)
Property file	Files used to store the configurable parameters of an application. They can also be used for storing strings for internationalisation. Each parameter is stored as a pair of strings (one storing the name of the parameter and the other storing the value of the parameter) separated by an equal sign (=).
Replica	Each execution of the same simulation scenario necessary for statistical analysis of stochastic simulations.
Rolling Capacity	A time-dependant airport capacity measure that represents a maximum number of arrival/departure/total slots available over a certain number of coordination time intervals. For instance, an airport may have 2 arrival slots available for each coordination interval, but allow a maximum of only 5 arrivals for 3 consecutive coordination intervals (instead of 6).
Rolling Capacity Interval (or Rolling Capacity Time Interval)	The number of coordination time intervals that comprise the definition of a certain rolling capacity constraint. (See also *Rolling Capacity* and *Coordination Time Interval*)
Scenario	A particular instance of the set of parameters of the model. The scenario space is composed by all possible combinations of those parameters that are relevant to, but exogenous to the model. (See also *Parameter*)
Secondary Slot Allocation (or Secondary Slot Assignment)	Second stage of the slot allocation process, where the airlines exchange slots subject to the approval of the coordinator. This is currently done in four different modalities: slot exchange without monetary compensation, slot transfers (one airline transfers the slots to another: just a transfer, without exchange), slot exchange with monetary compensation, and slot buy-sell (where this is allowed). (See also *Primary Slot Allocation*)
Simulated Time	Measure of time related to the virtual time elapsed in a simulation. Sometimes it applies to the virtual time horizon of a simulation. For instance, with some seconds of computer simulation in the real-life we might be able to virtually represent the evolution of a model over several years of simulated time. (See also *Processing Time*)
Simulation	Operation that runs certain programmed software models on computers, trying to reproduce a real-world situation over time.

Concept or term	Definition
Simulation time step	Temporal granularity of the simulated time. It is used to define the frequency of events during the simulation.
Slot	Permission given by a coordinator to use the full range of airport infrastructure necessary to operate an air service at a coordinated airport on a specific date and time for the purpose of landing or take-off.
Slot Allocation Mechanism (or Slot Assignment Mechanism)	Mechanism or scheme used to allocate slots.
Slot Trading	Exchange of slots with monetary compensation, or simple buy and sell of slots (where this is allowed).
Spot Market	A market where the items are traded for immediate delivery, typically a few days.
Stakeholder (or Actor)	A person, group or organisation that is interested in or concerned with slot allocation.
Stakeholder-specific Indicator	Indicator linked to a specific stakeholder or group of stakeholders. (See also *System-wide Indicator*)
System-wide (or Social) Indicators	Indicator measured at societal level. (See also *Stakeholder-specific Indicator*)
Toy Model (or Pilot Model)	A simplified model that is used to understand the fundamental mechanisms behind a complex phenomenon.
Turnaround	Period beginning when a flight arrives at an airport and ending when the aircraft takes off again. During turnaround, a defined series of actions has to be undertaken, involving both airline and airport operations as well as other parties such as ground handlers.
Variable	A quantity that varies within a simulation, as a result of its execution. (See also *Parameter*)

Table 1. Glossary of terms

1.4 Acronyms and abbreviations

Acronym	Definition
ACCESS	Application of Agent-Based Computational Economics to Strategic Slot Allocation
AE	Auction Engineering
ABM	Agent-Based Modelling
ATM	Air Traffic Management
DCA	Dynamic Combinatorial Auction
E-ATMS	European Air Traffic Management System
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
KPA	Key Performance Area
SESAR	Single European Sky ATM Research Programme
SJU	SESAR Joint Undertaking

Table 2. Acronyms and Terminology

2. Description of the ACCESS Simulation Platform

This section provides an overview of the ACCESS simulation platform, with particular focus on the simulation engine. More details on the simulation platform specification and the functional and technical design can be found in ACCESS Working Paper 4 'ACCESS Simulation Framework Specification' and Working Paper 5 'ACCESS Simulation and Analysis Toolset', available from the project website (https://www.access-sesar.eu/publications).

2.1 Architecture of the simulation platform

The ACCESS simulation platform is composed by three main modules/components:

- A simulation engine implementing the mathematical models specified in the project, which is the core of the toolset.
- A database with all the input data needed for simulation (airline data, airport data, demand data, scenarios configuration, additional parameters, etc.) and the output data generated after its execution.
- A graphical user interface that allows basic users to run pre-defined scenarios and visualise the results, and administrator users to insert new elements in the database (airlines, airports, scenarios, etc.).

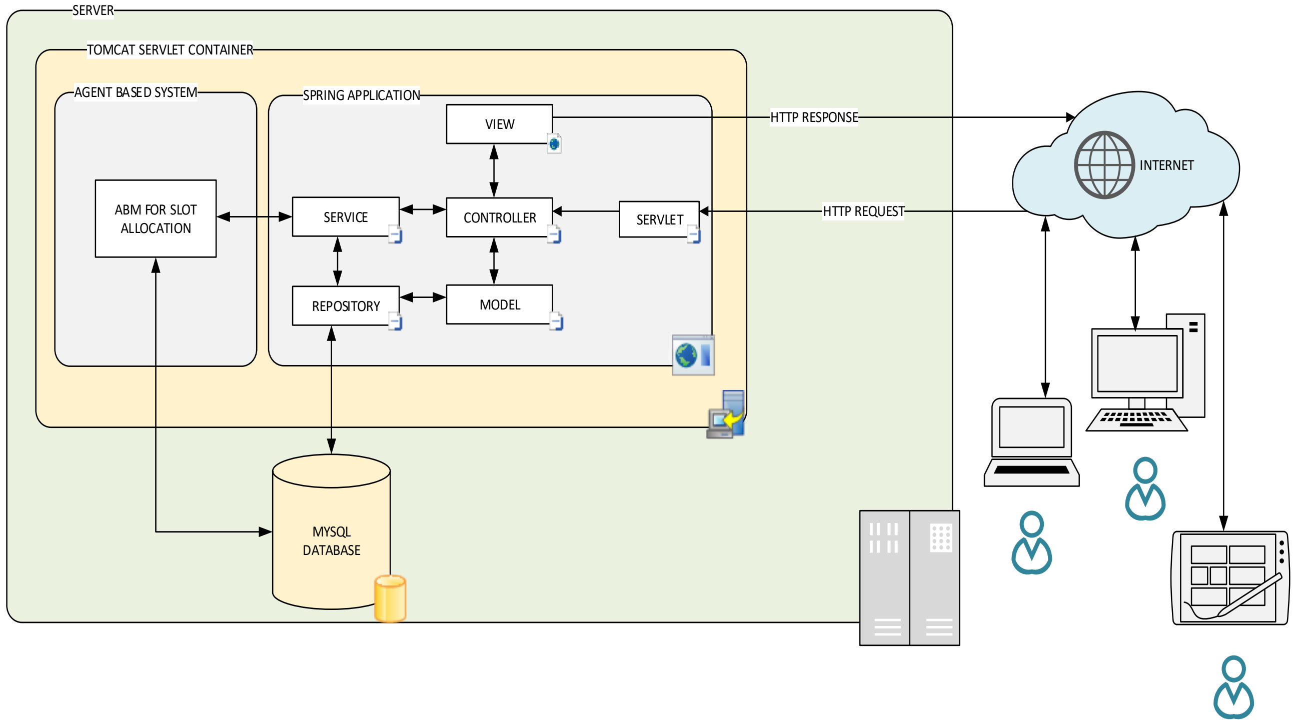

Figure 1. Architecture of the simulation platform

2.2 Simulation engine

2.2.1 Overall model structure

The overall structure of the ACCESS simulation engine is shown in Figure 2.

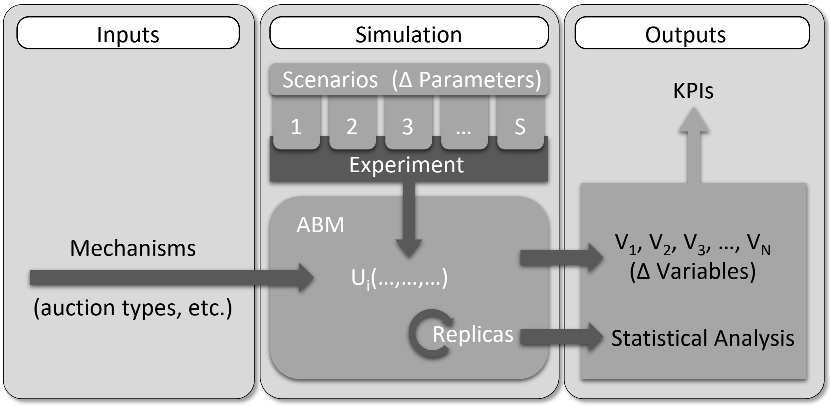

Figure 2. Overall structure of the ACCESS simulation engine

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 and the 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 Figure 3.

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 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).

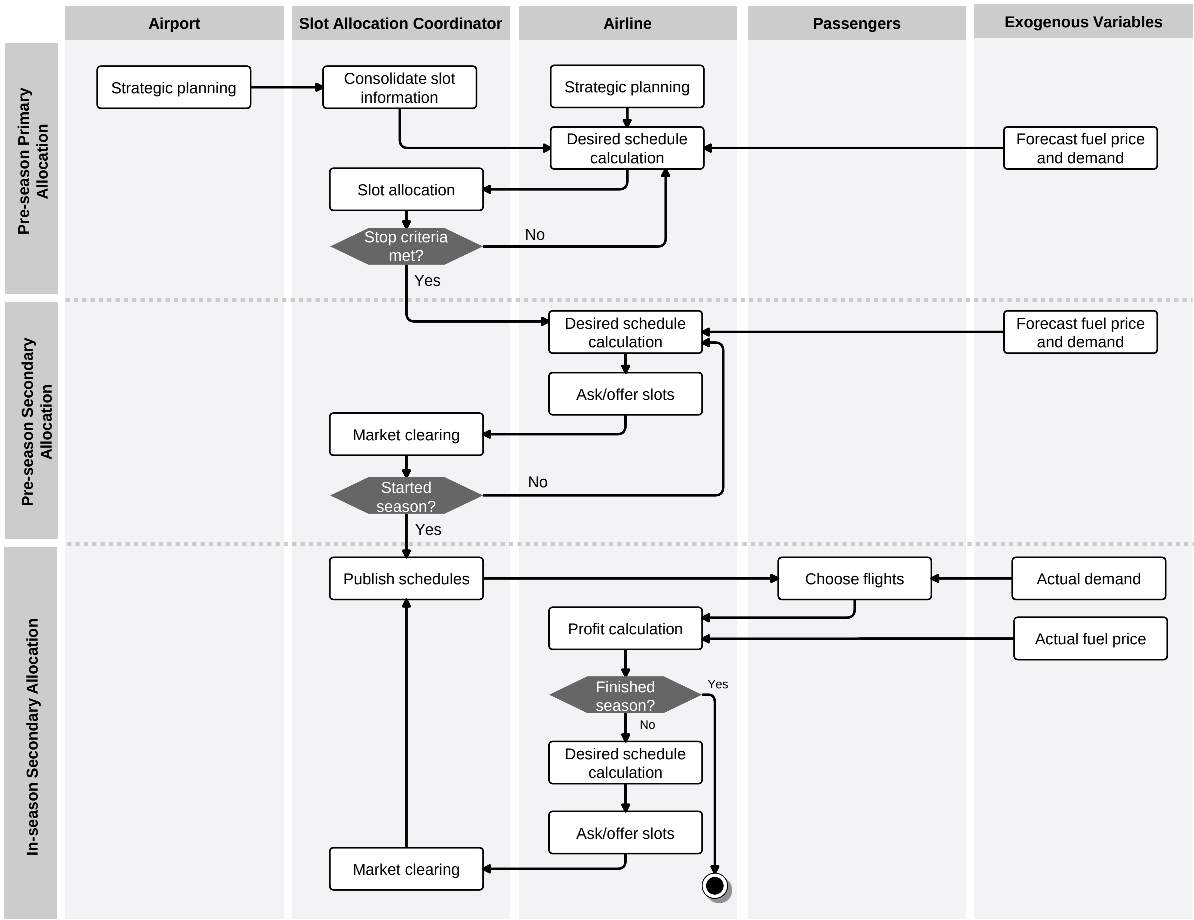

Figure 3. General logic of the simulation model

2.2.2 Model inputs: slot allocation mechanisms

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; and (iii) hybrid mechanisms, e.g., grandfather rights + auctioning of the slot pool.

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

2.2.3 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 passengers 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 generalised 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.

2.2.4 Agents' behaviour

Slot allocation coordinator

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.

Airports

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:

- maximum number of arrival, departure and total slots per coordination time interval along the day, and
- maximum number of arrival, departure and total slots during several consecutive coordination time intervals (rolling capacity).

Airlines

The airline agent is the most complex one. At each simulation step, airline agents take the following actions:

1. 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 re-calculated at each iteration;
2. define the fares for such desired schedule;
3. 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 behaviour of their competitors;
4. 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;
5. 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;
6. publish their final schedule and their final fares; and
7. calculate their actual profit, based on the actual behaviour of demand as well as on their operating costs.

Passengers

Each passenger agent 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 behaviour 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.

2.2.5 Model outputs: performance indicators

The output of the model is a set of indicators aimed to evaluate the performance of the slot allocation mechanisms, 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.

2.3 Data repository

The module responsible for data persistence is a central data repository that: (i) preserves the data describing the different stakeholders of the slot allocation process (airlines, airports, slot allocation coordinators, etc.) as well as external factors and common configurations; (ii) maintains the results of the experiments that are conducted in the platform; (iii) serves as an indirect communication mechanism between the simulation engine and the user interface.

The data repository has been implemented using an existing database management solution. The chosen solution provides standardised development interfaces in order not to influence the selection of the development technologies used in the rest of the modules of the prototype.

2.4 User interface

The user interface is the link between the users and the data repository, enabling the interaction with the simulation engine. The interface has been implemented as a web application following a Software as a Service (SaaS) delivery model. Consequently, the interface is accessible from anywhere and from a long range of devices, also making the maintenance process transparent to the users as the most updated version of the platform is always provided to them.

The components of the user interface are structured following the Model-View-Controller (MVC) architectural pattern to isolate the responsibilities of each component and create clear interfaces between them so as to make it possible a faster maintenance and allow extensibility.

The components of the user interface are executed in an application server. The application server typically collaborates with an external web server which acts as a gateway making no changes in the contents provided by the application. The elements generated by the View component are transmitted through these servers and the network to the user's web browser, where it is executed to render the visual aspect of the simulation platform.

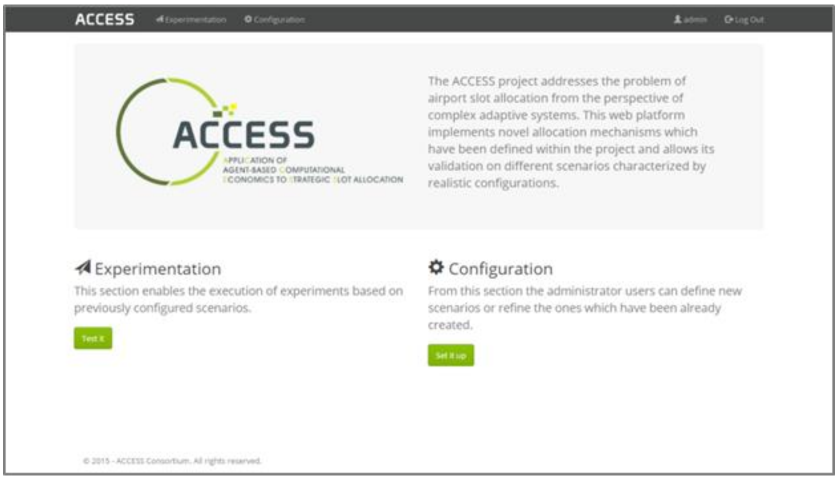

Figure 4. Visual aspect of the user interface (I)

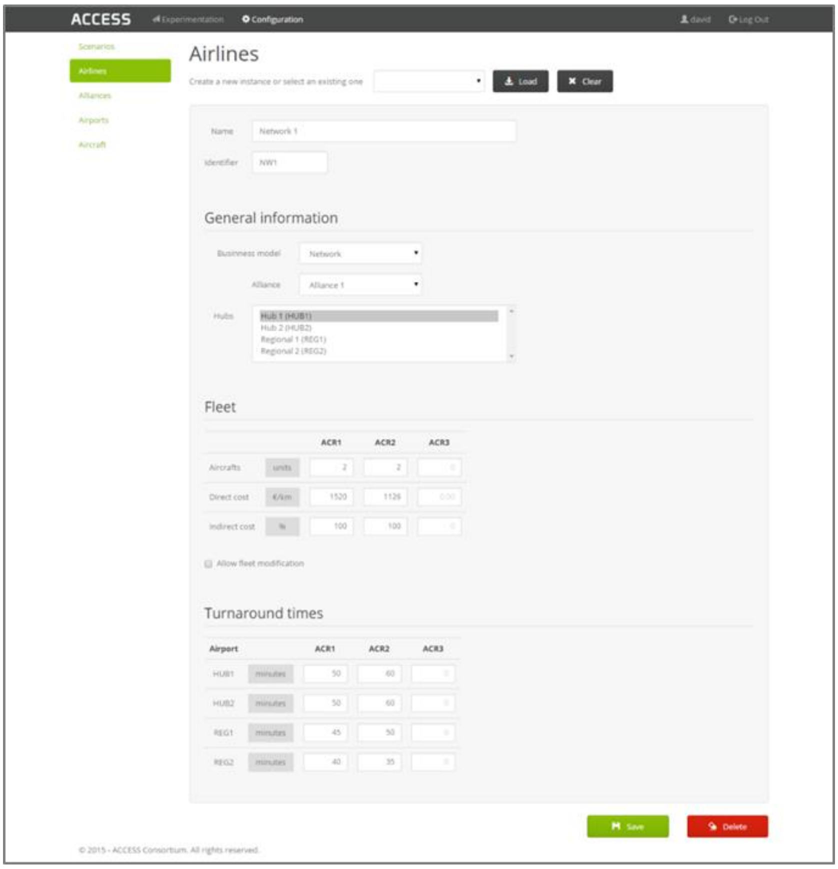

Figure 5. Visual aspect of the user interface (II)

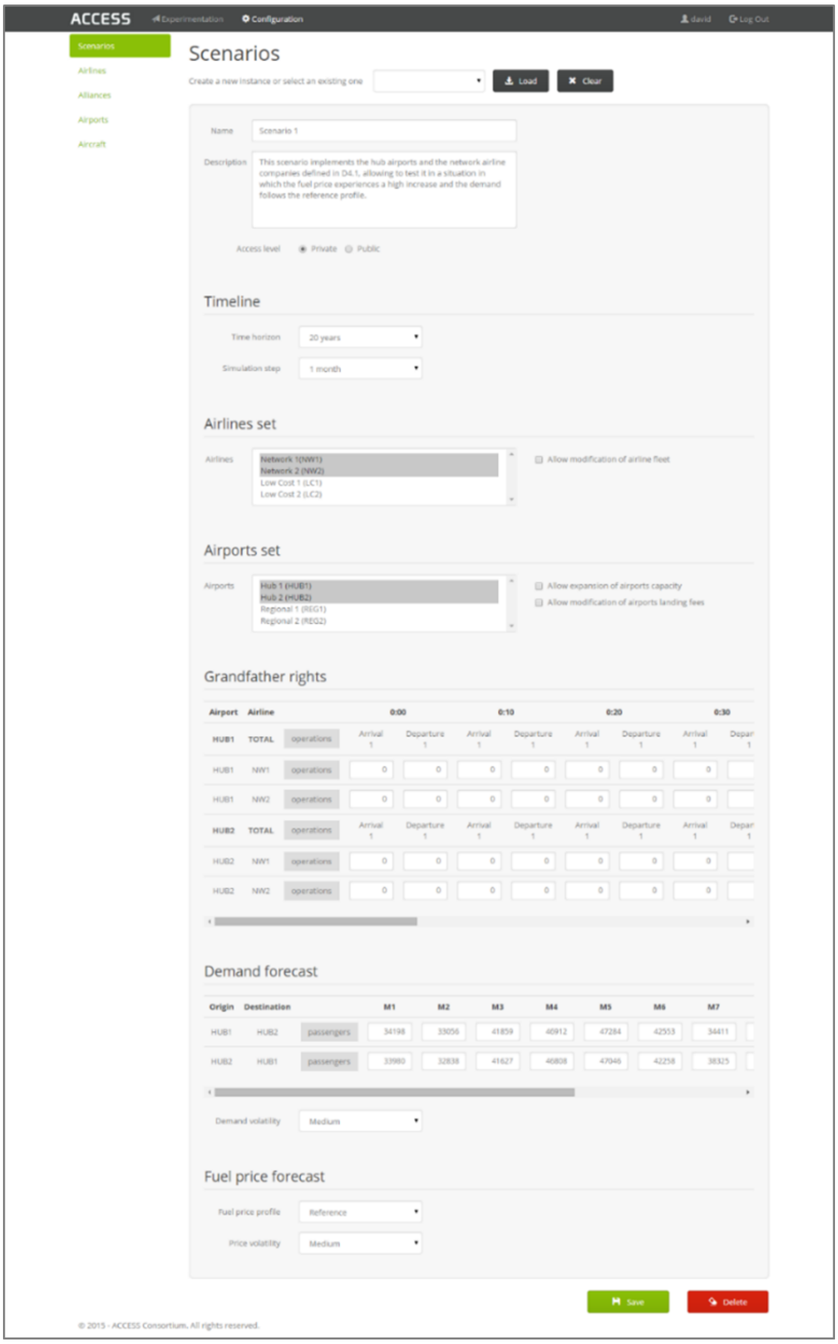

Figure 6. Visual aspect of the user interface (III)

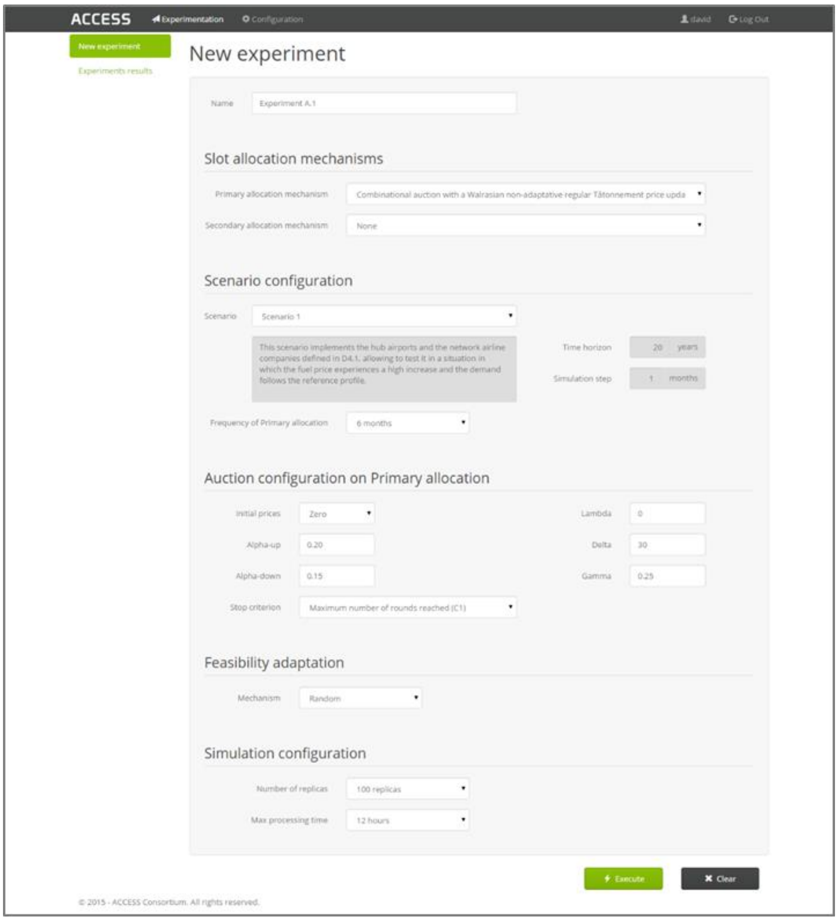

Figure 7. Visual aspect of the user interface (IV)

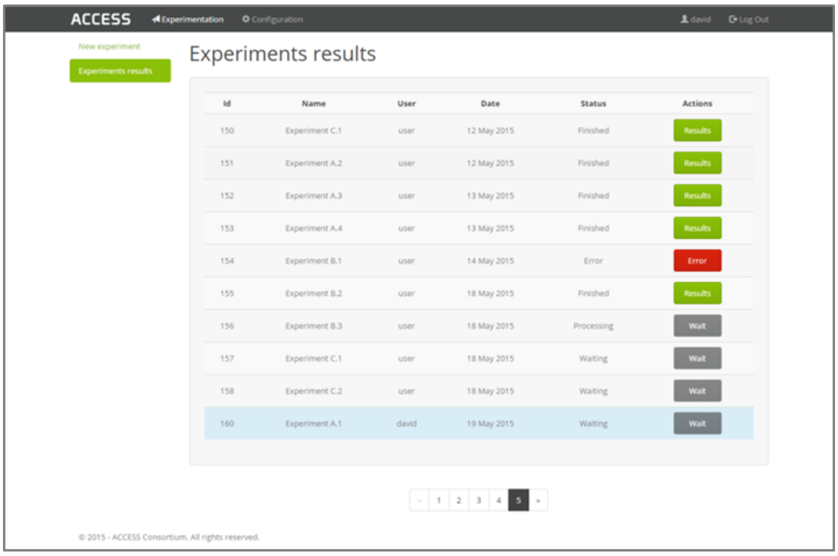

Figure 8. Visual aspect of the user interface (V)

3. Simulation results

The aim of this section is to analyse alternative slot allocation mechanisms in different realistic situations. We use a set of simplified scenarios in terms of number of airports and airlines in order to keep computational cost down to a level allowing us to test a sufficient number of variations to grasp the cause-effect relationships between the elements of the model.

The first set of simulation experiments explores the use of combinatorial price-setting auctions for primary slot allocation on a two-airport scenario and on a four-airport scenario. These experiments are focused on the ability of the auction to match supply and demand and on the performance of the auction in terms of convergence speed.

Then we present a second set of experiments aimed to compare the auction-based slot allocation and the current administrative slot allocation mechanism, focusing on three of the KPAs included in the ACCESS Performance Framework: economic efficiency, equity/distributional issues, and access and competition. The reason is that these are the KPAs where the current simulation platform is able to provide more added value for KPI evaluation. Other KPAs/KPIs are left outside the simulation experiments, either because they are subject to more qualitative considerations (e.g., interoperability) or because cannot be assessed with the current version of the simulation platform (e.g., the assessment of capacity and delay would require simulation features that are not yet implemented, such as the simulation of several seasons to evaluate the impact on capacity investments, or the coupling to a traffic simulation model to assess the impact on delay indicators). The indicators that have been assessed in each experiment and the traceability with the ACCESS Performance Framework are discussed below.

KPA	Indicators analysed in the simulation	Indicator type
Economic efficiency	Social welfare = consumer and producer surplus (sum of the effects on airlines, airports and passengers) (*) *(*) Net benefits to third parties (externalities) not considered*	Outcome indicator, global, system-wide
Access and competition	Individual rationality = All stakeholders get a non-negative utility	Outcome indicator, global, system-wide
	Utility per stakeholder = (Benefit - Cost) per stakeholder (airlines, airports, passengers)	Intermediate indicator, global, stakeholder-specific
Equity and distributional issues	Concentration of slots	Global / local, system-wide

Table 3. Performance indicators from the ACCESS Performance Framework analysed in the simulation

In section 3.1 we provide a general description of the different experiments that have been conducted. In section 3.2, we describe the experiments performed on the auction mechanism implemented by the ACCESS Simulation Platform and analyse the impact of the auction parameterisation. Finally, in section 3.3 we present a set of simulation experiments aimed to compare the current administrative system based on grandfather rights with primary allocation through combinatorial price-setting auctions.

3.1 Description of the simulation scenarios

The proposed scenarios encompass a reduced set of airports and airlines, with the aim to represent in a realistic yet simplified manner the characteristics of different airport and airline types. The scenarios include the airspace users that are most relevant to commercial aviation in Europe, in particular those that are mostly affected by the airport slot allocation system: 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. Only one season is simulated, assuming that all available capacity is simultaneously auctioned for all the coordinated airports in the network. Two reference scenarios are considered:

1. A scenario composed by two airports (one hub, HUB1, and a regional airport, REG1) and two airlines (one network carrier, NW1, and one low cost carrier, LC1) connecting the two airports (see Figure 9). We use this simplified scenario to test the platform and understand the basics of the allocation mechanism, including the influence of the auction parameters.
2. A more complex scenario comprising four airports and four airlines. The scenario includes two network carriers (NW1 and NW2) and two low cost carriers (LC1 and LC2), and two types of airports: two hubs (HUB1 and HUB2) and two regional airports considered as feeders for the hubs (see Figure 10). This second scenario is used to analyse in more detail the 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, and to compare these outcomes with those of the current administrative system.

Figure 9. Scenario with 2 airports and 2 airlines

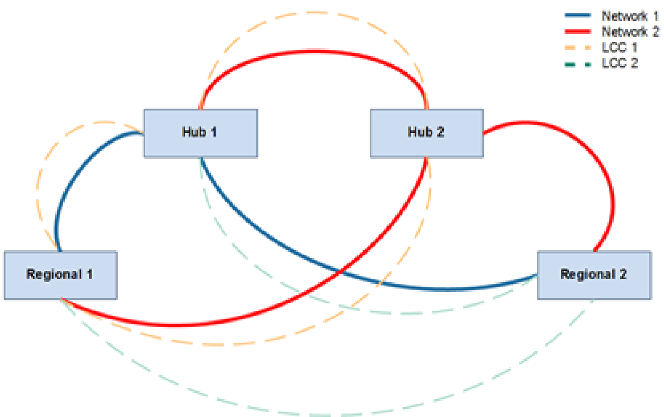

Figure 10. Scenario with 4 airports and 4 airlines

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 have rolling capacity constraints defined for 60 min intervals. The capacity constraints of the three coordinated airports are shown in Table 4. For HUB1, capacity is constant, while for HUB2 and REG1, it varies along the day.

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

HUB2	Coordination time interval					
	10 min			60min		
	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
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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

REG1	Coordination time interval					
	20 min			60min		
	ARR	DEP	TOTAL	ARR	DEP	TOTAL
0:00	3	3	4	--	--	--
9:00	2	2	3	--	--	--
10:00	3	3	4	--	--	--
20:00	2	2	3	--	--	--
21:00	3	3	4	--	--	--

Table 4. Airport capacity

3.2 Analysis of the auction mechanism

The slot allocation mechanism tested in this experiment is primary slot allocation through a regular Walrasian auction. The general objective of this experiment is to validate the simulation platform and understand the basics of the allocation mechanism, in particular how different auction parameters affect the outcome of the 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" agent) 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, while demand is determined by the schedules that the airlines wish to operate in order to maximise their profit, taking into account the forecasted passenger demand and airline operating costs.
- 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 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 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. The prices are raised if the demand is greater than the capacity and lowered if the capacity is greater than the demand.
- The 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.

The parameters related to slot auctioning that have to be defined in a simulation are the following:

- Initial slot price multipliers λ_0: the auction multipliers that generate the values of the initial slot prices.
- α_{up}: the initial value of the factor used to scale positive price multipliers between rounds.
- α_{down}: the initial value of the factor used to scale down price multipliers between rounds.
- δ: number of steps to modify α_{up} and α_{down}, i.e., the number of auction iterations after which α_{up} and α_{down} factors are revised.
- γ: α_{up} and α_{down} are revised by this factor after δ number of rounds.
- Prioritisation criterion for the feasibility mechanism: the criterion or set of criteria selected to prioritise slot requests when breaking a tie in the feasibility process after an auction.
- Stop criterion: the criterion or set of criteria selected to stop the auction process. In our case study, the stop criterion comprises the two following conditions: (i) all capacity constraints are respected; and (ii) prices reach a state of equilibrium.

3.2.1 Scenario 1: two airports and two airlines

In this first experiment, we test the auction mechanism in the simple scenario shown in Figure 9. Airline NW1 has a fleet of 2 aircraft, and airline LC1 has a fleet of 4 aircraft. The considered value of the parameter fuel price is 0.59 €/kg. The simulations have been performed with the following values of demand between airports (demand is expressed as the number of passengers willing to fly from the origin airport to the destination airport for an average day of the season):

Origin airport	Destination airport	Demand (No of passengers)
HUB1	REG 1	3,720
REG1	HUB1	3,703

Table 5. Demand between airports in the basic scenario

The preferred schedule of each airline (i.e., the one that maximises the utility of all the flights when the price of all the slots is 0) is shown in Table 6.

Airline	Departure Airport	Preferred TOD	Arrival Airport	Preferred TOA
LC1	HUB1	5:00	REG1	5:56
LC1	HUB1	7:30	REG1	8:26
LC1	HUB1	9:00	REG1	9:56
LC1	HUB1	11:15	REG1	12:11
LC1	HUB1	13:35	REG1	14:31
LC1	HUB1	15:45	REG1	16:41
LC1	HUB1	18:00	REG1	18:56
LC1	HUB1	21:35	REG1	22:31
LC1	HUB1	23:50	REG1	0:46
LC1	REG1	5:15	HUB1	6:11
LC1	REG1	7:30	HUB1	8:26
LC1	REG1	9:00	HUB1	9:56
LC1	REG1	11:15	HUB1	12:11
LC1	REG1	13:25	HUB1	14:21
LC1	REG1	15:45	HUB1	16:41
LC1	REG1	18:00	HUB1	18:56
LC1	REG1	21:35	HUB1	22:31
LC1	REG1	23:50	HUB1	0:46
NW1	HUB1	5:00	REG1	5:56
NW1	HUB1	7:45	REG1	8:41
NW1	HUB1	9:00	REG1	9:56
NW1	HUB1	11:15	REG1	12:11
NW1	HUB1	13:35	REG1	14:31
NW1	HUB1	15:45	REG1	16:41
NW1	HUB1	18:00	REG1	18:56

Airline	Departure Airport	Preferred TOD	Arrival Airport	Preferred TOA
NW1	HUB1	20:20	REG1	21:16
NW1	HUB1	22:35	REG1	23:31
NW1	REG1	5:00	HUB1	5:56
NW1	REG1	7:45	HUB1	8:41
NW1	REG1	9:00	HUB1	9:56
NW1	REG1	11:15	HUB1	12:11
NW1	REG1	13:25	HUB1	14:21
NW1	REG1	15:45	HUB1	16:41
NW1	REG1	18:00	HUB1	18:56
NW1	REG1	20:20	HUB1	21:16
NW1	REG1	22:35	HUB1	23:31

Table 6. Airlines' preferred schedule

We will focus on the congestion affecting HUB1, since the demand in the airport REG 1 never violates the airport's capacity limits.

Figure 11, Figure 12 and Figure 13 show the nominal capacity for the airport HUB1 (arrival, departure and total capacity, respectively) in red. The requested slots by the airlines are represented in blue.

Figure 11. Arrivals in HUB 1: nominal capacity (red) vs airline requests (blue)

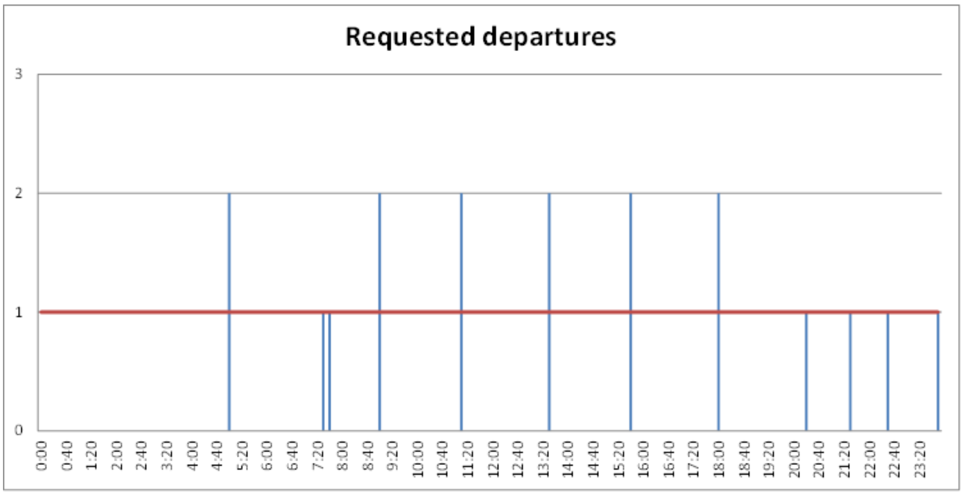

Figure 12. Departures from HUB1: nominal capacity (red) vs airline requests (blue)

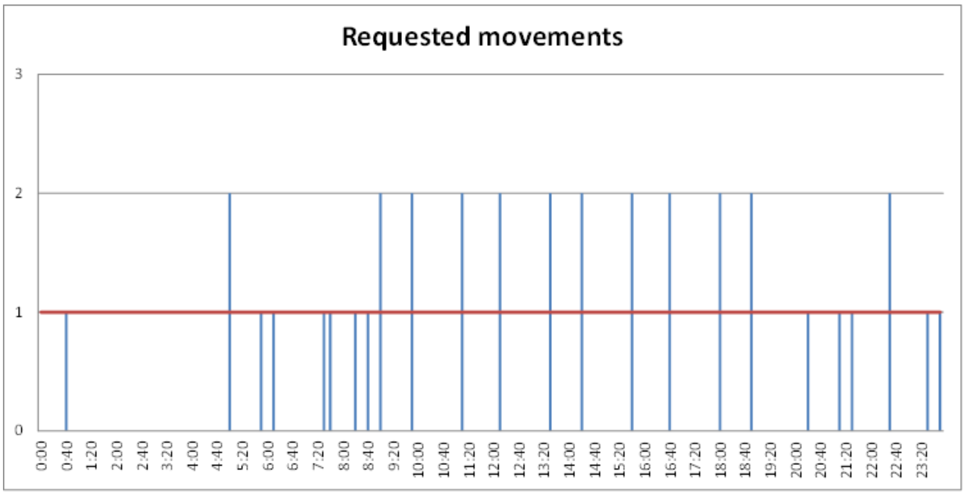

Figure 13. Total requested movements (arrivals and departures) at HUB 1: nominal capacity (red) vs airline requests (blue).

These figures show that the desired schedule violates the airport's maximum capacity on several occasions. The slot auction aims to find a set of prices solving these violations and leading to a feasible schedule.

The results of the slot auction are presented in Table 7.

Airline	Departure Airport	Departure time	Arrival Airport	Arrival time
LC1	HUB1	5:00	REG1	5:56
LC1	HUB1	7:30	REG1	8:26
LC1	HUB1	8:55	REG1	9:51
LC1	HUB1	11:20	REG1	12:16
LC1	HUB1	13:45	REG1	14:41
LC1	HUB1	17:55	REG1	18:51
LC1	HUB1	19:20	REG1	20:16
LC1	HUB1	21:35	REG1	22:31
LC1	HUB1	23:50	REG1	0:46
LC1	REG1	5:15	HUB1	6:11
LC1	REG1	7:30	HUB1	8:26
LC1	REG1	9:05	HUB1	10:01
LC1	REG1	11:50	HUB1	12:46
LC1	REG1	14:25	HUB1	15:21
LC1	REG1	16:40	HUB1	17:36
LC1	REG1	18:05	HUB1	19:01
LC1	REG1	21:20	HUB1	22:16
LC1	REG1	23:35	HUB1	0:31
NW1	HUB1	5:30	REG1	6:26
NW1	HUB1	7:45	REG1	8:41
NW1	HUB1	9:00	REG1	9:56
NW1	HUB1	11:15	REG1	12:11
NW1	HUB1	13:35	REG1	14:31
NW1	HUB1	15:45	REG1	16:41
NW1	HUB1	18:00	REG1	18:56
NW1	HUB1	20:20	REG1	21:16
NW1	HUB1	22:35	REG1	23:31
NW1	REG1	5:00	HUB1	5:56
NW1	REG1	7:45	HUB1	8:41
NW1	REG1	9:00	HUB1	9:56
NW1	REG1	11:15	HUB1	12:11
NW1	REG1	13:25	HUB1	14:21
NW1	REG1	15:45	HUB1	16:41
NW1	REG1	18:00	HUB1	18:56
NW1	REG1	20:20	HUB1	21:16
NW1	REG1	22:35	HUB1	23:31

Table 7. Slot allocation resulting from the auction

Figure 14, Figure 15 and Figure 16 show the final allocation for the airport HUB1 (arrival, departure and total slots, respectively).

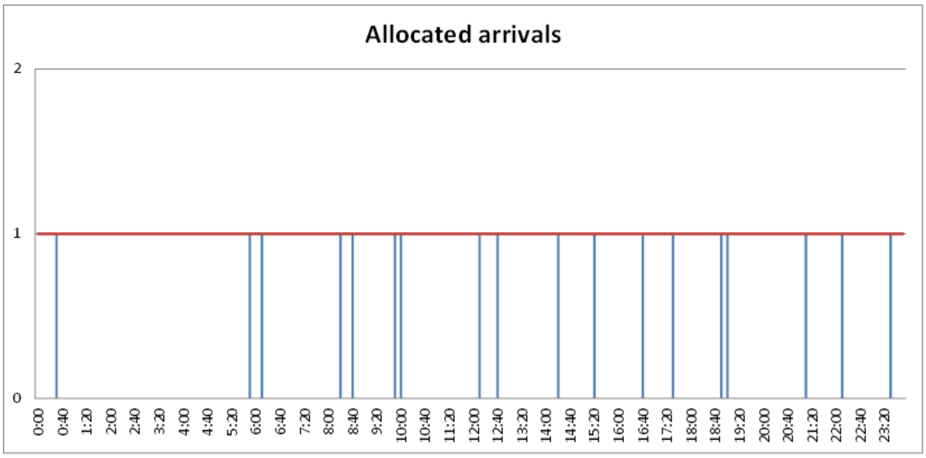

Figure 14. Arrivals in HUB 1: nominal capacity (red) vs cumulative allocated slots (blue)

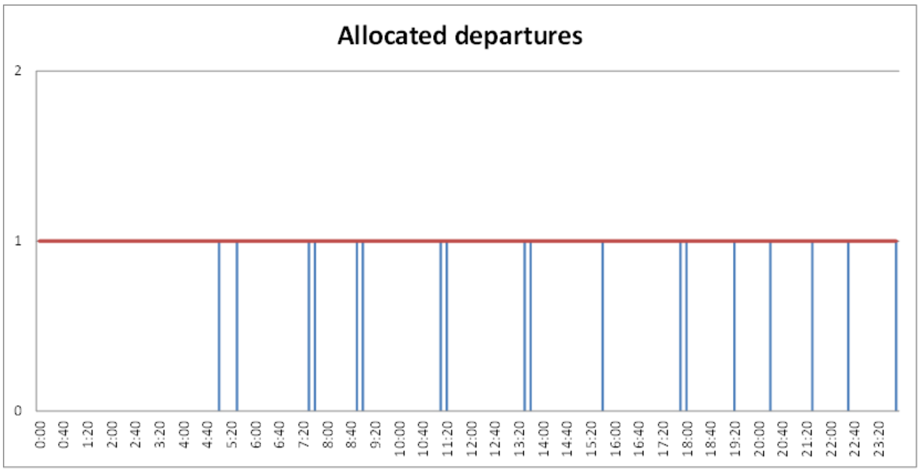

Figure 15. Departures from HUB 1: nominal capacity (red) vs cumulative allocated slots (blue)

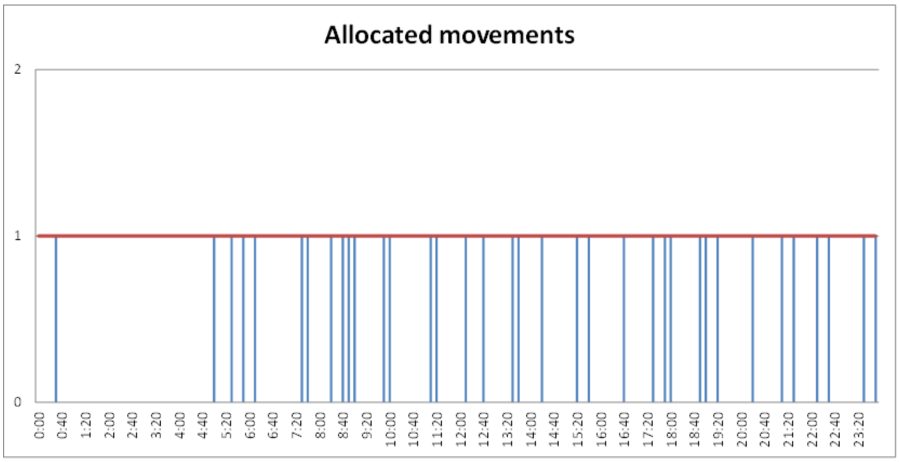

Figure 16. Total movements at HUB 1: capacity (red) vs cumulative number of allocated slots (blue)

After checking that the auction yields a feasible schedule, as it can be seen from the previous figures, we now look at the auction mechanism in more detail. We expect that the prices of the slots in the most congested intervals rise as a consequence of the high demand. The utility of the airlines at those congested intervals may drop and, as a result, the airlines might choose to shift their requests to other intervals with less congestion and, consequently, lower prices. Figure 17 and Figure 18 show the final arrival slot prices[1] in the airport HUB1 for different parameterisations of the auction.

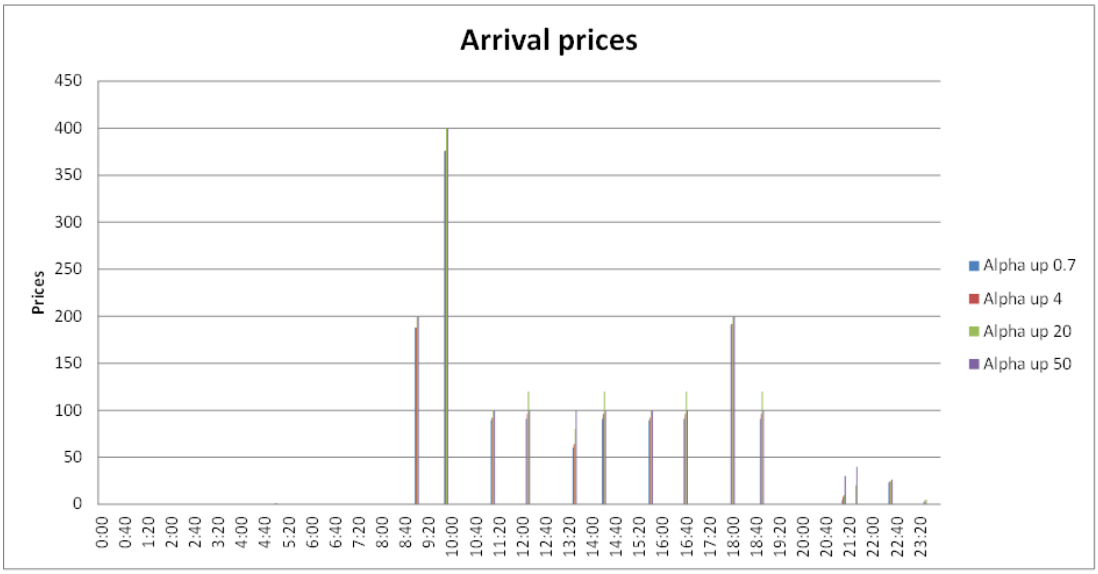

Figure 17. Final arrival slot prices in HUB1

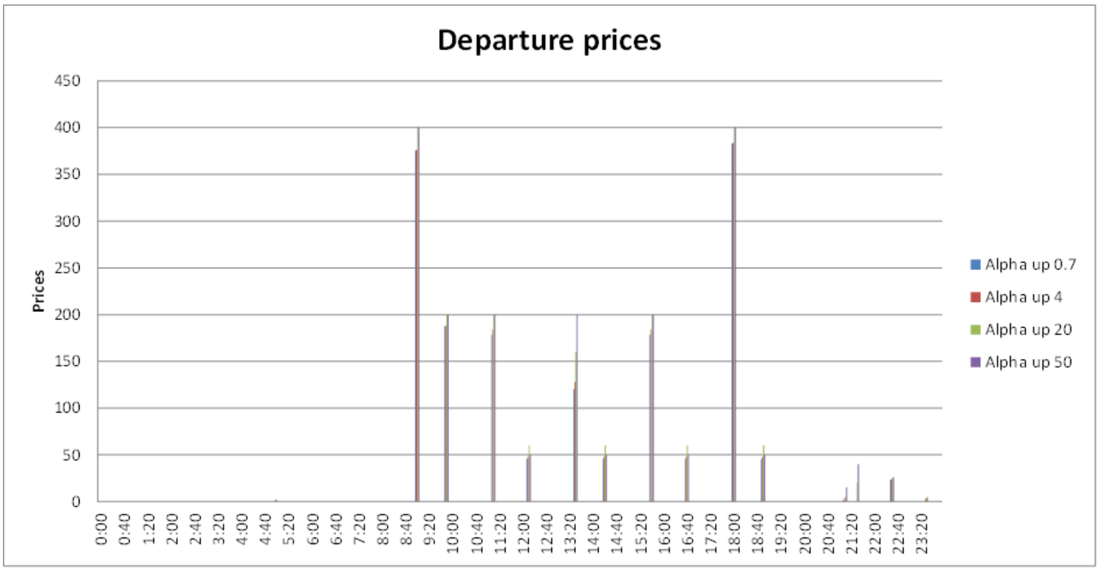

Figure 18. Final departure slot prices in HUB1

[1] The prices are the slot price for an average day of operations during the season.

If we compare the final prices shown in Figure 17 and Figure 18 with the requested movements shown in Figure 11, Figure 12 and Figure 13, we see that the slots with non-zero prices correspond to congested periods, which is consistent with the expected result.

Figure 19 provides a detailed view of the departure and arrival slot prices for alpha up = 0.7, which shows that the highest prices correspond to the most congested periods.

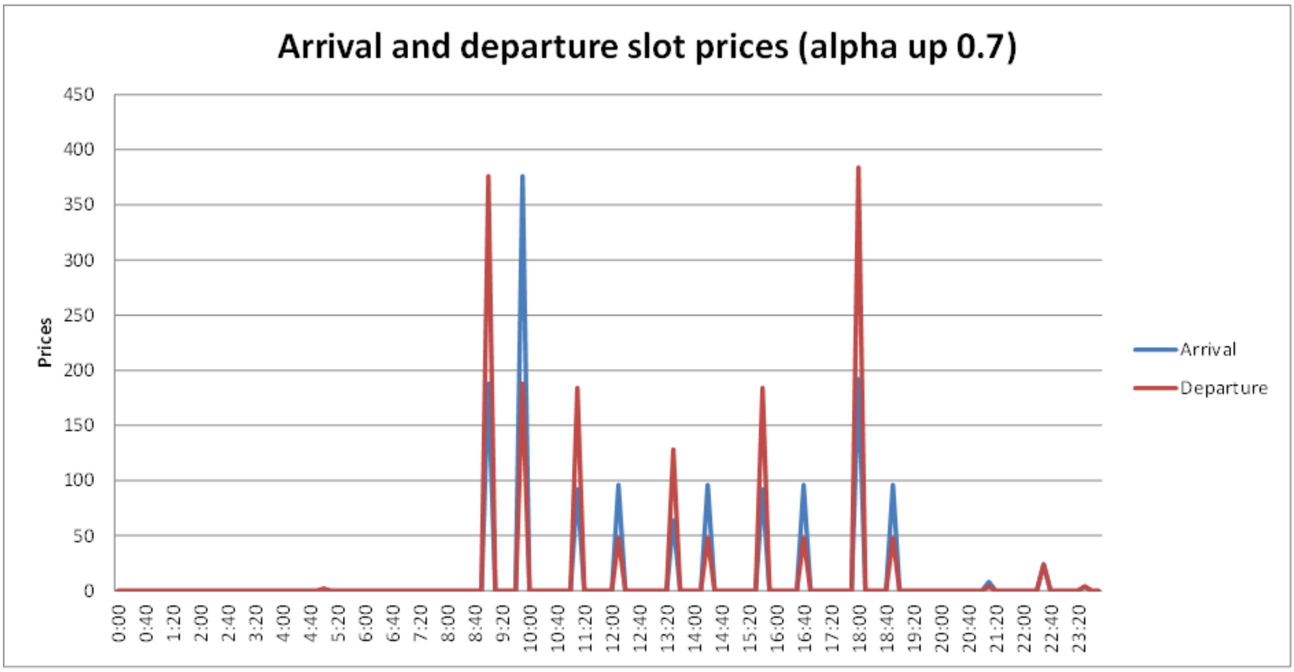

Figure 19. Final arrival and departure slot prices in HUB1 (alpha up = 0.7)

Although the value of the parameters alpha up and alpha down does not significantly affect the final slot prices, it has a clear impact on the dynamics of the auction. We will now focus on four intervals with non-zero final prices: two periods with high final prices and two periods with low final prices. The aim of this analysis is to study how the parameters alpha up and alpha down affect the evolution of the auction.

Figure 20 and Figure 21 show the evolution of the arrival and departure slot prices for several values of the parameter alpha up at two peak intervals where the auction resulted in particularly high prices: 9.00 and 11.10. In the cases where the final slot prices are high, for fixed values of the parameters delta (100) and gamma (25%), the convergence time decreases as the parameter alpha up is increased (the value of alpha down is always 75% the value of alpha up). Since alpha up represents the initial value of the factor used to scale up the price multipliers between rounds, a high value of alpha up accelerates the convergence to the final prices.

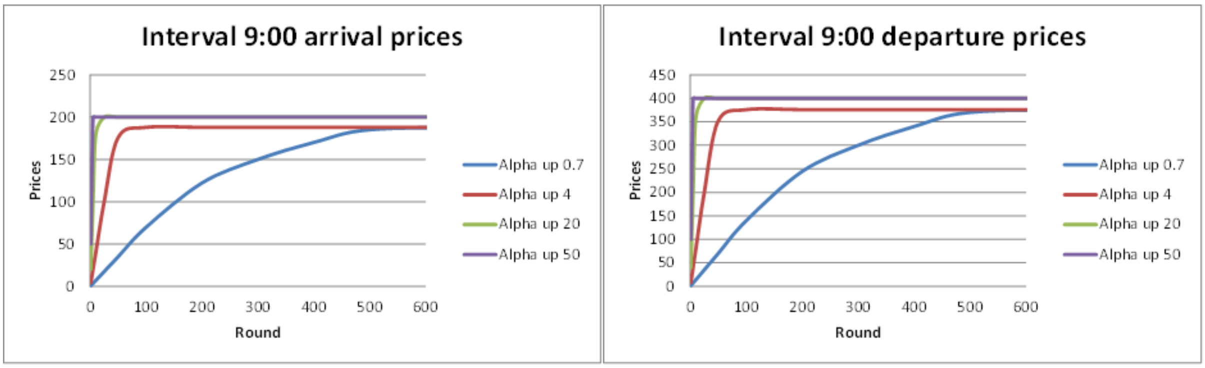

Figure 20. Evolution of the price for the arrival and departure slots at 9.00

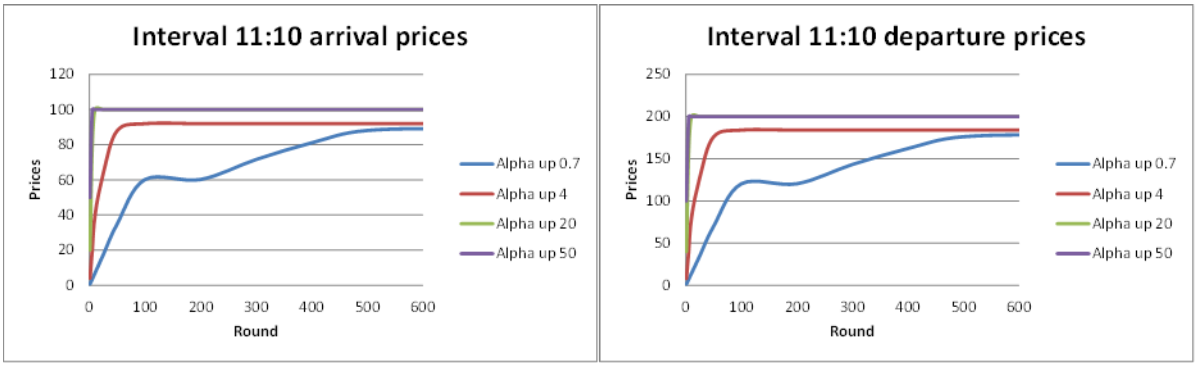

Figure 21. Evolution of the price for the arrival and departure slots at 11.10

Figure 22 and Figure 23 show the evolution of the arrival and departure slot prices for several values of the parameter alpha up at two peak intervals where the auction resulted in remarkably low prices (which occurs at periods with low congestion). In this case, the lower the value of alpha up, the faster the auction converges to the final price. Therefore, a high value of alpha up slows down the convergence to the final prices. Notice that the oscillations shown in these figures occur precisely every 100 rounds, which is in accordance with the parameter delta (i.e., the number of steps to modify alpha up and alpha down).

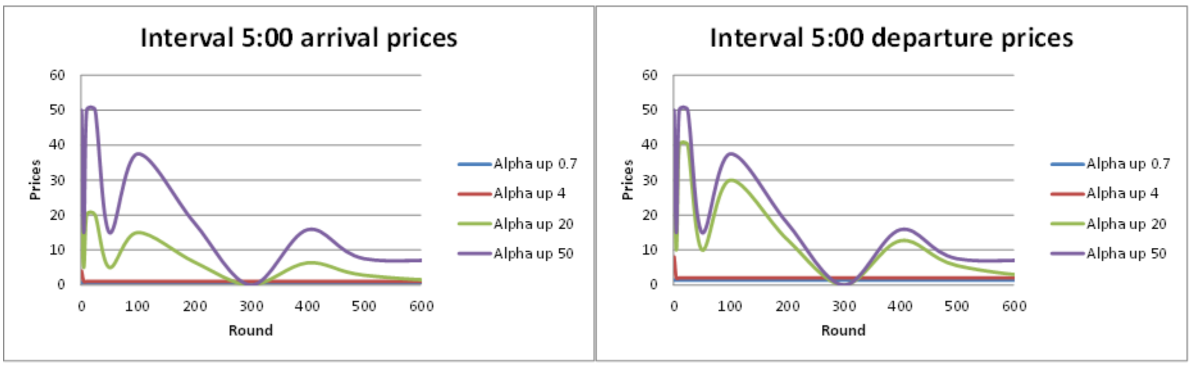

Figure 22. Evolution of the price for the arrival and departure slots at 5.00

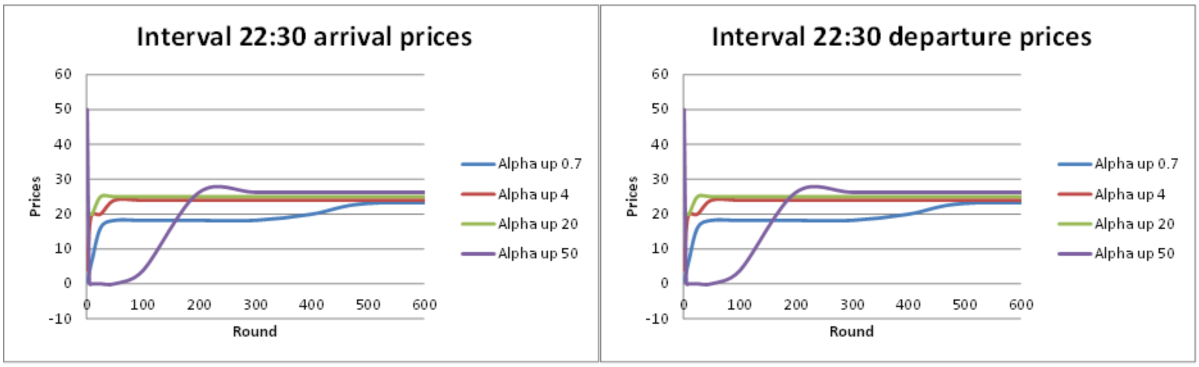

Figure 23. Evolution of the price for the arrival and departure slots at 22.30

3.2.2 Scenario 2: four airports and four airlines

Once we have analysed the proper functioning of the auction mechanism, we perform a new experiment to explore the scenario shown in Figure 10. This experiment allows us to study how changes in the parameterisation of the auctioning mechanism influence the final outcome in a more complex scenario.

The simulations have been performed with the following values of demand between airports:

Origin airport	Destination airport	Demand (No of passengers)
HUB1	HUB2	2326
HUB1	REG1	2428
HUB1	REG2	390
HUB2	HUB1	2276
HUB2	REG1	1192
HUB2	REG2	1876
REG1	HUB1	2474
REG1	HUB2	1200
REG1	REG2	312
REG2	HUB1	392
REG2	HUB2	1882
REG2	REG1	134

Table 8. Demand between airports

The airlines NW1, NW2, LC1 and LC2 have a fleet of 2, 8, 4 and 2 aircraft, respectively. The considered value of the parameter fuel price is 0.59.

The preferred schedule of each airline (i.e., the one that maximises the utility of all the flights when the price of all the slots is 0) is shown in Table 9.

Airline	Departure Airport	Preferred TOD	Arrival Airport	Preferred TOA
LC1	HUB1	8:55	HUB2	10:31
LC1	HUB1	9:00	REG1	9:56
LC1	HUB1	14:35	HUB2	16:11
LC1	HUB1	14:40	REG1	15:36
LC1	HUB1	17:55	HUB2	19:31
LC1	HUB1	18:05	REG1	19:01
LC1	HUB1	21:35	REG1	22:31
LC1	HUB2	9:00	HUB1	10:36
LC1	HUB2	14:45	HUB1	16:21
LC1	HUB2	18:00	HUB1	19:36
LC1	REG1	5:15	HUB1	6:11
LC1	REG1	9:00	HUB1	9:56
LC1	REG1	13:30	HUB1	14:26
LC1	REG1	18:00	HUB1	18:56
LC2	HUB1	5:00	HUB2	6:36
LC2	HUB1	9:10	HUB2	10:46
LC2	HUB1	14:50	HUB2	16:26
LC2	HUB1	17:55	HUB2	19:31
LC2	HUB2	9:30	HUB1	11:06
LC2	HUB2	14:45	HUB1	16:21
LC2	HUB2	18:00	HUB1	19:36
LC2	HUB2	21:20	HUB1	22:56
NW1	HUB1	8:55	HUB2	10:29
NW1	HUB1	11:50	REG2	13:05
NW1	HUB1	17:55	HUB2	19:29
NW1	HUB2	9:00	HUB1	10:34
NW1	HUB2	18:00	HUB1	19:34
NW1	REG2	14:00	HUB1	15:15
NW2	HUB1	5:30	REG1	6:26
NW2	HUB1	7:45	REG1	8:41
NW2	HUB1	8:40	REG2	9:57
NW2	HUB1	9:00	REG1	9:56
NW2	HUB1	11:15	REG1	12:11
NW2	HUB1	13:30	REG1	14:26
NW2	HUB1	15:05	REG2	16:22
NW2	HUB1	15:45	REG1	16:41
NW2	HUB1	17:55	HUB2	19:31
NW2	HUB1	18:00	REG1	18:56
NW2	HUB1	20:50	REG1	21:46
NW2	HUB1	22:05	REG2	23:22

Airline	Departure Airport	Preferred TOD	Arrival Airport	Preferred TOA
NW2	HUB1	23:05	REG1	0:01
NW2	HUB2	9:00	HUB1	10:36
NW2	HUB2	18:00	HUB1	19:36
NW2	REG1	7:30	HUB1	8:26
NW2	REG1	9:00	HUB1	9:56
NW2	REG1	11:15	HUB1	12:11
NW2	REG1	13:30	HUB1	14:26
NW2	REG1	15:45	HUB1	16:41
NW2	REG1	18:00	HUB1	18:56
NW2	REG1	18:00	HUB2	20:04
NW2	REG1	20:20	HUB1	21:16
NW2	REG1	22:35	HUB1	23:31
NW2	REG2	6:00	HUB1	7:17
NW2	REG2	14:00	HUB1	15:17
NW2	REG2	22:05	HUB1	23:22

Table 9. Airlines' preferred schedule

Figure 24, Figure 25 and Figure 26 show the nominal capacity for the airport HUB1 (arrival, departure, and total capacity, respectively) in red. The requested slots by the airlines are represented in blue.

Figure 24. Arrivals in HUB1: nominal capacity (red) vs airline requests (blue)

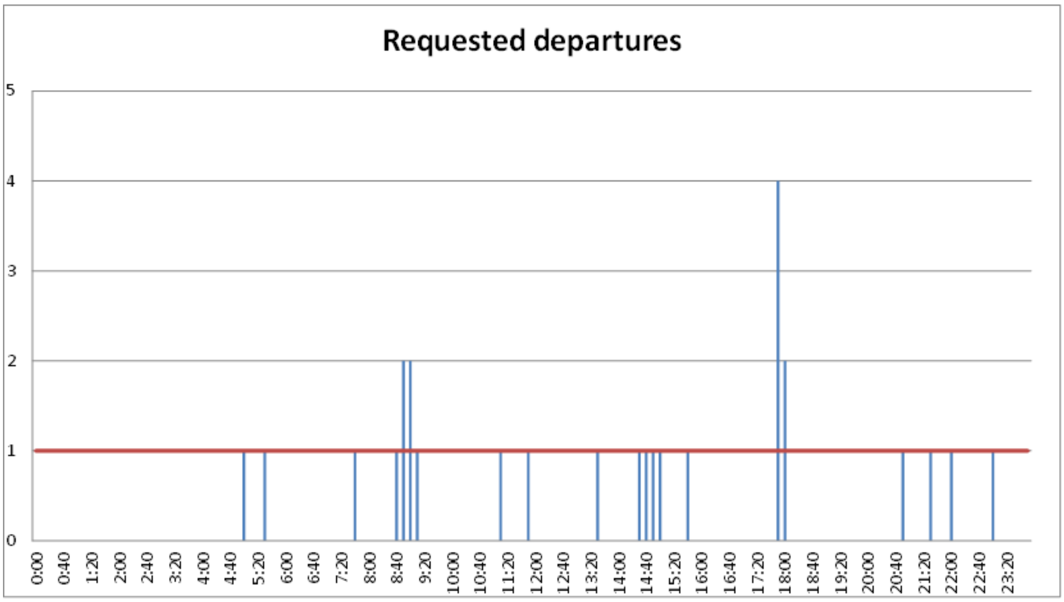

Figure 25. Departures from HUB1: nominal capacity (red) vs airline requests (blue)

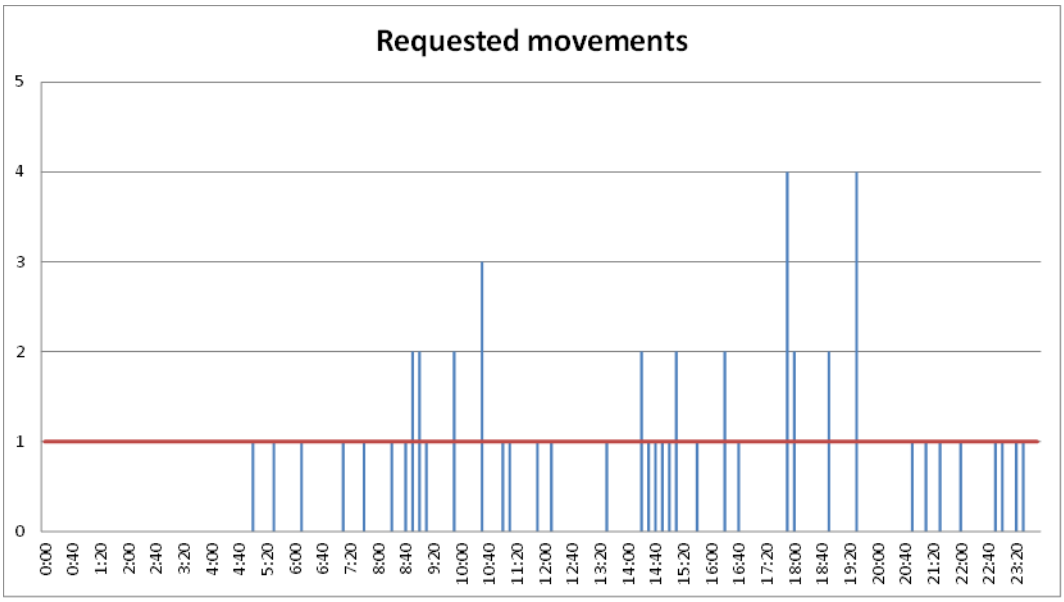

Figure 26. Total movements at HUB1: nominal capacity (red) vs total slot requests (blue)

These figures show that the desired schedule violates the airport's nominal capacity constraints.

Figure 27, Figure 28 and Figure 29 represent the rolling capacity for the airport HUB1 (arrival, departure, and total capacity, respectively) in red. The blue bars represent the requests from the airlines.

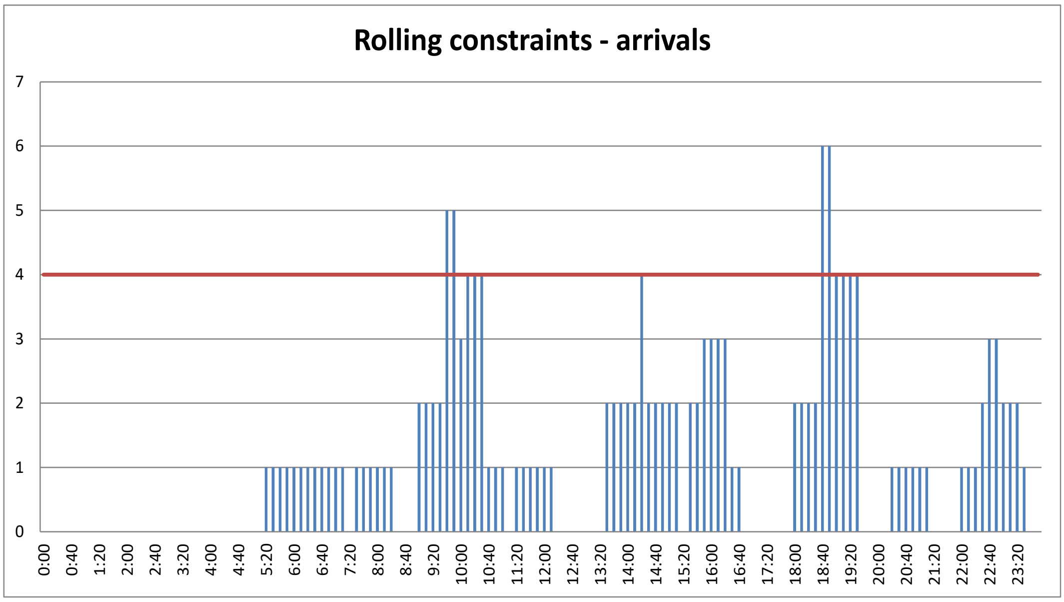

Figure 27. Arrivals in HUB1: rolling capacity (red) vs cumulative airline requests (blue)

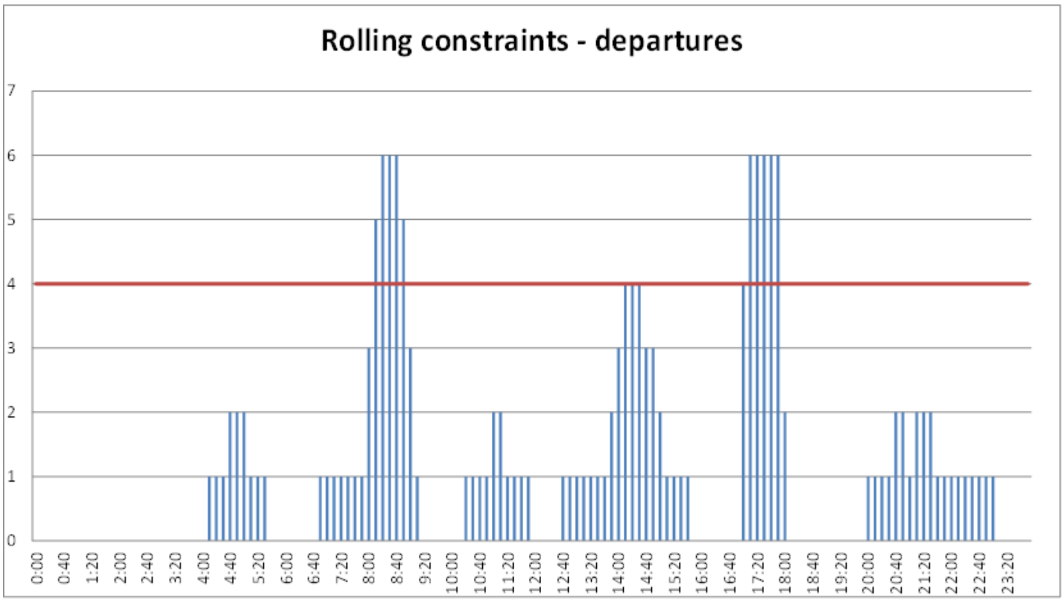

Figure 28. Departures from HUB1: rolling capacity (red) vs cumulative airline requests (blue)

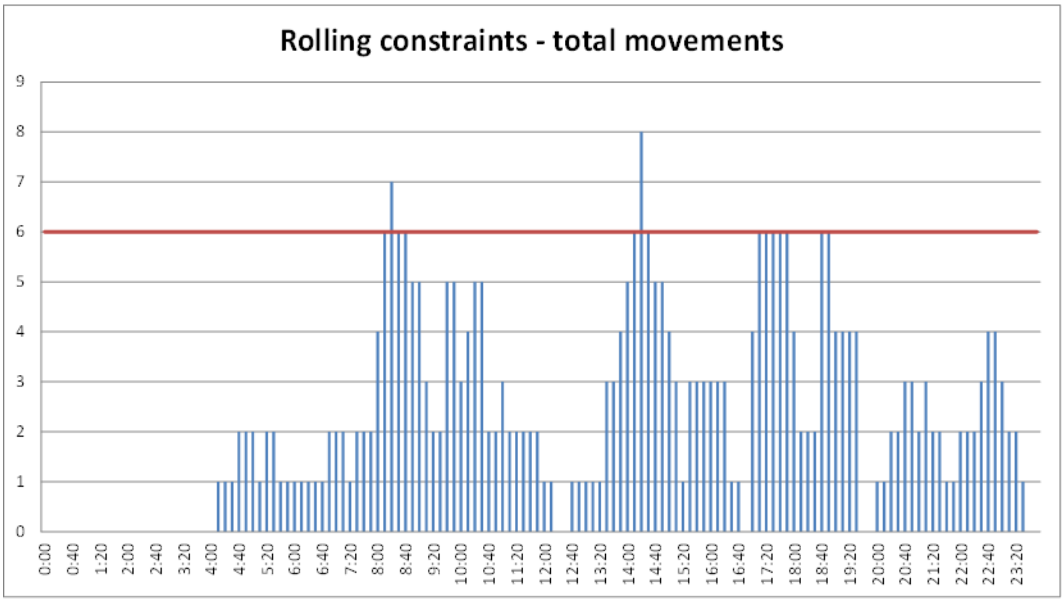

Figure 29. Total movements at HUB1: rolling capacity (red) vs cumulative airline requests (blue)

These figures show that the airline requests violate the airport's rolling constraints on several occasions. 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 9 am and 6 pm.

The auction runs for 1810 iterations until the stop criteria are met, i.e., until all capacity constraints are respected and the prices reach an equilibrium state. The results of the slot auction are presented in Table 10**¡Error! No se encuentra el origen de la referencia.**.

Airline	Departure Airport	Departure time	Arrival Airport	Arrival time
LC1	HUB1	8:25	HUB2	10:01
LC1	HUB1	9:10	REG1	10:06
LC1	HUB1	14:35	REG1	15:31
LC1	HUB1	17:15	HUB2	18:51
LC1	HUB1	18:20	REG1	19:16
LC1	HUB1	21:35	REG1	22:31
LC1	HUB2	9:15	HUB1	10:51
LC1	HUB2	18:10	HUB1	19:46
LC1	REG1	5:00	HUB1	5:56
LC1	REG1	9:05	HUB1	10:01
LC1	REG1	15:05	HUB1	16:01
LC1	REG1	17:50	HUB1	18:46
LC2	HUB1	9:20	HUB2	10:56
LC2	HUB1	14:40	HUB2	16:16
LC2	HUB1	17:25	HUB2	19:01
LC2	HUB1	20:50	REG2	22:07
LC2	HUB2	9:30	HUB1	11:06

Airline	Departure Airport	Departure time	Arrival Airport	Arrival time
LC2	HUB2	15:05	HUB1	16:41
LC2	HUB2	18:20	HUB1	19:56
LC2	REG2	5:15	HUB1	6:32
NW1	HUB1	8:55	HUB2	10:29
NW1	HUB1	11:35	REG1	12:31
NW1	HUB1	17:55	HUB2	19:29
NW1	HUB1	21:50	REG2	23:05
NW1	HUB2	8:55	HUB1	10:29
NW1	HUB2	17:55	HUB1	19:29
NW1	REG1	13:30	HUB1	14:26
NW1	REG2	5:30	HUB1	6:45
NW2	HUB1	5:30	REG1	6:26
NW2	HUB1	7:45	REG1	8:41
NW2	HUB1	8:10	REG2	9:27
NW2	HUB1	9:00	REG1	9:56
NW2	HUB1	11:45	REG1	12:41
NW2	HUB1	14:00	REG1	14:56
NW2	HUB1	15:05	REG2	16:22
NW2	HUB1	16:55	REG1	17:51
NW2	HUB1	18:00	HUB2	19:36
NW2	HUB1	18:10	REG1	19:06
NW2	HUB1	20:20	REG1	21:16
NW2	HUB1	22:05	REG2	23:22
NW2	HUB1	22:35	REG1	23:31
NW2	HUB2	9:00	HUB1	10:36
NW2	HUB2	18:00	HUB1	19:36
NW2	REG1	5:15	HUB1	6:11
NW2	REG1	7:45	HUB1	8:41
NW2	REG1	9:00	HUB1	9:56
NW2	REG1	11:20	HUB1	12:16
NW2	REG1	15:30	HUB1	16:26
NW2	REG1	18:00	HUB1	18:56
NW2	REG1	18:00	HUB2	20:04
NW2	REG1	20:20	HUB1	21:16
NW2	REG1	22:35	HUB1	23:31
NW2	REG2	6:00	HUB1	7:17
NW2	REG2	14:00	HUB1	15:17
NW2	REG2	22:05	HUB1	23:22

Table 10. Slot allocation resulting from the auction

Figure 30, Figure 31, Figure 32, Figure 33, Figure 34 and Figure 35 show that, after the execution of the auction, the slots allocated in HUB1 do not exceed neither nominal nor rolling capacity constraints. 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.

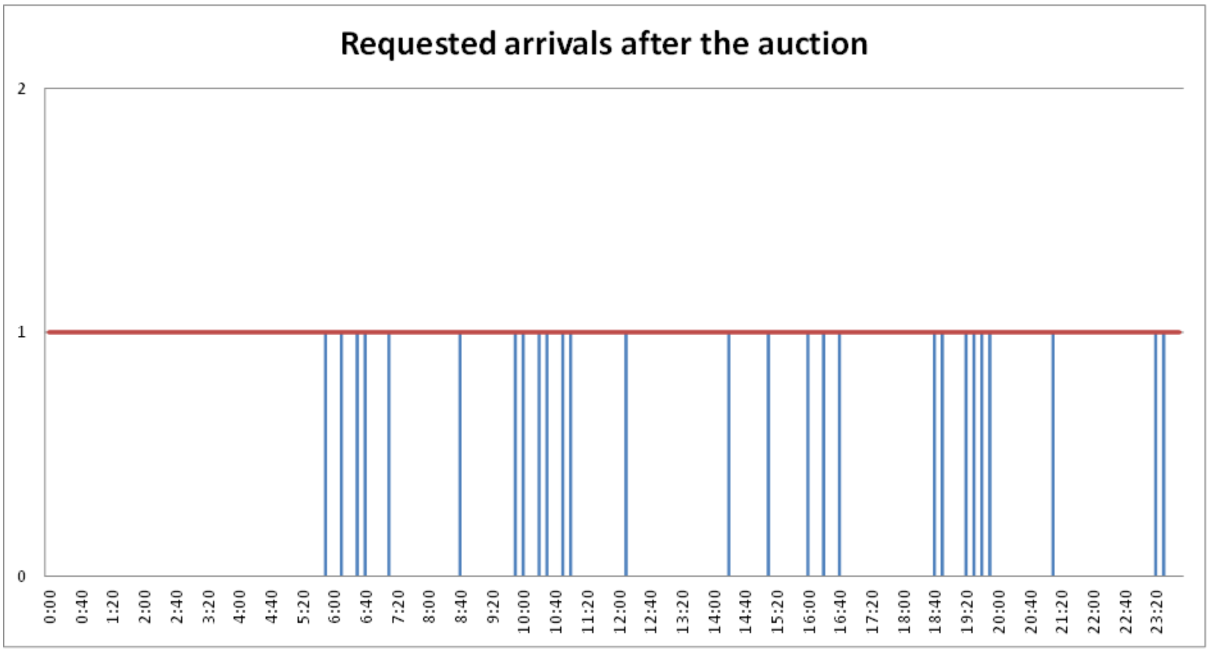

Figure 30. Arrivals in HUB1 after the auction: nominal capacity (red) vs airline requests (blue)

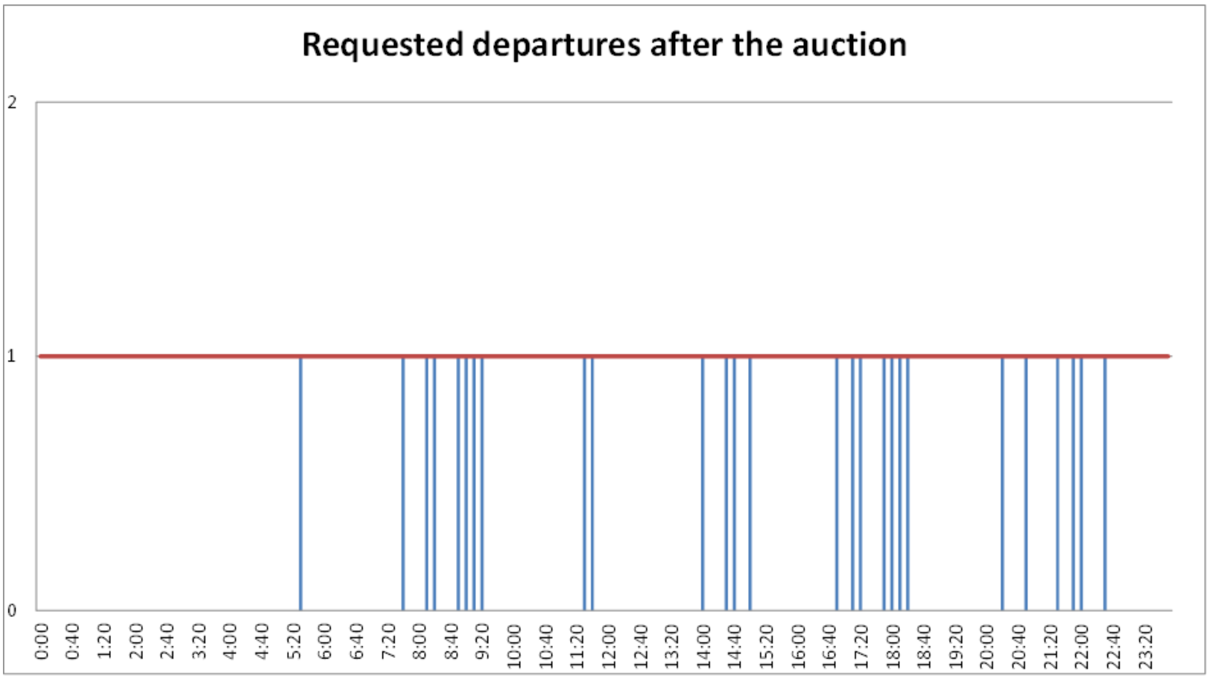

Figure 31. Departures from HUB1 after the auction: nominal capacity (red) vs airline requests (blue)

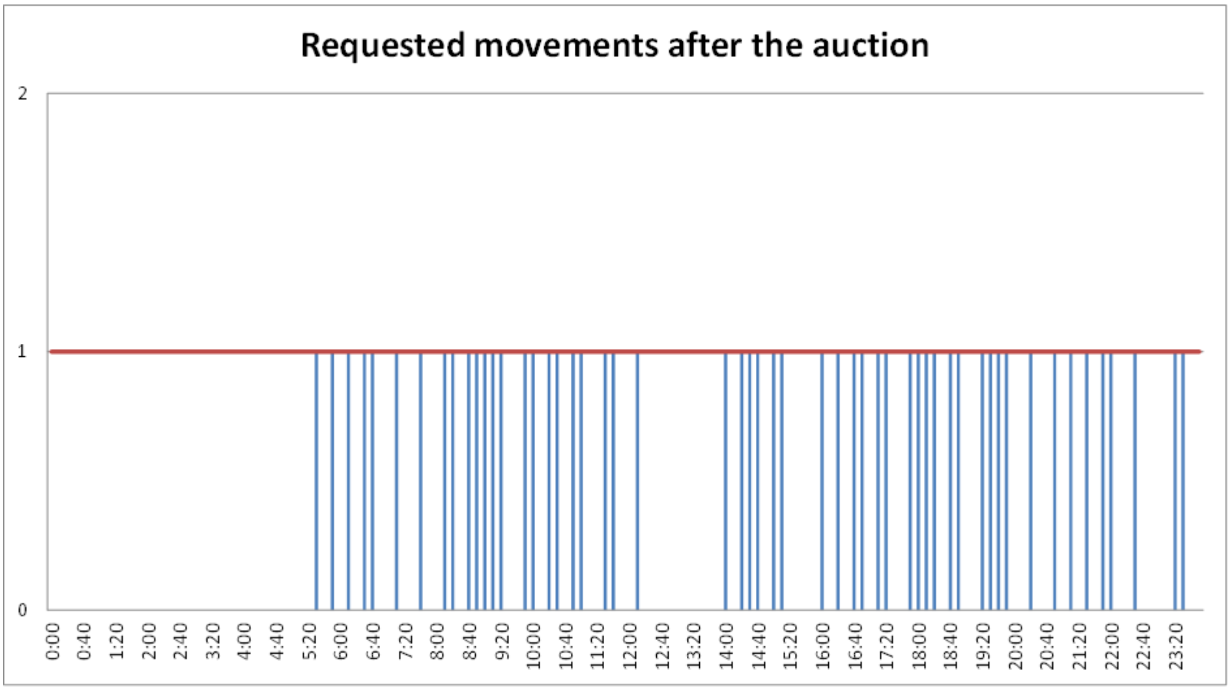

Figure 32. Total movements at HUB1 after the auction: nominal capacity (red) vs total slot requests (blue)

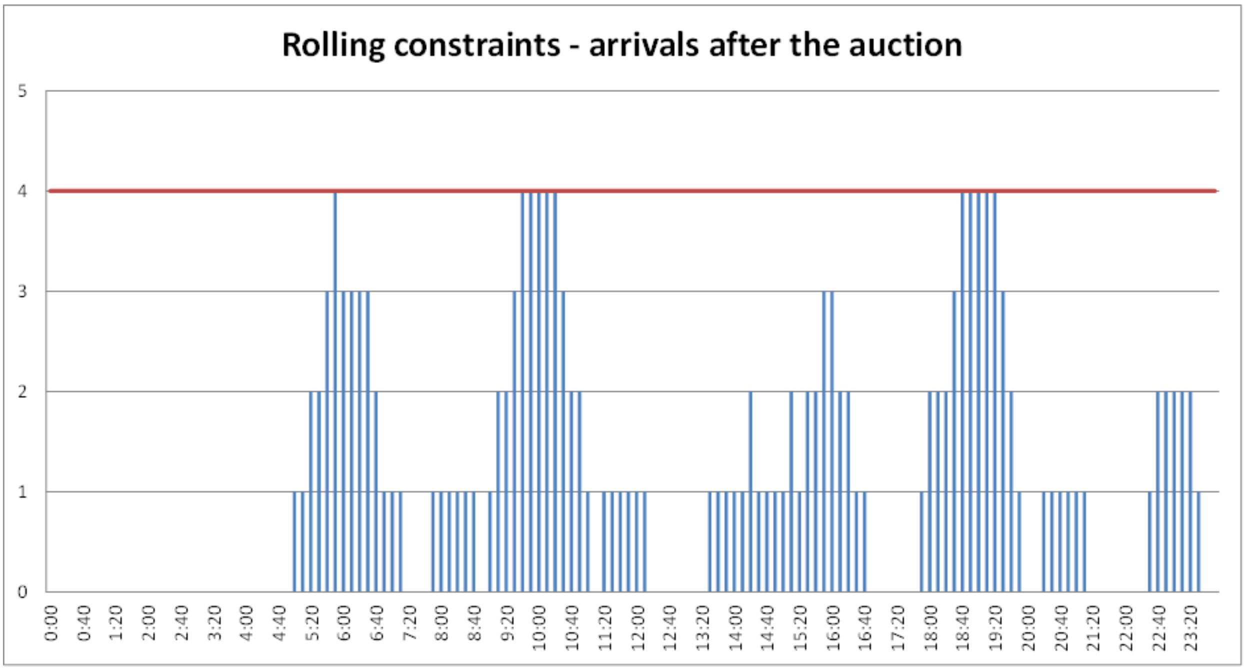

Figure 33. Arrivals in HUB1 after the auction: rolling capacity (red) vs cumulative airline requests (blue)

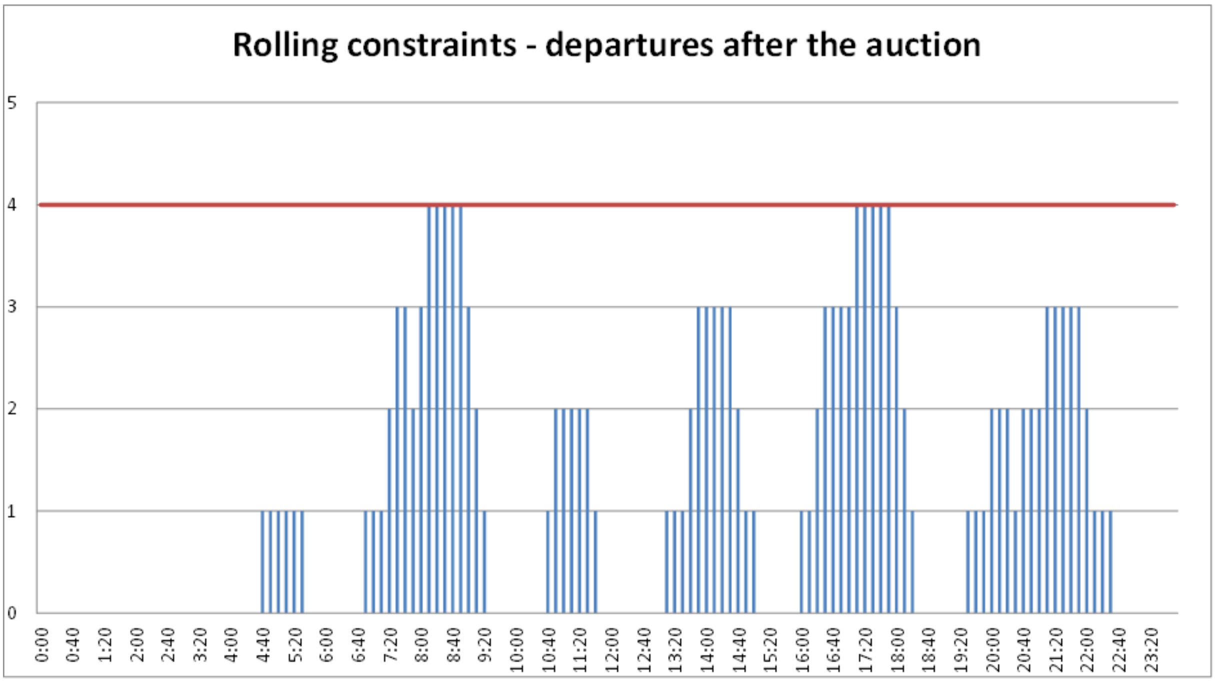

Figure 34. Departures from HUB1 after the auction: rolling capacity (red) vs cumulative airline requests (blue)

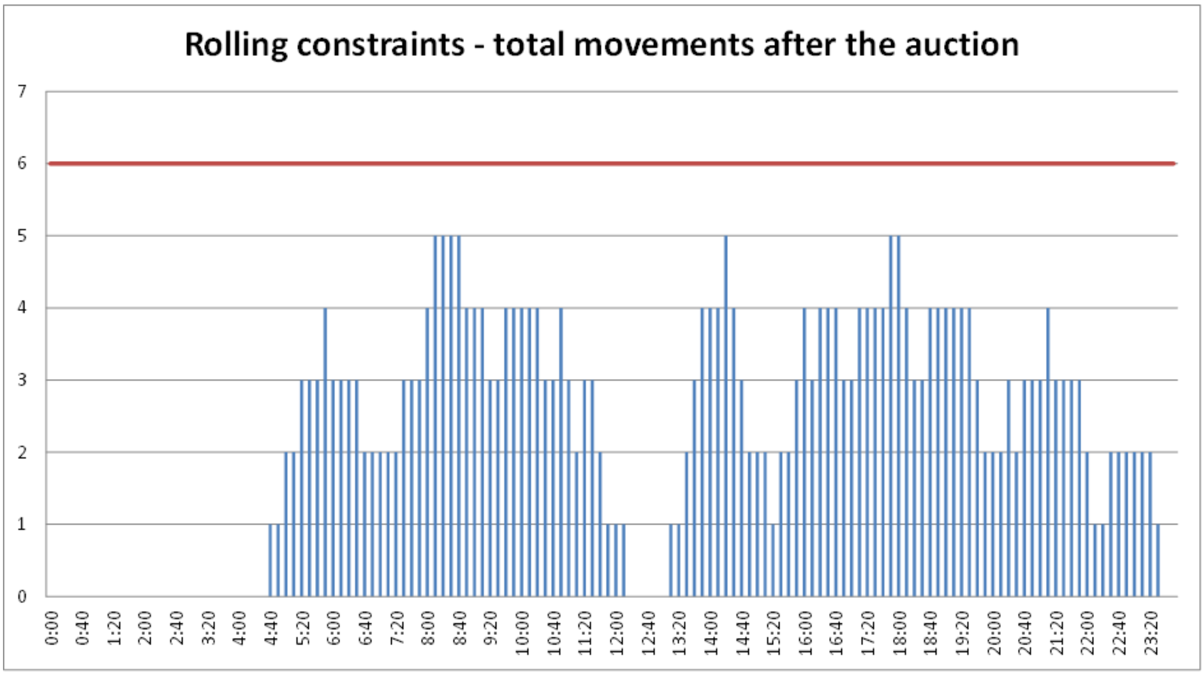

Figure 35. Total movements at HUB1 after the auction: rolling capacity (red) vs cumulative requests (blue)

The previous figures show that the auction yields a feasible schedule. We will now check the dynamics of the auction. We expect that the prices of the slots in the most congested intervals rise as a consequence of the high demand. The utility of the airlines at those congested intervals may drop and, as a result, airlines may choose to shift their requests to other intervals with less congestion and, consequently, lower prices. Figure 36 and Figure 37 show the final arrival and departure prices in the airport HUB1, respectively.

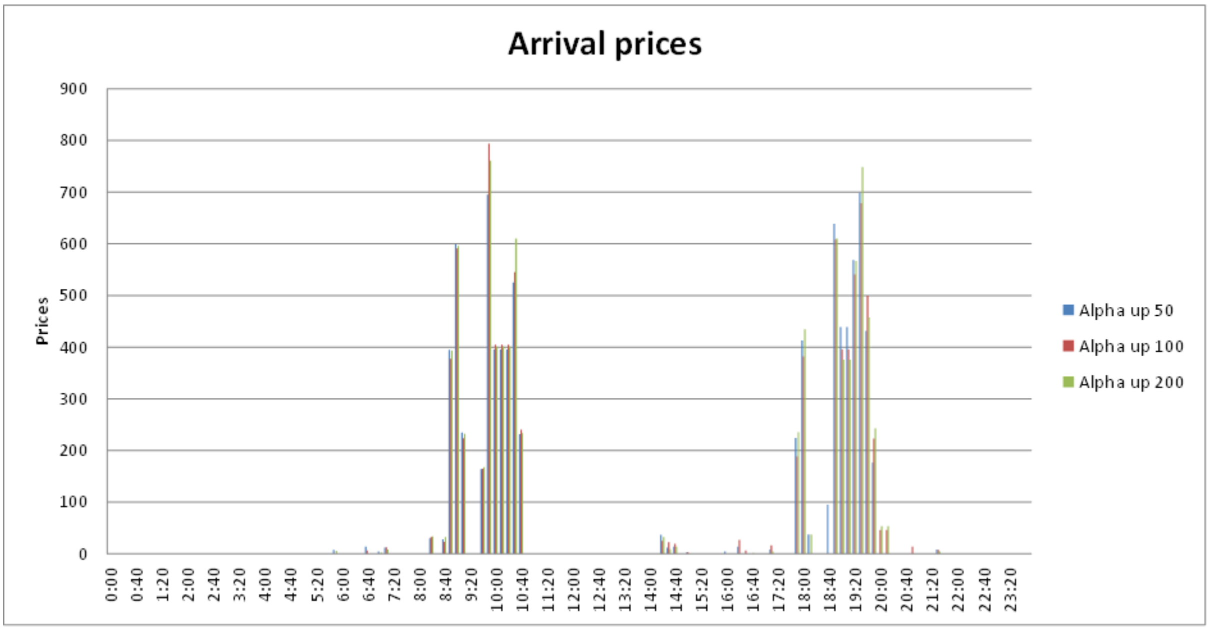

Figure 36. Final arrival slot prices in HUB 1

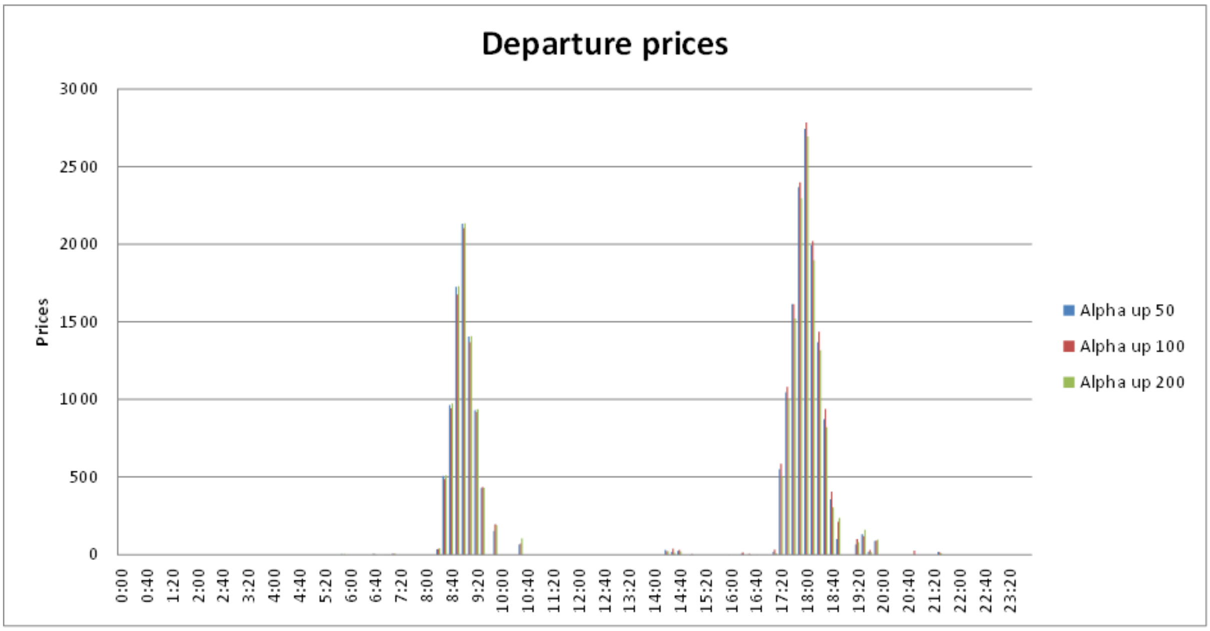

Figure 37. Final departure slot prices in HUB 1

If we compare the final prices shown in Figure 36 and Figure 37 with the requested movements shown in Figure 26, Figure 25, Figure 26, Figure 27, Figure 28 and Figure 29, we observe that the highest prices correspond to the most congested periods. Figure 38 provides a more detailed view of this situation.

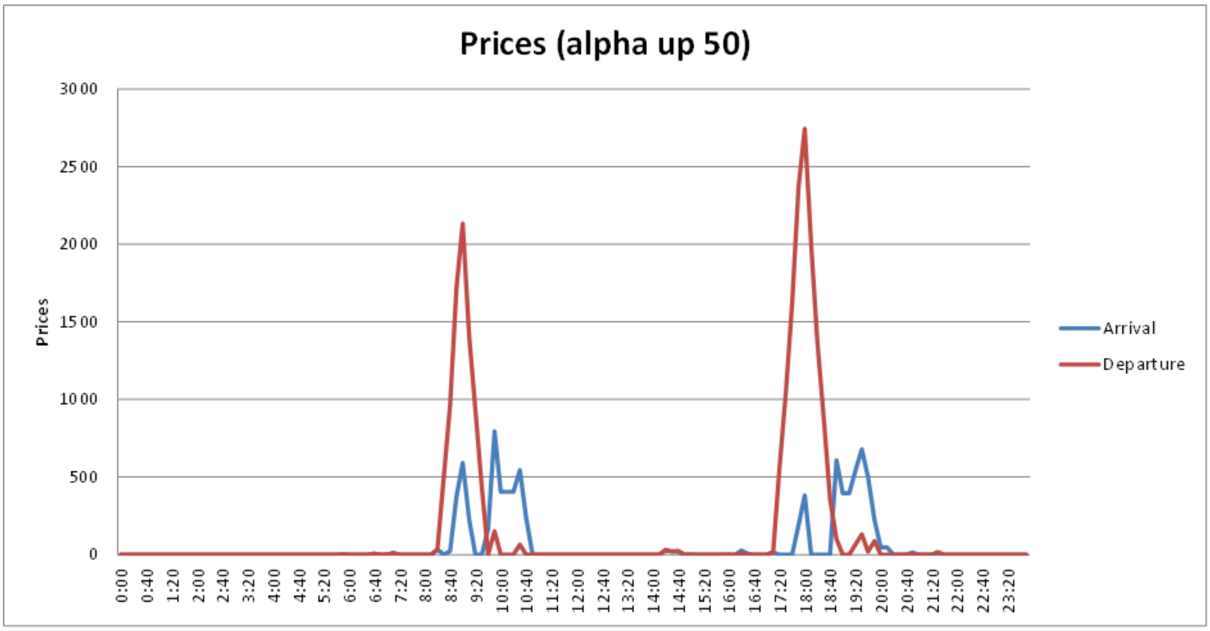

Figure 38. Final arrival and departure slot prices in HUB1 (alpha up = 50)

We have simulated this scenario with several values of alpha up and alpha down. Figure 36 and Figure 37 show the simulation results for three values of alpha: 50, 100 and 200. Alpha down is 75% of the value of alpha up. The value of the parameter delta (i.e., the number of steps to modify alpha up and alpha down) is 100 in the four experiments. This means that the values of alpha up and alpha down are revised every 100 iterations in the auction. The value of the parameter gamma (i.e., the magnitude by which the values of alpha up and alpha down are revised after delta number of rounds) is 25% in the four experiments. We observe that regardless of the value of alpha up and alpha down, the auction always converges to approximately the same prices in the same slots, which proves the robustness of the auction mechanism.

Although the value of the parameters alpha up and alpha down does not significantly affect the final slot price, it has a clear impact on the dynamics of the auction. In order to study how the parameters alpha up and alpha down affect the evolution of the prices, we will focus on four intervals with non-zero final prices, as we did for the two-airport scenario: two periods with high final prices and two periods with low final prices.

Figure 39 and Figure 40 show the price convergence speed in the auctioning process. These charts show the evolution of the arrival and departure slot prices for several values of the parameter alpha up at two peak intervals where the auction resulted in relatively high prices: 9.00 and 18.00. Figure 41 and Figure 42 show the evolution of the arrival and departure slot prices for several values of the parameter alpha up at two peak intervals where the auction resulted in relatively low prices (which occurs at periods with low congestion). In all these cases, the best convergence behaviour corresponds to alpha up equal to 50.

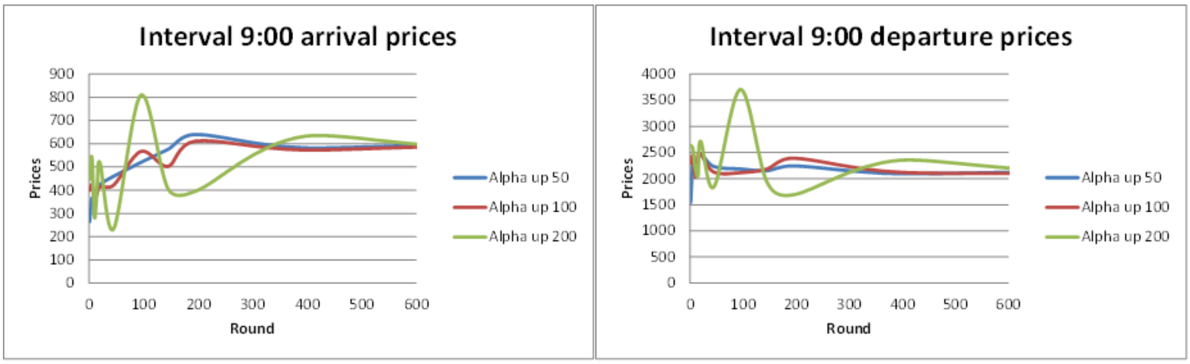

Figure 39. Evolution of the price for the arrival and departure slots at 9.00

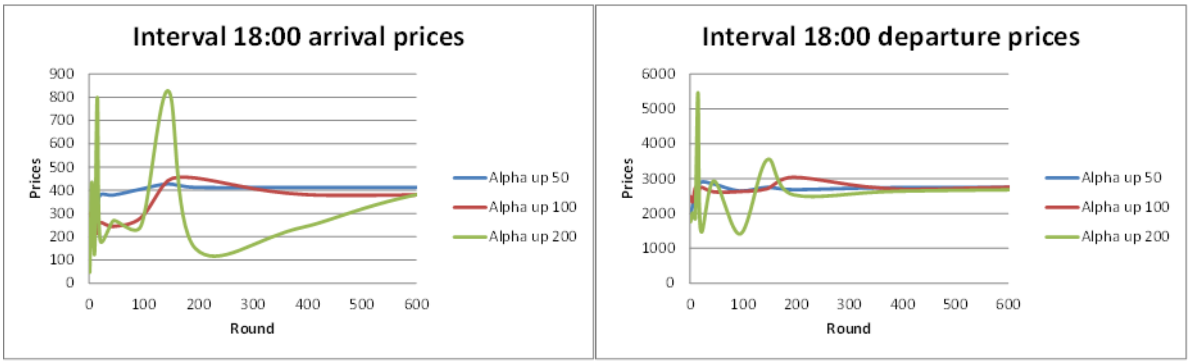

Figure 40. Evolution of the price for the arrival / departure slots at 18.00

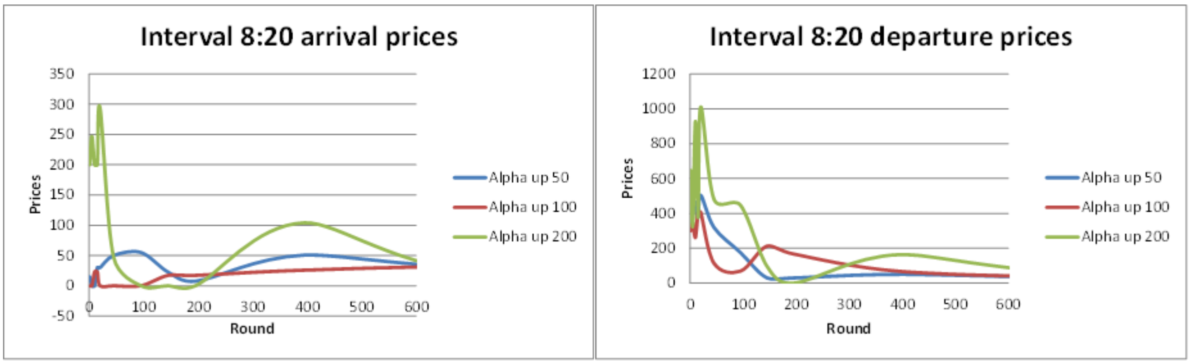

Figure 41. Evolution of the price for the arrival and departure slots at 8.20

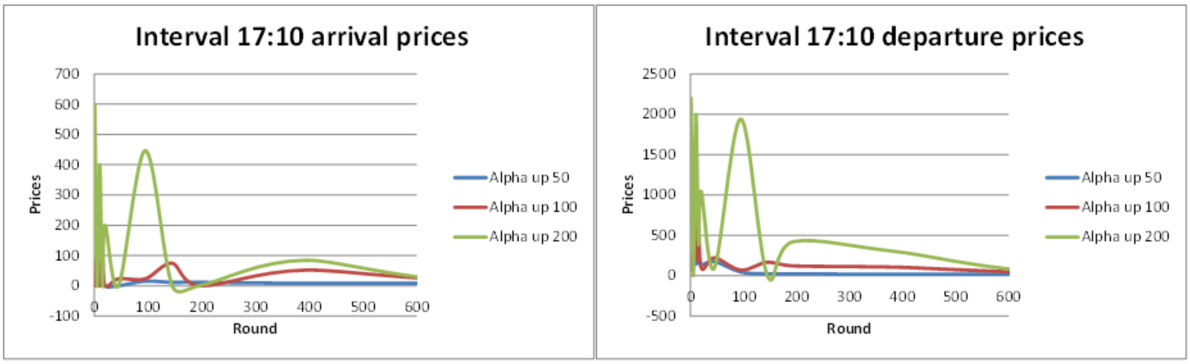

Figure 42. Evolution of the price for the arrival and departure slots at 17.10

Table 11 shows the number of arrival, departure and total slots requested by and allocated to each airline in each of the three coordinated airports. The field 'coincidences' represents the number of flights whose slots initially requested match the slots resulting from the auction. For example, LC2 requested 4 arrival slots and 4 departure slots in HUB2, i.e. 8 in total (see blue box in Table 11). After executing the auction, LC2 received 3 arrival slots and 3 departure slots (6 in total). However, the concrete slots that the airline get do not necessarily coincide with the slots initially requested. In this example, none of the received arrival slots matched the requested ones, and only 1 departure slot coincides with the requested departure slots.

LC2 requested 8 slots in HUB1, 8 slots in HUB2 and 0 slots in REG1, which makes 16 total requests (see green boxes in Table 11). However, if we focus on the number of slots allocated on exactly the same time of the day when LC2 requested them, they get 1 slot in HUB1, 1 slot in HUB 2 and 0 slots in REG1, i.e., 2 matching slots in total (see red boxes in Table 11). Therefore, out of the 16 slots that LC2 requested, they only get 2 at exactly the same time they requested them, which makes 12.5% of coincidences. If we perform the same analysis for the other three airlines, NW1, NW2 and LC1, we observe they get a coincidence of 40%, 57.4%, and 25% respectively (see shaded cells in the last row of Table 11).

		NW1			NW2			LC1			LC2			Total					
		Arrival	Depart.	Total	Arrival	Depart.	Total	Arrival	Depart.	Total	Arrival	Depart.	Total	Arrival		Departure		Total	
HUB1	Requested	3	3	6	13	13	26	7	7	14	4	4	8	27		27		54	
	Assigned	4	4	8	13	13	26	6	6	12	4	4	8	27		27		54	
	Coincidences	0	2	2	10	6	16	0	2	2	1	0	1	11	40.7%	8.4	31.1%	21.0	38.9%
HUB2	Requested	2	2	4	2	2	4	3	3	6	4	4	8	11		11		22	
	Assigned	2	2	4	2	2	4	2	2	4	3	3	6	9		9		18	
	Coincidences	2	0	2	2	2	4	0	0	0	0	1	1	4	36.4%	3.4	30.6%	7.0	31.8%
REG1	Requested	0	0	0	9	8	17	4	4	8	0	0	0	13		12		25	
	Assigned	1	1	2	9	8	17	4	4	8	0	0	0	14		13		27	
	Coincidences	0	0	0	3	4	7	3	2	5	0	0	0	6	46.2%	6.5	53.8%	12.0	48.0%
Total	Requested	5	5	10	24	23	47	14	14	28	8	8	16						
	Assigned	7	7	14	24	23	47	12	12	24	7	7	14						
	Coincidences	2	2	4	15	12	27	3	4	7	1	1	2						
	Coincidences (%)	40.0%	40.0%	40.0%	62.5%	52.2%	57.4%	21.4%	28.6%	25.0%	12.5%	12.5%	12.5%						

Table 11. Number of slots requested by and allocated to each airline in each airport

Figure 43 shows the percentage of flights that each airline retains at exactly the same slot they requested. It is noticeable that the network airlines (NW1 and NW2) are more prone to succeed in retaining the requested slots than the low cost airlines (LC1 and LC2).

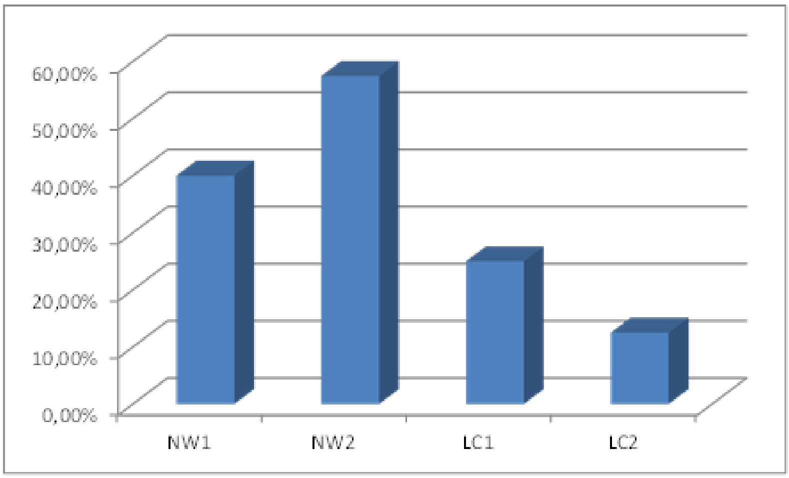

Figure 43. Percentage of retained flights after the auction in each airline

It should be highlighted that it is possible that an airline initially requests a flight between two airports and, as a result of the prices emerging over the execution of the auction, it decides later on to discard the original plan and operate a different route between two other airports. For example, prior to the auction, HUB1 gets 6 requests from NW1, 26 requests from NW2, 14 requests from LC1 and 8 requests from LC2, which makes a total of 54 requests (see purple boxes in Table 11). After the auction, the number of matching slots is 2 for NW1, 16 for NW2, 2 for LC1 and 1 for LC2, which makes 21 matching slots (see orange boxes in Table 11). Therefore, the coincidence for HUB1 is 38.9%. If we conduct a similar reasoning for HUB2 and REG1, we get a coincidence of 31.8% and 48%, respectively (see shaded cells in the last column of Table 11).

Figure 44 shows the percentage of retained flights for the three coordinated airports. It is noticeable that HUB2 is the one that retains the lowest number of flights and, however, it is not the airport with the most restrictive constraints according to Table 4. The reason for this is that most requests occur at short periods of time (see Table 9), which results in a violation of the airport capacities mainly at those periods and, consequently, the airlines decide to shift their flights to other close slots.

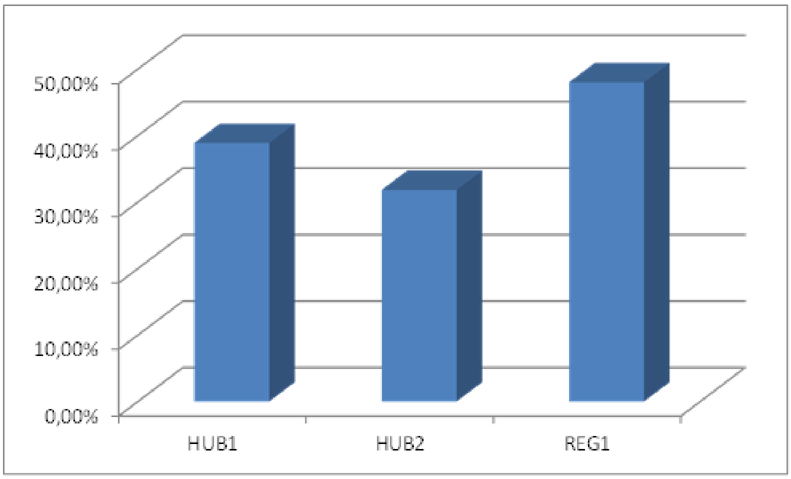

Figure 44. Percentage of retained flights in each airport

Figure 45 shows the total expected airlines' profit across the execution of the auction. The profit is maximum in the first round since the airlines bid for their preferred slots as if the prices were zero. In the successive rounds of the simulation, the expected profit tends to fall until it reaches its final value. This is due to the presence of other airlines bidding for the same slots, which results in an increase of the price of those slots. The airlines, then, bid for other slots that involve a lower benefit. A more detailed view of the evolution of the expected benefit is shown in Figure 46.

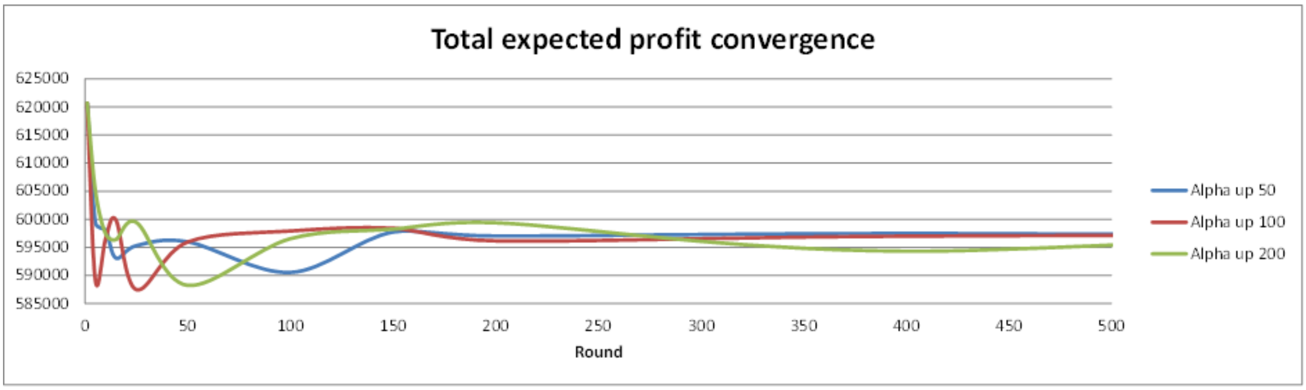

Figure 45. Convergence of the airlines' total expected profit

Figure 46 shows the expected profit convergence for the four airlines (LC1, LC2, NW1 and NW2).

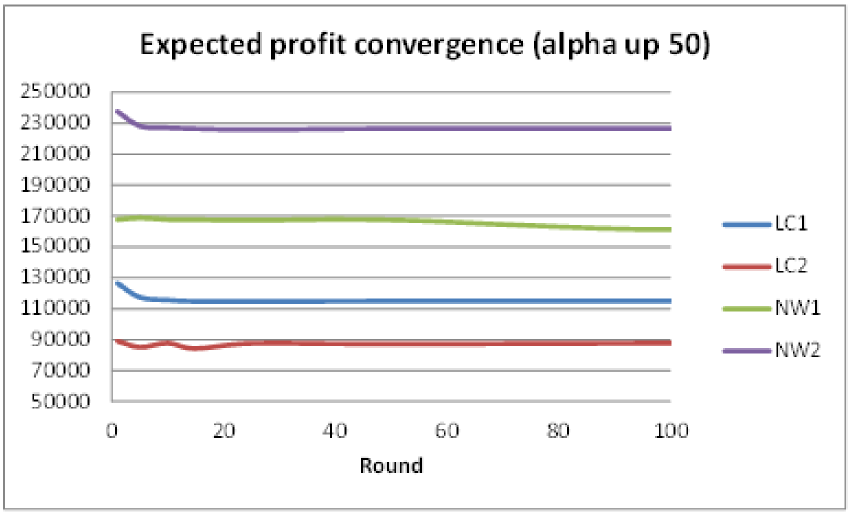

Figure 46. Expected profit convergence for the four airlines

3.3 Comparative analysis: current administrative mechanism vs primary auctioning

The third experiment of this series has been conducted to analyse and compare the performance of different slot allocation mechanisms. The simulations have been performed with the following values of demand between airports:

Origin airport	Destination airport	Demand business	Demand leisure	Total demand
HUB1	HUB2	465	698	1163
HUB1	REG1	496	745	1241
HUB1	REG2	78	117	195
HUB2	HUB1	455	683	1138
HUB2	REG1	238	358	596
HUB2	REG2	375	563	938
REG1	HUB1	494	743	1237
REG1	HUB2	240	360	600
REG1	REG2	62	94	156
REG2	HUB1	78	118	196
REG2	HUB2	376	565	941
REG2	REG1	26	41	67

Table 12. Demand between airports

In this case, the airlines NW1, NW2, LC1 and LC2 have a fleet of 4 aircraft each, and the considered value of the parameter fuel price is 0.59.

For the application of the administrative mechanism, it is considered that NW1 has grandfather rights over one slot for each of the following coordination intervals at HUB1:

Airport	Slot type	Time
HUB1	DEPARTURE	5:00
HUB1	DEPARTURE	5:10
HUB1	DEPARTURE	7:10
HUB1	DEPARTURE	8:30
HUB1	DEPARTURE	12:40
HUB1	DEPARTURE	13:00
HUB1	DEPARTURE	14:40
HUB1	DEPARTURE	17:10
HUB1	DEPARTURE	17:20
HUB1	DEPARTURE	20:30

Airport	Slot type	Time
HUB1	ARRIVAL	5:50
HUB1	ARRIVAL	9:00
HUB1	ARRIVAL	9:30
HUB1	ARRIVAL	9:40
HUB1	ARRIVAL	13:30
HUB1	ARRIVAL	13:40
HUB1	ARRIVAL	17:00
HUB1	ARRIVAL	22:50
HUB1	ARRIVAL	23:00
HUB1	ARRIVAL	23:10

Table 13. NW1 grandfather rights

The rest of airlines are assumed to have no grandfather rights over any slot of the airports included in the scenario.

Sections 3.3.1 and 3.3.2 present the following information for the administrative mechanism and the primary auctioning, respectively:

- the airlines schedule;
- the ticket fares;
- the number of tickets that the airline agents expected to sell for each flight (for the chosen ticket prices and assuming a perfect knowledge of the existing demand for each OD pair, but without knowing what their competitor will offer, i.e., based on certain assumptions about the market share they will be able to capture), on which they base in turn the calculation of the expected profit;
- the tickets sold for each flight after simulating the behaviour of the passengers, broken down into business and leisure passengers;
- the utility (surplus) obtained by each airline for each flight, calculated as the income obtained from the sold tickets minus the cost of operating the flight (including the landing fees and the price paid for the slots in the case of the auction).

For the auction, the final price of the slots at HUB1 and HUB2 resulting from the auction is also provided (see Figure 47 and Figure 48).

Section 3.3.3 compares the net utility (i.e., the surplus) obtained by the different stakeholders, as well as the total social welfare, under each of the two mechanisms under study.

It is important to highlight that, in this example, only primary allocation is considered, i.e., the schedule presented in sections 3.3.1 and 3.3.2 and the utilities presented in section 3.3.3 are the ones that would result from primary allocation, without the possibility for secondary slot trading, transfers or exchanges. In the real life, of course, slot transfers, exchanges and trades would arguably be expected to improve the schedules of the airlines.

3.3.1 Results of the administrative mechanism

Airline	Departure airport	Departure time	Arrival airport	Arrival time	Aircraft type	Ticket fare (€)	Offered tickets	Expected sold tickets	Sold tickets	Business passengers	Leisure passengers	Utility obtained by the airline (€)
LC1	HUB1	12:50	REG2	14:07	ACR1	122.37	171	58	29	8	21	-201.25
LC1	HUB1	14:45	HUB2	16:21	ACR1	62.83	171	171	171	27	144	6,050.14
LC1	HUB1	21:05	REG2	22:22	ACR1	122.37	171	58	72	25	47	5,060.66
LC1	HUB2	8:20	REG2	9:26	ACR1	148.80	171	171	116	53	63	14,000.18
LC1	HUB2	8:40	HUB1	10:16	ACR1	72.73	171	171	171	114	57	7,506.00
LC1	HUB2	17:00	REG2	18:06	ACR1	148.59	171	171	171	124	47	22,148.27
LC1	HUB2	23:50	REG2	0:56	ACR1	148.35	171	171	97	33	64	11,129.33
LC1	REG2	5:00	HUB2	6:06	ACR1	109.80	171	171	94	39	55	6,962.02
LC1	REG2	5:45	HUB1	7:02	ACR1	128.82	171	61	33	10	23	165.48
LC1	REG2	12:20	HUB2	13:26	ACR1	109.80	171	171	100	45	55	7,620.82
LC1	REG2	17:30	HUB1	18:47	ACR1	131.29	171	60	33	10	23	246.99
LC1	REG2	19:50	HUB2	20:56	ACR1	109.80	171	171	171	116	55	15,416.62
LC2	HUB1	17:40	REG2	18:57	ACR3	119.70	189	64	93	72	21	7,724.54
LC2	HUB2	8:30	REG2	9:37	ACR3	147.53	189	189	132	53	79	16,465.84
LC2	HUB2	14:25	HUB1	16:01	ACR3	73.02	189	189	189	80	109	9,297.62
LC2	HUB2	17:10	REG2	18:17	ACR3	147.31	189	189	120	56	64	14,669.08
LC2	REG2	8:40	HUB2	9:47	ACR3	109.75	189	189	102	47	55	8,088.93
LC2	REG2	13:55	HUB2	15:02	ACR3	109.06	189	189	90	35	55	6,709.83
LC2	REG2	21:35	HUB2	22:42	ACR3	109.06	189	189	189	134	55	17,506.77
NW1	HUB1	5:00	HUB2	6:34	ACR2	66.98	100	100	100	27	73	2,421.84
NW1	HUB1	5:15	REG1	6:11	ACR2	51.68	100	100	100	48	52	2,519.82
NW1	HUB1	8:30	REG1	9:26	ACR2	279.00	100	23	100	100	0	25,251.82

Airline	Departure airport	Departure time	Arrival airport	Arrival time	Aircraft type	Ticket fare (€)	Offered tickets	Expected sold tickets	Sold tickets	Business passengers	Leisure passengers	Utility obtained by the airline (€)
NW1	HUB1	12:40	REG1	13:36	ACR2	51.68	100	100	100	72	28	2,519.82
NW1	HUB1	17:15	REG2	18:30	ACR2	135.47	100	46	100	100	0	10,152.18
NW1	HUB1	17:20	REG1	18:16	ACR2	269.00	100	23	100	100	0	24,251.82
NW1	HUB1	20:35	REG1	21:31	ACR2	51.68	100	100	100	76	24	2,519.82
NW1	HUB2	7:30	REG2	8:35	ACR2	175.72	100	100	76	30	46	10,395.22
NW1	HUB2	22:20	REG2	23:25	ACR2	175.72	100	100	76	30	46	10,395.22
NW1	REG1	5:00	HUB1	5:56	ACR2	50.16	100	98	100	72	28	2,239.72
NW1	REG1	8:35	HUB1	9:31	ACR2	279.00	100	22	100	100	0	25,123.72
NW1	REG1	12:35	HUB1	13:31	ACR2	50.16	100	98	100	76	24	2,239.72
NW1	REG1	16:05	HUB1	17:01	ACR2	50.16	100	98	100	100	0	2,239.72
NW1	REG1	22:20	HUB1	23:16	ACR2	50.16	100	98	100	48	52	2,239.72
NW1	REG2	7:45	HUB1	9:00	ACR2	155.76	100	49	26	8	18	446.38
NW1	REG2	13:30	HUB2	14:35	ACR2	126.90	100	100	82	37	45	7,392.07
NW1	REG2	21:50	HUB1	23:05	ACR2	155.76	100	49	100	82	18	11,972.62
NW2	HUB1	12:05	REG2	13:22	ACR1	137.63	171	46	42	24	18	1,459.68
NW2	HUB1	17:30	REG2	18:47	ACR1	135.39	171	48	171	161	10	18,830.91
NW2	HUB2	7:15	REG2	8:21	ACR1	133.33	171	171	112	35	77	11,183.08
NW2	HUB2	14:45	HUB1	16:21	ACR1	67.14	171	131	171	52	119	5,838.46
NW2	HUB2	15:25	REG2	16:31	ACR1	133.33	171	171	112	35	77	11,183.08
NW2	REG2	8:10	HUB1	9:27	ACR1	157.46	171	50	27	10	17	-404.96
NW2	REG2	12:40	HUB2	13:46	ACR1	96.66	171	155	132	49	83	8,910.68
NW2	REG2	17:25	HUB2	18:31	ACR1	98.90	171	152	111	49	62	7,129.46
NW2	REG2	21:50	HUB2	22:56	ACR1	96.66	171	155	171	107	64	12,680.42

Table 14. Schedule and sold tickets resulting from slot allocation using the current administrative mechanism

3.3.2 Results of the auction mechanism

Airline	Departure airport	Departure time	Arrival airport	Arrival time	Aircraft type	Ticket fare (€)	Offered tickets	Expected sold tickets	Sold tickets	Business passengers	Leisure passengers	Utility obtained by the airline (€)
LC1	HUB1	5:30	REG1	6:26	ACR1	45.98	171	135	171	52	119	4,932.11
LC1	HUB1	8:00	HUB2	9:36	ACR1	63.62	171	170	165	79	86	5,775.89
LC1	HUB1	13:30	REG2	14:47	ACR1	122.37	171	58	32	6	26	165.81
LC1	HUB1	14:45	HUB2	16:21	ACR1	62.83	171	171	135	48	87	3,788.26
LC1	HUB1	21:20	HUB2	22:56	ACR1	62.83	171	171	125	38	87	3,106.80
LC1	HUB1	22:20	REG2	23:37	ACR1	122.37	171	58	32	6	26	165.86
LC1	HUB2	8:20	HUB1	9:56	ACR1	75.24	171	166	171	90	81	7,883.62
LC1	HUB2	8:45	REG2	9:51	ACR1	148.77	171	171	91	46	45	10,277.45
LC1	HUB2	15:00	HUB1	16:36	ACR1	72.73	171	171	171	56	115	7,506.00
LC1	HUB2	17:00	REG2	18:06	ACR1	148.59	171	171	171	132	39	22,147.74
LC1	HUB2	22:05	HUB1	23:41	ACR1	72.73	171	171	171	30	141	7,433.05
LC1	HUB2	23:50	REG2	0:56	ACR1	148.35	171	171	78	32	46	8,205.07
LC1	REG1	9:50	HUB1	10:46	ACR1	45.41	171	133	171	171	0	4,613.76
LC1	REG2	5:00	HUB2	6:06	ACR1	109.80	171	171	76	30	46	4,956.55
LC1	REG2	5:15	HUB1	6:32	ACR1	128.82	171	61	45	23	22	1,711.32
LC1	REG2	12:20	HUB2	13:26	ACR1	109.80	171	171	77	30	47	5,094.62
LC1	REG2	17:30	HUB1	18:47	ACR1	131.29	171	60	36	15	21	628.98
LC1	REG2	19:50	HUB2	20:56	ACR1	109.80	171	171	77	30	47	5,089.19
LC2	HUB1	5:45	HUB2	7:21	ACR3	63.24	189	189	166	38	128	6,232.84
LC2	HUB1	12:35	HUB2	14:11	ACR3	63.24	189	189	189	189	0	7,686.79
LC2	HUB1	19:05	HUB2	20:41	ACR3	63.24	189	189	189	82	107	7,688.42
LC2	HUB2	8:00	REG2	9:07	ACR3	147.37	189	189	89	43	46	10,101.74

Airline	Departure airport	Departure time	Arrival airport	Arrival time	Aircraft type	Ticket fare (€)	Offered tickets	Expected sold tickets	Sold tickets	Business passengers	Leisure passengers	Utility obtained by the airline (€)
LC2	HUB2	9:15	HUB1	10:51	ACR3	73.02	189	189	189	167	22	9,297.62
LC2	HUB2	14:55	REG2	16:02	ACR3	146.95	189	189	75	29	46	8,013.13
LC2	HUB2	16:00	HUB1	17:36	ACR3	73.02	189	189	189	61	128	9,297.62
LC2	HUB2	21:35	REG2	22:42	ACR3	146.95	189	189	75	29	46	7,985.24
LC2	HUB2	22:35	HUB1	0:11	ACR3	73.02	189	189	189	33	156	9,265.63
LC2	REG2	5:30	HUB2	6:37	ACR3	109.06	189	189	78	30	48	5,401.11
LC2	REG2	12:55	HUB2	14:02	ACR3	109.06	189	189	78	30	48	5,400.31
LC2	REG2	20:35	HUB2	21:42	ACR3	109.06	189	189	119	71	48	9,872.57
NW1	HUB1	5:15	REG1	6:11	ACR2	51.68	100	100	100	51	49	2,473.32
NW1	HUB1	8:30	REG1	9:26	ACR2	279.00	100	23	100	100	0	25,121.82
NW1	HUB1	12:45	REG2	14:00	ACR2	140.36	100	44	27	6	21	394.63
NW1	HUB1	17:15	REG2	18:30	ACR2	135.47	100	46	100	77	23	10,036.50
NW1	HUB1	17:20	REG1	18:16	ACR2	269.00	100	23	100	100	0	24,237.27
NW1	HUB1	23:50	REG1	0:46	ACR2	51.68	100	100	100	7	93	2,351.90
NW1	HUB2	7:15	REG2	8:20	ACR2	175.72	100	100	55	22	33	6,573.36
NW1	HUB2	14:30	REG2	15:35	ACR2	175.72	100	100	100	54	46	14,611.82
NW1	HUB2	21:50	REG2	22:55	ACR2	175.72	100	100	55	22	33	6,650.69
NW1	REG1	5:00	HUB1	5:56	ACR2	50.16	100	98	100	51	49	2,016.46
NW1	REG1	8:35	HUB1	9:31	ACR2	279.00	100	22	43	43	0	8,943.51
NW1	REG1	12:05	HUB1	13:01	ACR2	50.16	100	98	100	51	49	2,239.72
NW1	REG1	22:20	HUB1	23:16	ACR2	50.16	100	98	100	51	49	2,198.55
NW1	REG2	6:30	HUB2	7:35	ACR2	126.90	100	100	69	30	39	5,738.48
NW1	REG2	13:20	HUB2	14:25	ACR2	126.90	100	100	67	28	39	5,488.04
NW1	REG2	14:45	HUB1	16:00	ACR2	155.76	100	49	68	26	42	6,988.30

Airline	Departure airport	Departure time	Arrival airport	Arrival time	Aircraft type	Ticket fare (€)	Offered tickets	Expected sold tickets	Sold tickets	Business passengers	Leisure passengers	Utility obtained by the airline (€)
NW1	REG2	20:20	HUB2	21:25	ACR2	126.90	100	100	67	28	39	5,488.57
NW1	REG2	21:20	HUB1	22:35	ACR2	155.76	100	49	100	93	7	11,972.62
NW2	HUB1	5:00	REG1	5:56	ACR1	50.88	171	108	171	66	105	5,305.86
NW2	HUB1	7:00	HUB2	8:36	ACR1	60.66	171	120	171	58	113	4,966.41
NW2	HUB1	11:55	REG1	12:51	ACR1	50.88	171	108	171	171	0	5,354.88
NW2	HUB1	13:50	REG2	15:07	ACR1	137.63	171	46	27	6	21	-604.77
NW2	HUB1	18:50	REG1	19:46	ACR1	50.88	171	108	171	99	72	5,347.19
NW2	HUB1	20:50	HUB2	22:26	ACR1	60.66	171	120	171	81	90	4,952.30
NW2	HUB1	22:05	REG1	23:01	ACR1	50.88	171	108	171	33	138	5,343.61
NW2	HUB2	7:00	REG2	8:06	ACR1	133.33	171	171	81	26	55	6,907.32
NW2	HUB2	10:50	HUB1	12:26	ACR1	67.14	171	131	171	58	113	5,838.07
NW2	HUB2	15:25	REG2	16:31	ACR1	133.33	171	171	114	41	73	11,449.71
NW2	HUB2	18:55	HUB1	20:31	ACR1	67.14	171	131	171	83	88	5,838.10
NW2	HUB2	23:35	REG2	0:41	ACR1	133.33	171	171	88	33	55	7,878.09
NW2	REG1	5:15	HUB1	6:11	ACR1	49.57	171	105	171	51	120	4,844.68
NW2	REG1	8:45	HUB1	9:41	ACR1	271.18	171	22	135	135	0	32,937.92
NW2	REG1	16:05	HUB1	17:01	ACR1	49.57	171	105	171	61	110	4,908.15
NW2	REG1	22:35	HUB1	23:31	ACR1	49.57	171	105	171	51	120	4,888.12
NW2	REG2	8:40	HUB2	9:46	ACR1	98.80	171	152	98	44	54	5,833.96
NW2	REG2	14:25	HUB2	15:31	ACR1	96.66	171	155	89	34	55	4,754.24
NW2	REG2	17:15	HUB1	18:32	ACR1	155.15	171	51	61	35	26	4,807.77
NW2	REG2	21:35	HUB2	22:41	ACR1	96.66	171	155	115	60	55	7,247.29

Table 15. Schedule and sold tickets resulting from slot allocation through primary auctioning

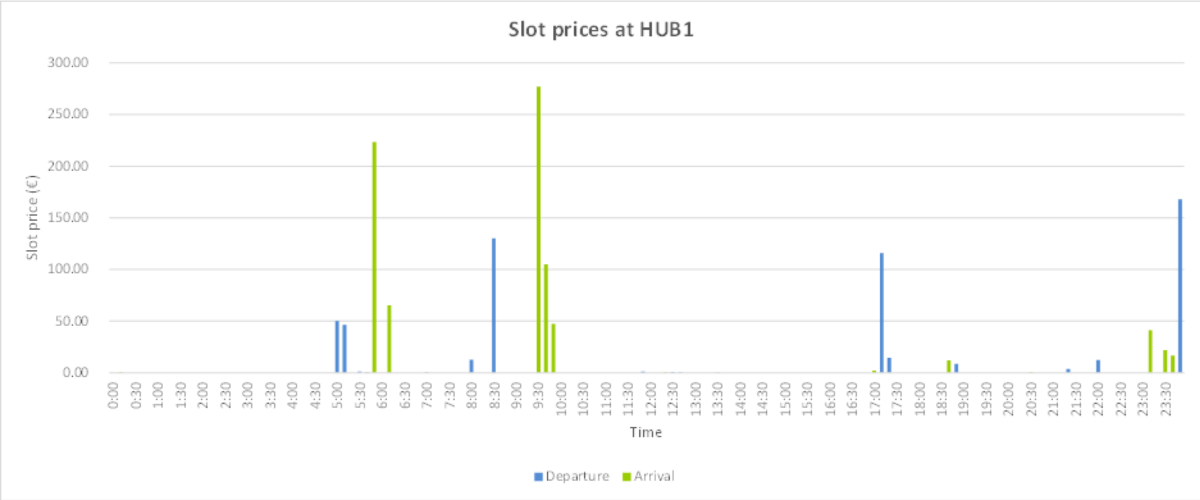

Figure 47. Final slot prices at HUB1

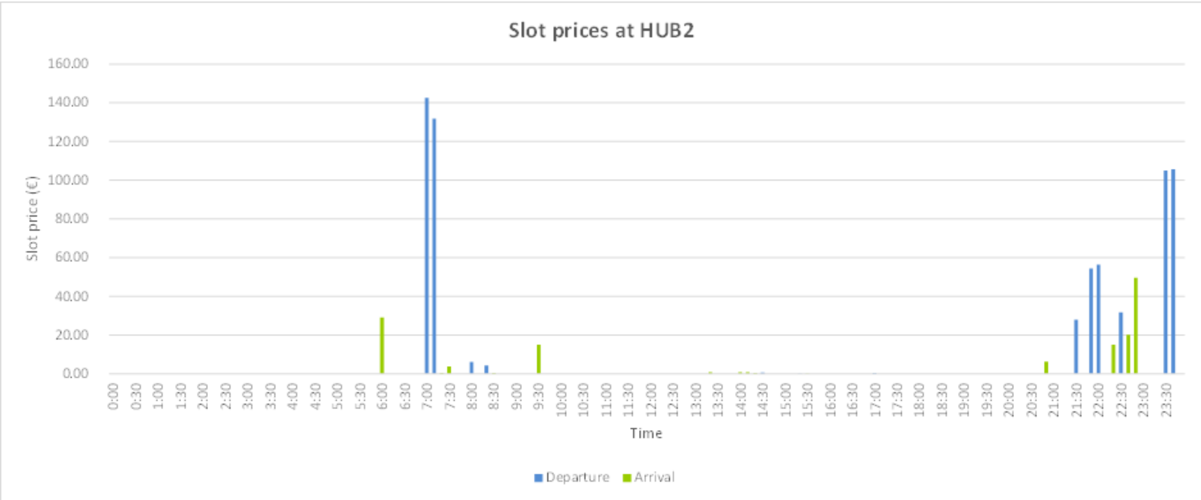

Figure 48. Final slot prices at HUB2

A first conclusion that can be extracted by looking at Table 14 and Table 15 is that the auction mechanism leads to a higher number of flights and a better utilisation of airport capacity, as it would be expected. In particular, there is a notable increase in the number of flights operated by NW2, LC1 and LC3; this is not the case for NW1, due to its position as incumbent carrier enjoying grandfather rights at the airport from/to which it operates most of its flights (HUB1). This result is also consistent with the fact that the current administrative mechanism usually needs a number of adjustments, such as slot transfers and exchanges, where users need to interact several times with coordinators to build and re-build their schedules, based on the accepted and rejected slot requests, before reaching a feasible schedule. The simulation shows that the auction would largely mitigate the need for such adjustments in the secondary market.

3.3.3 Comparative analysis

The following subsections compare the impact of the two slot allocation mechanisms under study on the different stakeholders (passengers, airlines, and airports), as well as on total social welfare.

3.3.3.1 Analysis of impact on passengers

Origin airport	Destination airport	Demand business	Demand leisure	Total demand	Business Passengers	Leisure Passengers	Total passengers	Utility business (€)	Utility leisure (€)	Total utility (€)	Average utility business (€)	Average utility leisure (€)	Average utility (€)
HUB1	HUB2	465	698	1163	304	217	521	2,775.96	706.43	3,482.39	9.14	3.26	6.68
HUB1	REG1	496	745	1241	396	104	500	1,201.88	197.04	1,398.92	3.04	1.90	2.80
HUB1	REG2	78	117	195	78	117	195	8,694.61	3,843.85	12,538.46	111.47	32.86	64.30
HUB2	HUB1	455	683	1138	288	266	554	3,490.52	879.17	4,369.69	12.12	3.31	7.89
HUB2	REG1	238	358	596	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
HUB2	REG2	375	563	938	375	563	938	4,736.41	2,362.05	7,098.46	12.64	4.20	7.57
REG1	HUB1	494	743	1237	334	104	438	1,042.24	206.16	1,248.40	3.13	1.99	2.85
REG1	HUB2	240	360	600	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
REG1	REG2	62	94	156	62	0	62	3,661.09	0.00	3,661.09	59.05	0.00	59.05
REG2	HUB1	78	118	196	78	118	196	8,053.54	2,762.99	10,816.53	103.26	23.42	55.19
REG2	HUB2	376	565	941	376	565	941	2,936.25	2,924.95	5,861.20	7.81	5.18	6.23
REG2	REG1	26	41	67	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00

Table 16. Passenger's surplus upon administrative slot allocation

Origin airport	Destination airport	Demand business	Demand leisure	Total demand	Business Passengers	Leisure Passengers	Total passengers	Utility business (€)	Utility leisure (€)	Total utility (€)	Average utility business (€)	Average utility leisure (€)	Average utility (€)
HUB1	HUB2	465	698	1163	465	698	1163	3,729.34	2,107.54	5836.88	8.03	3.02	5.02
HUB1	REG1	496	745	1241	442	345	787	2,311.98	560.34	2872.32	5.24	1.63	3.65
HUB1	REG2	78	117	195	78	117	195	4,316.87	3,641.15	7958.02	55.35	31.13	40.81
HUB2	HUB1	455	683	1138	455	613	1068	6,290.86	2,011.53	8302.39	13.83	3.29	7.77
HUB2	REG1	238	358	596	211	231	442	3,348.08	659.12	4007.2	15.87	2.86	9.07
HUB2	REG2	375	563	938	375	563	938	5,475.24	2,515.43	7990.67	14.61	4.47	8.52
REG1	HUB1	494	743	1237	494	497	991	1,830.78	938.34	2769.12	3.71	1.89	2.79
REG1	HUB2	240	360	600	171	0	171	2,866.42	0.00	2866.42	16.77	0.00	16.76
REG1	REG2	62	94	156	0	0	0	0.00	0.00	0	0.00	0.00	0.00
REG2	HUB1	78	118	196	78	118	196	10,095.91	3,278.48	13374.39	129.44	27.79	68.24
REG2	HUB2	376	565	941	376	565	941	2,888.50	2,742.84	5631.34	7.69	4.86	5.98
REG2	REG1	26	41	67	26	0	26	8,422.24	0.00	8422.24	323.94	0.00	323.93

Table 17. Passenger's surplus upon slot auctioning

Table 15 and Table 16 and Figure 49, Figure 50, Figure 51 and Figure 52 show the number of passengers and the passenger surplus for the different OD pairs, as well as at network level. Passenger surplus is calculated as the utility they get from travelling from their origin to their destination, minus the cost of time for the duration of the flight(s) and the price paid for the tickets. Overall, the auction increases the number of passengers that choose to fly and the total passenger surplus; however, the effect is not homogeneous, but instead affects different OD pairs in different manners, which suggests that the impact on connectivity of European regions and other externalities should be considered to carry out a comprehensive comparison of different slot allocation mechanisms, confirming the assumptions made in this respect in the performance framework defined in ACCESS Working Paper 3.

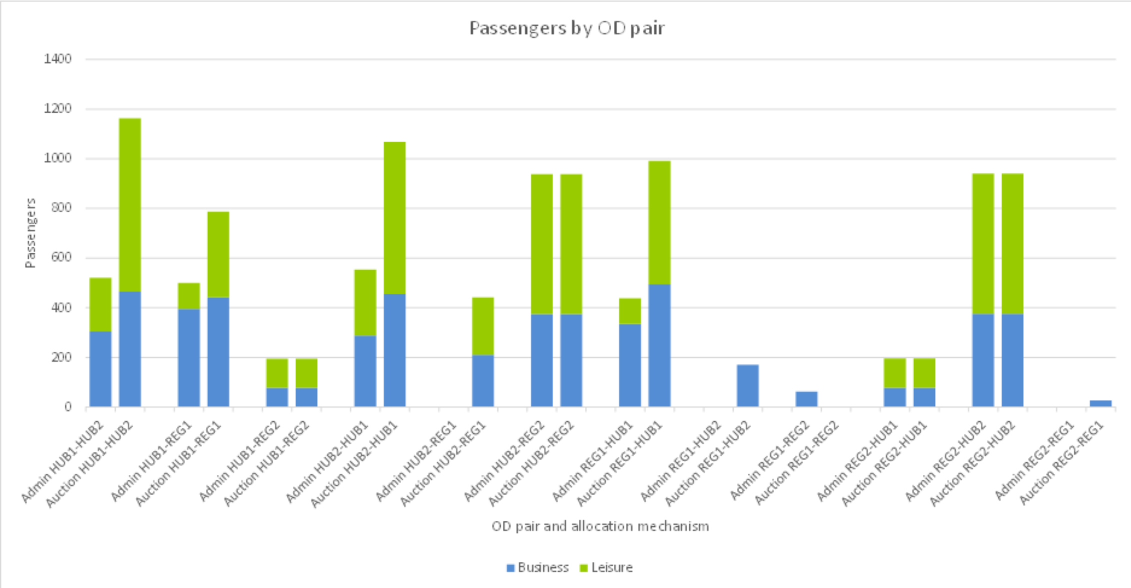

Figure 49. Number of passengers per OD pair and slot allocation mechanism

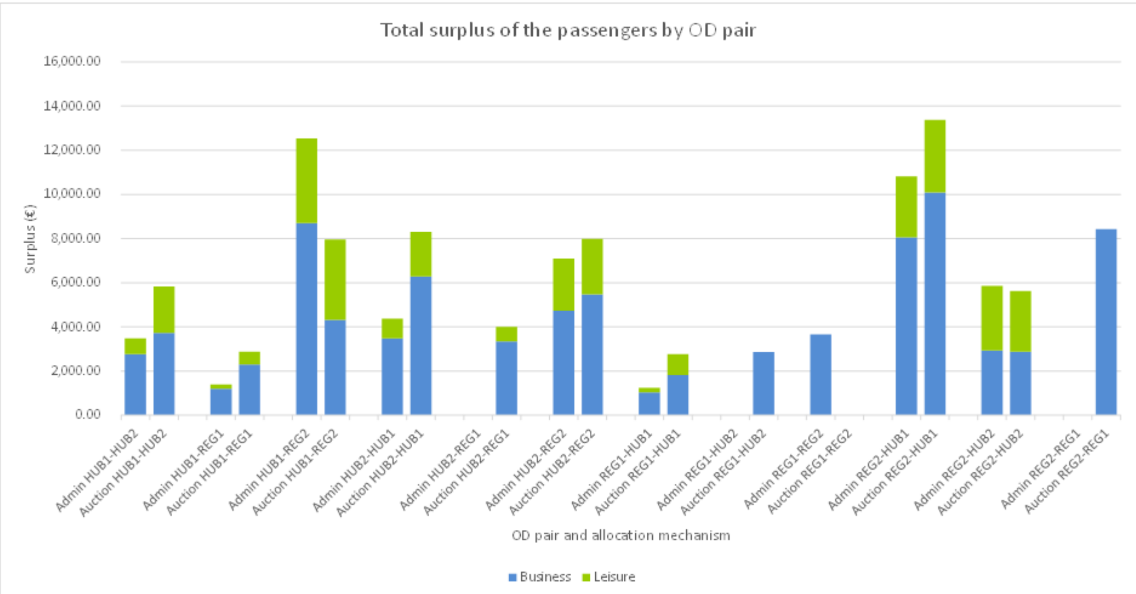

Figure 50. Total surplus of the passengers per OD pair and allocation mechanism

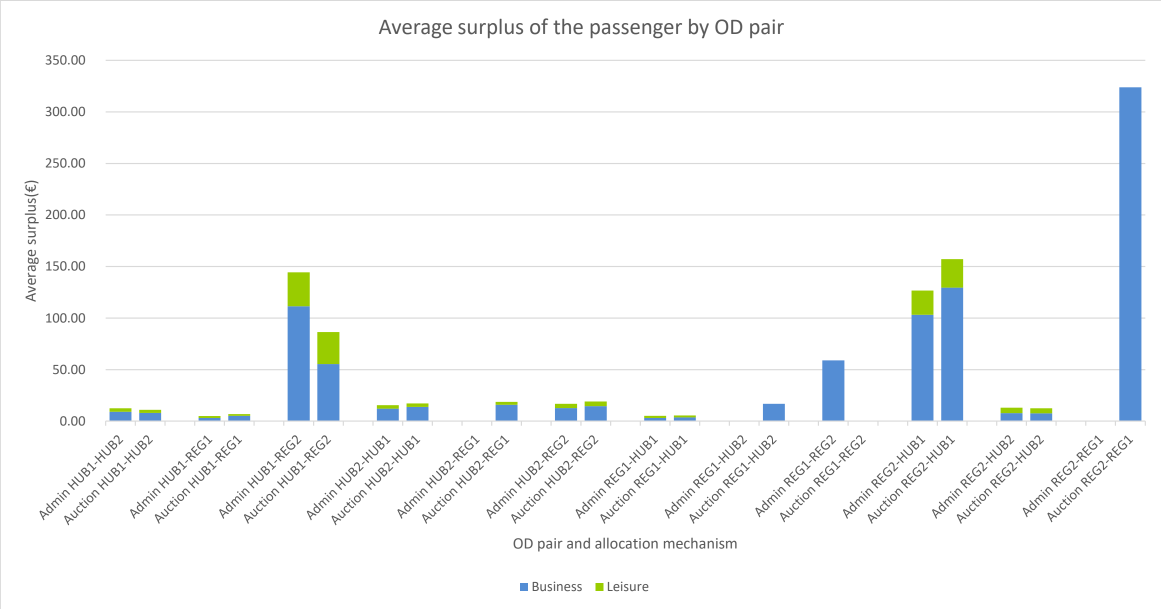

Figure 51. Average surplus of the passengers per OD pair and allocation mechanism

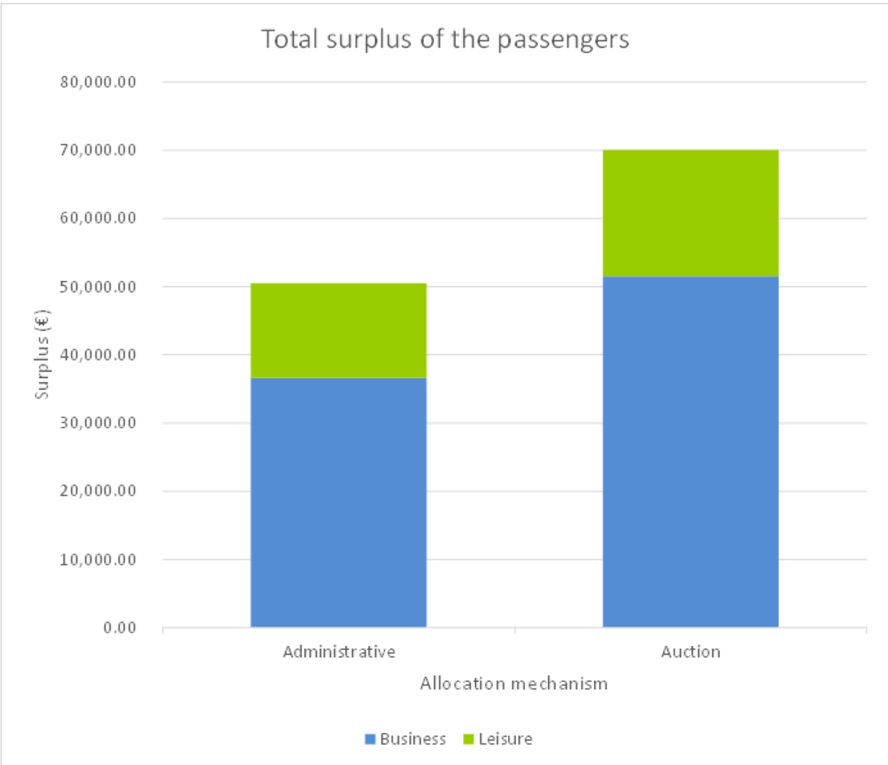

Figure 52. Total surplus of the passengers per allocation mechanism

3.3.3.2 Analysis of impact on airlines

Table 18 shows the number of passengers flying with each airline for each of the two slot allocation mechanisms under study. The auction increases the number of passengers captured by all the airlines except NW1, which was the one that had grandfather rights in the administrative mechanism.

Airlines	Administrative		Auction	
	Business passengers	Leisure passengers	Business passengers	Leisure passengers
LC1	604	654	914	1,081
LC2	477	438	802	823
NW1	1,106	454	840	611
NW2	522	527	1,226	1,463
Total	**2,709**	**2,073**	**3,782**	**3,978**

Table 18. Number and type of passengers captured by each airline for each slot allocation mechanism

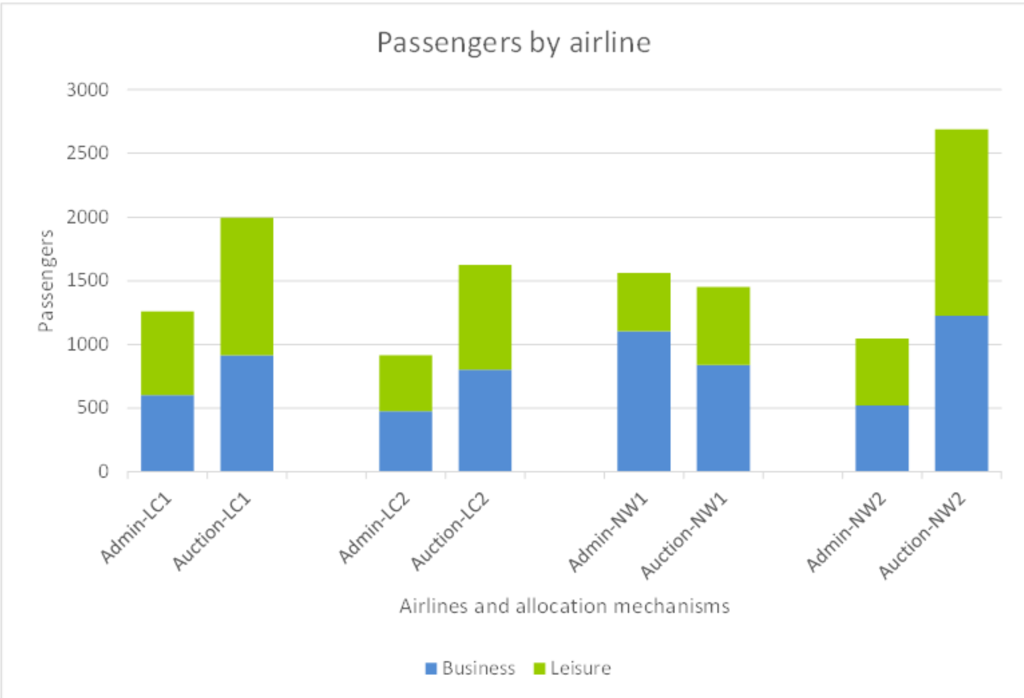

Figure 53. Passengers captured by each airline for each slot allocation mechanism

Table 19 and Table 20 show the income and the different operating costs of each airline under each mechanism. The cost breakdown under each mechanism is also represented in Figure 54. In all the cases, the cost of the slots constitutes a small portion of the total operating costs; it is worth noting, however, that this is due to the fact that in the scenario under study, only HUB1 and HUB2 are congested, and only for some time intervals along the day, which leads to a reduced number of slots with non-zero prices. In more congested scenarios, the cost of acquiring the slots would logically increase. Table 19 and Table 20 also show that, with the auction mechanism, the surplus of NW2, LC1 and LC2 increases, while the surplus of NW1 slightly decreases.

Airline	Slots cost (€)	Fuel cost (€)	Other direct cost (€)	Indirect cost (€)	Landing fees (€)	Total cost (€)	Income (€)	Surplus (€)
LC1	0.00	21,199.36	15,814.40	2,846.58	5,294.80	45,155.14	141,260.40	96,105.26
LC2	0.00	12,019.28	7,010.40	1,261.88	2,952.11	23,243.67	103,706.28	80,462.61
NW1	0.00	18,666.12	16,521.75	11,565.21	4,179.66	50,932.74	195,254.00	144,321.26
NW2	0.00	15,544.62	11,596.05	6,957.63	3,887.20	37,985.50	114,796.31	76,810.81
Total	**0.00**	**67,429.38**	**50,942.60**	**22,631.30**	**16,313.77**	**157,317.05**	**555,016.99**	**397,699.94**

Table 19. Airline income and cost breakdown for administrative slot allocation

Airline	Slots cost (€)	Fuel cost (€)	Other direct cost (€)	Indirect cost (€)	Landing fees (€)	Total cost (€)	Income (€)	Surplus (€)
LC1	360.56	32,934.72	24,568.80	4,422.36	8,559.25	70,845.69	174,327.77	103,482.08
LC2	69.44	23,139.48	13,496.40	2,429.34	5,577.15	44,711.81	140,954.83	96,243.02
NW1	1,207.81	19,778.44	17,506.28	12,254.36	4,074.81	54,821.70	198,347.30	143,525.60
NW2	550.92	32,698.12	24,392.30	14,635.38	9,786.20	82,062.92	220,861.82	138,798.90
Total	**2,188.73**	**108,550.76**	**79,963.78**	**33,741.44**	**27,997.41**	**252,442.12**	**734,491.72**	**482,049.60**

Table 20. Airline income and cost breakdown for slot auctioning

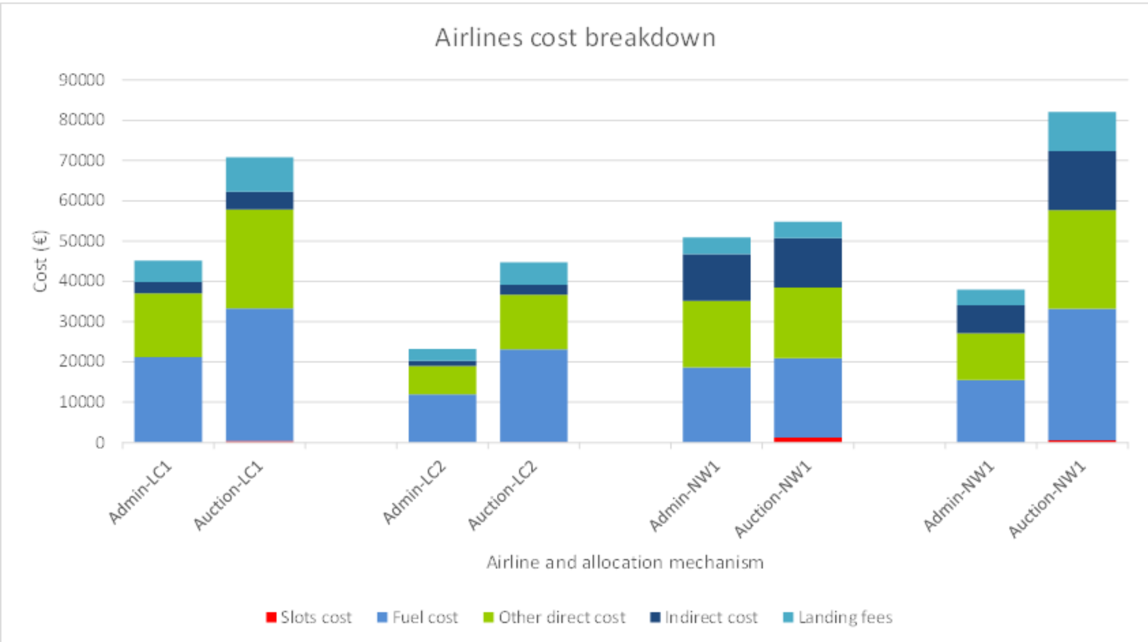

Figure 54. Airline cost breakdown for each slot allocation mechanism

Figure 55 shows the surplus obtained by each airline for each OD pair upon administrative slot allocation and slot auctioning. Figure 56 presents the aggregated surplus for each airline under each of the two mechanisms under study.

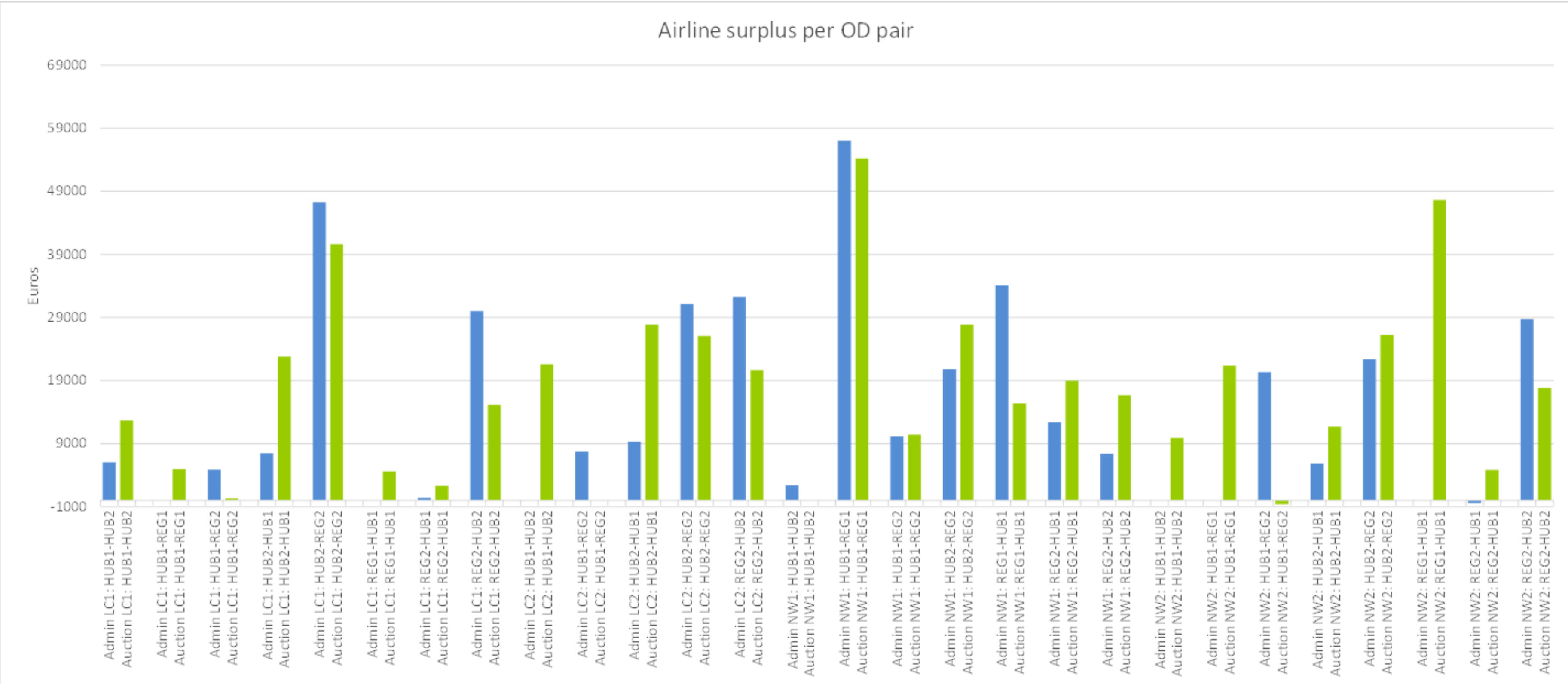

Figure 55. Surplus (profit) obtained by each airline for each OD pair

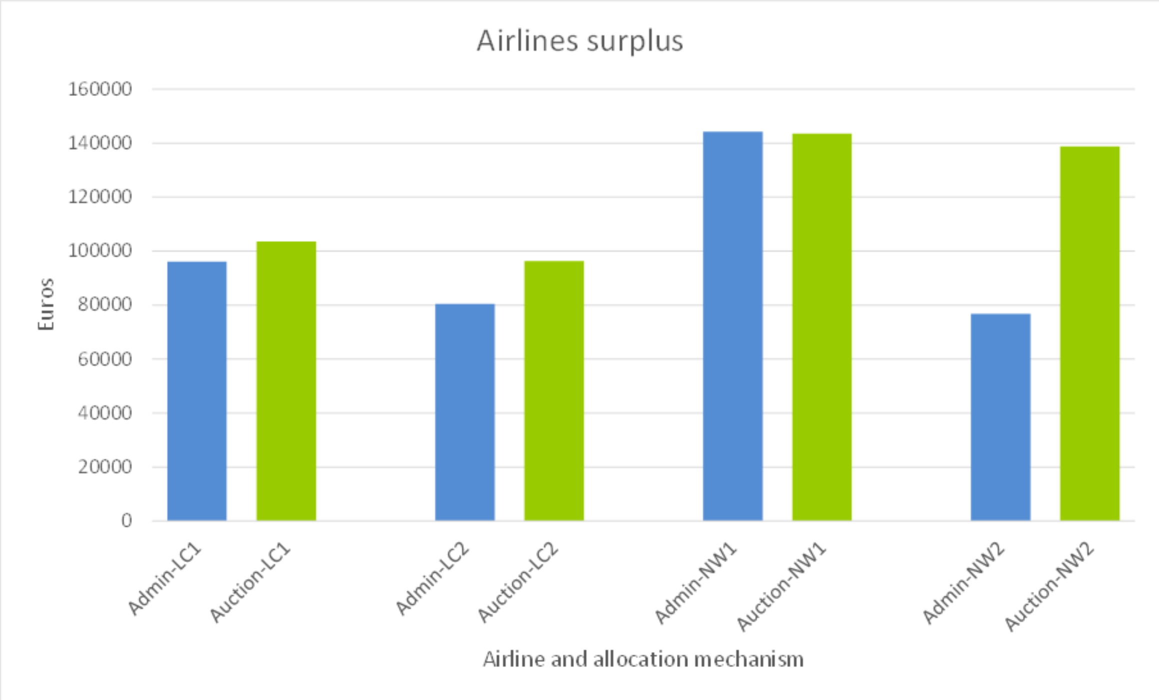

Figure 56. Total surplus (profit) obtained by each airline

3.3.3.3 Analysis of impact on airports

Table 21 shows the surplus obtained by each airport under each slot allocation mechanism. The auction increases the surplus of the four airports included in the scenario, thanks to a more efficient utilisation of airport capacity.

Though this effect is qualitatively relevant, its quantification shall be taken with precaution, since in the current version of the ACCESS simulation platform, airport surplus is simply calculated at the landing fees plus the prices paid for the slots, without taking into account neither the impact of the traffic increase on the airport costs nor the increase of non-aeronautical revenues. An estimation of these effects would have to be incorporated into the ACCESS model for a rigorous and comprehensive evaluation of the impact on airport surplus.

Airport	Surplus upon administrative slot allocation (€)	Surplus upon slot auctioning (€)
HUB1	6,338.44	13,996.50
HUB2	4,617.58	8,591.76
REG1	1,052.00	3,032.25
REG2	4,305.75	4,565.63

Table 21. Airport surplus

3.3.3.4 Analysis of social welfare

Figure 57 and Figure 58 show the distribution of surplus among airlines, airports and passengers. Here again, the ratios between these quantities shall be taken with caution, due to the fact that in the current implementation of the ACCESS simulation platform, some factors included in airport surplus are not implemented yet, namely airport costs and airport non-aeronautical revenues.

Despite this limitation, the figures are useful to show that the extra surplus generate by the auction is distributed in a rather homogeneous manner among stakeholders, although the increase in surplus is relatively bigger for passengers and airports than for airlines. However, it is not possible to generalise this result to other scenarios. In particular, further simulations would be required to investigate whether this ratio remains stable for higher levels of congestion.

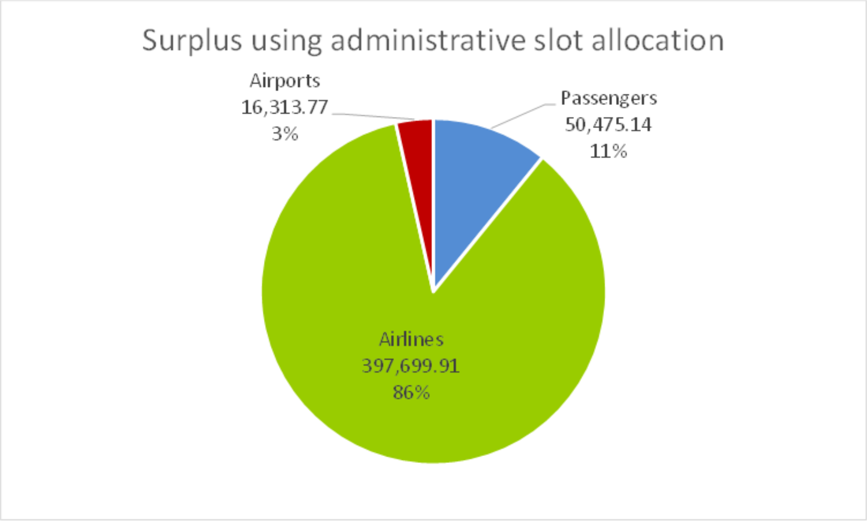

Figure 57. Distribution of surplus among stakeholders upon administrative slot allocation

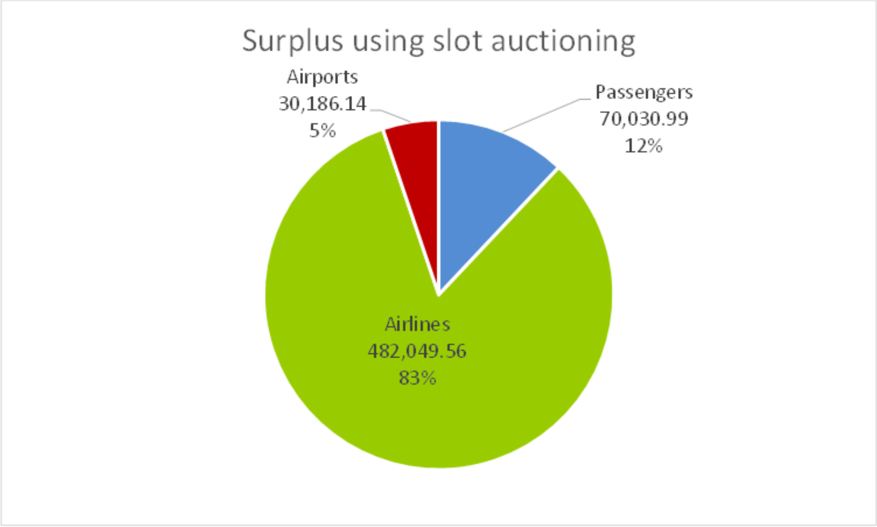

Figure 58. Distribution of surplus among stakeholders upon slot auctioning

4. Conclusions

The ACCESS Simulation Platform implements an agent-based model that allows the analysis of the effects of different airport slot allocation mechanisms. The model simulates the behaviour of a set of airlines competing over a congested airport network, allowing the prediction of the resulting schedule and the surplus obtained by the different stakeholders. 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 proposed auctioning mechanism allows the balancing of capacity and demand in a decentralised manner, without the need for airlines to disclose sensitive information. Different types of airlines are impacted 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 auctioning process.

The simulation of the auction in a scenario with two airports and two airlines shows that the auction yields a feasible schedule that respects all the capacity constraints, and has allowed us to study how different values of the parameters affect the outcome of the auction. Then we use the ACCESS Simulation Platform to explore a more complex scenario with four airports and four airlines, analysing the influence of the auction parameters and observing the impact on the different airlines.

Finally, we have performed several simulation experiments to compare the auction-based slot allocation and the current administrative slot allocation mechanism based on grandfather rights. The simulation shows that the auction yields a more efficient use of airport capacity, increasing the number of flights, the number of passengers, and the total social welfare. However, the extra surplus is not homogeneously distributed among all stakeholders: while some airlines improve their profits, the profit of the airline that enjoyed grandfather rights in the baseline scenario is reduced. This can be interpreted as the combination of two effects: first, with the auction the incumbent airline loses the grandfather rights and therefore its privileged access to its preferred slots; additionally, the fact that the auction leads to a more efficient allocation of capacity helps the other airlines get better slots, thus rendering them more competitive and allowing them to capture part of the market share originally belonging to the incumbent airline in the administrative allocation scenario.

The simulation experiments show the potential of the ACCESS simulation model to conduct a comprehensive analysis of different slot allocation mechanisms, and reinforce the ACCESS assumption about the importance of distributional effects, opening interesting lines of future research:

- Different model extensions can be used to enhance the realism of the model and the variety of issues that can be explored, in particular a more realistic airport model including airport costs and non-aeronautical revenues, as well as a more complex airline behavioural model. For example, airline agents could be endowed with learning capabilities, so that they are able to improve their estimation of future profits from the observed behaviour of their competitors in previous seasons. Behaviours other than utility maximisation could also be explored, e.g., anticompetitive practices.
- Additional experiments would allow the optimisation of the design of the auctions as well as to explore how the presence of more airports and airlines affects the results and the convergence time. In the light of the results presented in the current document, particularly interesting would be the design of adaptive price update mechanisms able to minimise convergence time for different levels of congestion.
- It would also be interesting to compare the outcome of slot auctioning with the slot allocation obtained by solving the equivalent optimisation problem, in order to evaluate the ability of auctions to yield an optimal (or nearly optimal) solution according to different optimisation criteria (e.g., maximisation of social welfare).

- The execution of simulations testing different combinations of primary and secondary slot allocation mechanisms along several seasons would allow the exploration of medium-term and long-term effects of different slot allocation mechanisms, as well as their ability to adapt to abrupt changes in demand or in other exogenous variables.
- Finally, the construction of more complex and realistic model calibrated with real data would be very useful to inform decision making in the real world.

In summary, the simulation framework and the computational experiments developed by ACCESS open the door to a more comprehensive understanding of the benefits and risks of market mechanisms, as a as a necessary step for informing future policy developments.

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