Working Paper 3

Market-Based Mechanisms for Airport Slot Allocation: Formalisation and Assessment Criteria

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Executive summary

Airlines that intend to fly scheduled operations to/from coordinated airports need to obtain airport slots for these operations. Airport coordinators allocate the slots in a two-stage process. The first stage is called primary slot allocation. The second stage, called secondary allocation, involves the exchange and transfer of slots among airlines trying to obtain more suitable slots, always subject to the approval of the coordinator.

Currently, the primary allocation of slots in European airports is an administrative process governed by the European Union Regulation 95/93 and its respective amendments, largely based on the global principles defined by the IATA Worldwide Slot Guidelines. Slots are allocated according to two fundamental criteria: historical precedence (the so-called grandfather rights) and time adjustments of historical slots. Airlines can earn historic rights to a series of slots provided they operate the slots as allocated by the coordinator at least 80% of the time during a season (use-it-or-lose-it rule, also called 80-20 rule). Time adjustments are made after historical precedence has been taken into account (for operational reasons or for improvement of the slot timing of the applicant air carrier) and before the allocation of the remaining slots from the pool. After this first slot assignment to incumbent airlines and the slot reservation for Public Service Obligations, a slot pool is created with the remaining slots, fifty percent of these being allocated free of charge to new entrant airlines.

Different mathematical optimisation approaches have been proposed to improve the current administrative system. The objective of these approaches is to optimise the distribution of slots to better accommodate airlines’ preferences. The objective function seeks to minimise the difference between the requested slot time and the slot time allocated to airlines (the so-called scheduled delays). As an alternative to the current system, many researchers are advocating the use of auctions as a more efficient means to allocate slots. Airport slot allocation is a combinatorial allocation problem (CAP) that can be solved by means of auctions. Another market approach for primary slot allocation is congestion pricing, which consists in surcharging airspace users for the use of scarce capacity to regulate demand, by establishing different prices along the day based on marginal congestion costs. Unlike auctions, which automatically reveal information about relevant parameters as well as acting as allocation mechanisms, congestion charges need to be set by an external body that needs to calculate their appropriate level by estimating demand elasticity and marginal congestion costs.

Secondary slot allocation can also take different forms: slot exchanges and transfers without monetary compensation, slot exchange with monetary compensation, and slot buy-sell. As the applicable European regulation is unclear on slot trading, the European Commission issued a communication in 2008 stating that it does not intend to “pursue infringement proceedings against Member States where such exchanges take place in a transparent manner”. Secondary trading can take the form of bilateral trading or occur in a single, organised market. Here again, mathematical programming approaches and auctions can be used to implement such market, though the problem to be solved is slightly different due to the fact that the agents can be both buyers and sellers at the same time.

The following table summarises the different approaches proposed for the allocation of airport capacity, which can be classified in two main categories: administrative slot allocation and market-based mechanisms:

<table>
<thead>
<tr>
<th>Method</th>
<th>Primary Allocation</th>
<th>Secondary Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Administrative</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current system</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Mathematical optimisation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td><strong>Market-based</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exchanges</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Trades</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auctions</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Congestion pricing</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

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The stakeholders involved in airport slot allocation can be classified into five groups: regulators, airport coordinators, airspace users, airport operators, and end users (passengers). Each of these stakeholders plays a role in the system and has its own interests and strategies, which need to be taken into account for the design of the slot allocation system. We discuss this role and analyse the factors influencing stakeholders’ objectives and behaviour, with particular focus on airports and airlines. Airports’ objectives and attitude towards slot allocation may vary depending on the airport business model (single till vs dual till), the airport ownership (privately owned vs publicly owned), or the airport management unit (e.g. for companies managing more than one airport at a time, the company strategy will be to maximise the benefits from a global unit formed by all airports within the system). The interests and strategies of airspace users are strongly dependent on factors such as the airlines route structure, scheduling strategies, airport network or pricing policies, which are in turn conditioned by the airline business model (network carriers, low cost carriers, charter operators). The attitude of individual airlines may also be influenced by airline alliances, whose strategy often prevails over individual interests; airlines’ attitude modification due to alliances may sometimes be subject to anti-trust considerations. Finally, there are not only horizontal alliances between airlines (airline alliances) or airports (being part of the same management unit), but also vertical alliances involving an airline and an airport. This is mainly the case of hub airports, where a major airline commits to exploit the airport infrastructure as much as possible and the airport provides the airline with special dedicated services. Collaboration goes from joint airline-airport marketing to investments in new airport infrastructure. This type of alliances cannot really help airlines in terms of slot allocation, due to the current administrative mechanism, but is rather a consequence of an airline’s dominance at an airport due to grandfather rights. However, airline-airport alliances may be of much importance when applying other mechanisms for slot allocation as their behaviour may vary due to a joint strategy.

The ACCESS project will model, simulate and compare different slot allocation mechanisms: we will first model the current administrative approach to primary slot allocation, and will investigate how it can be improved through a mathematical optimisation approach. This approach will be compared to a market approach based on auctions. As for secondary allocation, we will consider a single market for slot trading, formulated as a centralised combinatorial exchange and modelled as a mixed integer linear programming problem. This formulation allows the exact identification of the optimal solution, but may become unpractical to solve when the size of the instances grows significantly. For this reason, the ACCESS project also proposes a decentralised agent-based approach that allows tackling large sets of data, as the single market approach over the whole Europe would likely require. All models for primary and secondary slot allocation consider a multi-airport (or simultaneous) allocation, the single-airport allocation model being a particular case of the multi-airport allocation. The present document formalises the above mechanisms, describing the flow of information among stakeholders, the decision points, the solution of the slot allocation problem, or how to start up, configure and operate the system, among other aspects.

Finally, we introduce some considerations about the conditions to be met by a performance framework to allow a sound comparative evaluation of different slot allocation mechanisms, and we propose a set of performance areas and indicators. Administrative slot allocation has its drawbacks and advantages: the process is simple and predictable, and is implemented throughout the world in one form or the other; on the other hand, different studies conclude that administrative slot controls lead to inefficiencies and, despite the provisions for new entrants, often prevent competition by creating barriers to entry. Market mechanisms are expected to provide the right incentives for a more efficient use of the available capacity, but they also raise a number of concerns, from the potentially negative impact on airline operating costs to market failures. There is therefore a need for a comprehensive assessment of different market designs. We propose a comprehensive performance framework encompassing six performance areas: economic efficiency; equity and distributional aspects; access and competition; flexibility, resilience and adaptability; interoperability; capacity and delay.
1. Introduction

1.1 Scope and objectives

The general purpose of this document is to define the slot allocation mechanisms that will be evaluated within the ACCESS project and the performance framework that will be used to assess and compare the proposed mechanisms. The document will be used as a basis for the specification of the ACCESS simulation model.

The document is expected to meet a number of lower level objectives:

1. present a detailed classification of slot allocation mechanisms;
2. discuss the applicability of different mechanisms for primary and/or secondary slot allocation;
3. formalise the slot allocation mechanisms that will be developed and tested within the ACCESS project. The aspects to be defined include the flow of information between stakeholders, the solution of the slot allocation problem, or how to start up, configure and operate the system, among others;
4. analyse the stakeholders involved in slot allocation and the factors that may vary their attitude and objectives;
5. define the criteria according to which the proposed market-based approaches shall be evaluated, including a set of performance areas and performance indicators.

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 presents a classification of slot allocation mechanisms.
- Section 3 describes the different stakeholders involved in slot allocation, their role in the system, and their interests and strategies.
- Section 4 formalises the slot allocation mechanisms that will be studied within the ACCESS project, including the flow of information among stakeholders, the decision points, the solution of the slot allocation problem, and how to start up, configure and operate the system, among other aspects.
- Section 5 proposes a performance framework for the comparative evaluation of different slot allocation mechanisms. The proposed framework encompasses six performance areas: economic efficiency; equity and distributional aspects; access and competition; flexibility, resilience and adaptability; interoperability; capacity and delay.
- Section 6 includes a synthesis of the main findings and the conclusions.
1.3 Glossary of terms

1.3.1 Concepts and definitions related to slot allocation

<table>
<thead>
<tr>
<th>Concept or term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot</td>
<td>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.</td>
</tr>
<tr>
<td>Primary Slot Allocation (or Primary Slot Assignment)</td>
<td>The first stage of slot allocation process is the primary allocation, during which most of the slots for the scheduled operations are allocated, usually based on the IATA's World Slot Guidance.</td>
</tr>
<tr>
<td>Secondary Slot Allocation (or Secondary Slot Assignment)</td>
<td>This is the second stage of 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).</td>
</tr>
<tr>
<td>Slot Allocation Mechanism (or Slot Assignment Mechanism)</td>
<td>Mechanism or scheme used to allocate slots.</td>
</tr>
<tr>
<td>Stakeholder</td>
<td>Actor in slot allocation process.</td>
</tr>
</tbody>
</table>

Table 1. Glossary of terms

1.3.2 Concepts and definitions related to mechanisms for slot allocation

<table>
<thead>
<tr>
<th>Concept or term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Administrative Assignment</td>
<td>Administrative assignment is the current slot allocation process based on the EU regulation and IATA slot guidelines. We refer to it as administrative assignment as the process is basically administrative, not including market or other types of mechanisms.</td>
</tr>
<tr>
<td>Auction</td>
<td>Models of markets in which products, services or rights are bought and sold through a formal bidding process.</td>
</tr>
<tr>
<td>Combinatorial auction</td>
<td>A type of smart market in which participants can place bids on combinations of discrete items, or “packages”, rather than individual items or continuous quantities.</td>
</tr>
<tr>
<td>Congestion Pricing</td>
<td>Congestion pricing consists of surcharging users for the use of scarce capacity to regulate demand, by establishing different prices along the day based on marginal congestion costs.</td>
</tr>
<tr>
<td>Grandfather Rights</td>
<td>Grandfather right is a historical precedence for a series of slots an airline earns if it operates the said series of slots at least 80% of the time in a previous equivalent season.</td>
</tr>
<tr>
<td>Market</td>
<td>Systems, institutions, procedures, social relations and infrastructures where parties engage in exchange.</td>
</tr>
</tbody>
</table>
Market equilibrium
It refers to 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. This price is often called the competitive price or market clearing price and will tend not to change unless demand or supply change.

Non-monetary Exchanges
Slot exchanges between airlines where no money is involved.

Optimisation
Mathematically formulated problem whose solution is used to select a best option from a set of available alternatives.

Price-setting auctions
Combinatorial iterative auction where the auctioneer sets and modifies the prices of the items as a function of demand and supply.

Stakeholder
Actor in the slot allocation process.

Trading
Exchange of slots with monetary compensation, or simple buy and sell of slots (where this is allowed).

Table 2. Glossary of terms

1.3.3 Concepts and definitions related to performance assessment

<table>
<thead>
<tr>
<th>Concept or term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance Framework</td>
<td>Set of performance areas and indicators that guide the evaluation of a particular slot allocation mechanism.</td>
</tr>
<tr>
<td>Performance Area</td>
<td>Broad focus area encompassing one or several goals or objectives.</td>
</tr>
<tr>
<td>Performance Indicators</td>
<td>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. Indicators can be classified according to different criteria: Outcome indicators measure progress towards policy objectives (i.e. the variables one wants to optimise in the system). Intermediate indicators (also called process indicators, or surrogate indicators) 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. Quantitative indicators use numbers and express amounts or quantities. Qualitative indicators use words, symbols or colours to express attitudes and views. Local indicators are measured at airport level. Global indicators are measured at network level. System-wide (or social) indicators are measured at societal level. Stakeholder-specific indicators are linked to a specific stakeholder or group of stakeholders.</td>
</tr>
</tbody>
</table>

Table 3. Glossary of terms
1.3.4 Concepts and definitions related to models and tools

<table>
<thead>
<tr>
<th>Concept or term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>A model is defined a simplified description of a complex entity or process, often in mathematical terms, that helps us in conceptualising and analysing the problem.</td>
</tr>
<tr>
<td>Scenario</td>
<td>A scenario is to be understood as a particular instance of the scenario space. The scenario space is composed by all possible combinations of those parameters that are relevant to, but exogenous to the model. 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 and we exclude them from the model. Everything outside the model boundary is, therefore, exogenous. These components, which are relevant but unaffected by the model, are taken into account as exogenous parameters. They can be static, be varied individually, or be varied together.</td>
</tr>
</tbody>
</table>

Table 4. Glossary of terms

1.4 Acronyms and abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AENA</td>
<td>Aeropuertos Españoles y Navegación Aérea</td>
</tr>
<tr>
<td>ACCESS</td>
<td>Application of Agent-Based Computational Economics to Strategic Slot Allocation</td>
</tr>
<tr>
<td>ACI</td>
<td>Airports Council International</td>
</tr>
<tr>
<td>ACL</td>
<td>Airport Coordination Limited</td>
</tr>
<tr>
<td>AEA</td>
<td>Association of European Airlines</td>
</tr>
<tr>
<td>AER</td>
<td>Assembly of European Regions</td>
</tr>
<tr>
<td>ALG</td>
<td>Advanced Logistic Group</td>
</tr>
<tr>
<td>AOP</td>
<td>Airport Operations Plan</td>
</tr>
<tr>
<td>ATC</td>
<td>Air Traffic Control</td>
</tr>
<tr>
<td>ATM</td>
<td>Air Traffic Management</td>
</tr>
<tr>
<td>BA</td>
<td>British Airways</td>
</tr>
<tr>
<td>BAA</td>
<td>British Airports Authority</td>
</tr>
<tr>
<td>CAP</td>
<td>Combinatorial Allocation Problem</td>
</tr>
<tr>
<td>CBA</td>
<td>Cost-Benefit Analysis</td>
</tr>
<tr>
<td>E-ATMS</td>
<td>European Air Traffic Management System</td>
</tr>
<tr>
<td>EBAA</td>
<td>European Business Aviation Association</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>EEC</td>
<td>European Economic Community</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Association</td>
</tr>
<tr>
<td>IATA</td>
<td>International Air Transport Association</td>
</tr>
<tr>
<td>KLM</td>
<td>Royal Dutch Airlines</td>
</tr>
<tr>
<td>KPA</td>
<td>Key Performance Area</td>
</tr>
</tbody>
</table>
### Table 5. Acronyms and abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCC</td>
<td>Low Cost Carriers</td>
</tr>
<tr>
<td>MILP</td>
<td>Mixed Integer Linear Programming</td>
</tr>
<tr>
<td>NMOC</td>
<td>Network Manager Operations Center</td>
</tr>
<tr>
<td>NOP</td>
<td>Network Operations Plan</td>
</tr>
<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
</tr>
<tr>
<td>PSO</td>
<td>Public Service Obligation</td>
</tr>
<tr>
<td>SC</td>
<td>Slot Conference</td>
</tr>
<tr>
<td>SESAR</td>
<td>Single European Sky ATM Research Programme</td>
</tr>
<tr>
<td>SJU</td>
<td>SESAR Joint Undertaking (Agency of the European Commission)</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>USA</td>
<td>United States of America</td>
</tr>
<tr>
<td>VFR</td>
<td>Visual Flight Rules</td>
</tr>
<tr>
<td>WSG</td>
<td>Worldwide Slot Guidelines</td>
</tr>
</tbody>
</table>
2. Overview and classification of slot allocation mechanisms

Capacity at congested airports can be allocated to airlines by means of two widely studied approaches: administrative slot allocation and market-based mechanisms. Current practice is to use administrative slot allocations, which are based on IATA’s worldwide slot guidelines [1]. On the other hand, “market-based mechanisms like slot auctions and congestion pricing, which have a stronger justification in economic theory have thus far failed to gain significant traction in practice” [2].

Administrative slot allocation has its drawbacks and advantages [2]. The main drawback are the administrative rules themselves, as they often prevent the competition by creating barriers to entry, despite the provisions for new entrants, which usually provide just a very fragmented access to the market. The main advantages are that the administrative rules are simple, the process is predictable and is implemented throughout the world in one form or the other, and because of these reasons has almost unwavering support from the airlines. This process is described in detail in ACCESS Working Paper 1 [3].

The advantages and the support of the administrative rule from the airlines made them a fertile ground for the research topics that consider the inclusion of congestion mitigation mechanisms directly into the administrative rules. However, this presents some, often not easy to solve difficulties. To begin with, “the administrator must place a value, either explicitly or implicitly, on key criteria like equity, competition, and airline profitability” [2]. In order to be able to do so, there are basically two challenges to address [2]:

a) “to develop a better understanding of the economic value of each slot based on the foregoing criteria,

b) to estimate airline response to different allocation schemes in order to better balance these criteria.”

Market-based mechanisms should in principle overcome some of the drawbacks of the administrative allocation process. Economic theory indicates that the willingness-to-pay by a user reflects the welfare enjoyed by that user, which in turn is a reflection of the social welfare. Auctions and congestion pricing are the methods that are widely proposed to achieve this goal. The values users attach to the resource are directly uncovered during the auctions. This is one of the reasons for the encouragement of the introduction of auctions. According to Ball et al., [4] the advantage of auctions is that they provide stability of long-term leases and render the congestion levels predictable. The idea behind congestion pricing is surcharging airspace users for the use of scarce capacity to regulate demand, by establishing different prices along the day (e.g. peak / off-peak charges). The main barrier for the implementation of congestion pricing is the need for an external estimation of demand elasticity and marginal congestion costs, and this is probably the main reason why, despite being conceptually well developed in the economics literature, and in theory providing greater flexibility for quick schedule changes [4], congestion pricing has found limited practical application. Nonetheless, market-based mechanisms pose many implementation problems compared to the status quo that in turn increases the number of opponents to these methods. Furthermore, congestion pricing and auctions would generate revenue, and there is still no agreement on how these revenues should be used (by whom and for what).

Market-based mechanisms have been formulated and modelled by means of different approaches, such as:

• queuing models for congestion pricing [5];
• equilibrium models for non-atomistic airport users [6];
• multi-airport modelling of market mechanisms [7];
• optimal design of slot auctions [8].

Comparison of auction-based and pricing-based mechanisms can be found in [9].
Non-monetary mechanisms and flight-prioritisation schemes have also been investigated by researchers and it seems that some of these mechanisms, if designed correctly, could overcome opposition. This is another avenue to explore.

To sum up, “research aimed at understanding and modelling desirable changes in airline operations and pricing as a result of market mechanisms will facilitate both airlines’ meaningful participation in such mechanisms and regulators’ ability to predict the true impact of their implementation” [2].

2.1 Primary vs secondary allocation

All the airlines that intend to fly scheduled operations to and/or from coordinated airports need to obtain airport slots for these operations. Airport coordinators allocate the slots for scheduled operations in a two-stage process. The first stage is the primary allocation, during which most of the slots for the scheduled operations are allocated, usually based on the IATA’s World Slot Guidance (more details on the process can be found in section 0). So far, all over the world, this is an administrative process that deals with the allocation of slots, slot returns and slot adjustments.

The second stage of the process can be called secondary allocation. In this second stage, the airlines exchange slots trying to obtain more suitable slots, always subject to the approval of the coordinator. This process is currently done in four different modalities: slot exchange without monetary compensation, slot transfers (one airline transfers the slots to another; just a transfer, not an exchange), slot exchange with monetary compensation, and slot buy-sell (where this is allowed). This second stage is of importance for the scheduled operations as this permits the airlines to consolidate their schedules and to keep the obtained slots, based on the use-it-or-lose-it rules. Figure 1 below depicts the current slot coordination process, the actors and the actions performed by each actor. The red blocks represent the different steps of the primary allocation phase, whereas the blue blocks define the secondary allocation.

Figure 1. Current slot coordination process, primary (red) and secondary phase (blue)
It is very rare that all the slots in all the hours of the day are assigned. The ad-hoc flight operations, business and general aviation operations and some cargo flights ask for a slot assignment on ad-hoc bases, from the pool of available slots. These slots cannot be used to obtain grandfather rights on the slot.

Table 6 maps the administrative and market-based mechanisms with different methods that are either in use, or are being proposed. Each method is mapped onto a slot allocation phase (primary or secondary) that it is most suited for. Following section depicts shortly administrative and market-based mechanisms.

<table>
<thead>
<tr>
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<tr>
<td>Mathematical optimisation</td>
<td>X</td>
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<td>Market-based</td>
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<tr>
<td>Exchanges</td>
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<tr>
<td>Trades</td>
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<tr>
<td>Auctions</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Congestion pricing</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Table 6. Mapping methods with the slot allocation process phase

2.1 Slot allocation mechanisms

2.2.1 Administrative mechanisms (current system)

The current primary allocation of slots in European airports is an administrative process: Member States designate congested airports as coordinated, and slot coordinators at each of these airports seek to balance the demand for slots with the supply. Each coordinated airport must specify a declared capacity (in number of aircraft movements per unit of time) taking into account all the constraints affecting availability of resources.

Users interested in scheduling operations at these airports must send a formal request for each desired slot. Slots are allocated in series, i.e. sequences of at least five slots at the same time on the same day of the week, distributed regularly in the same scheduling season, e.g., a series of 09:15 departure slots over at least five consecutive Mondays.

Two fundamental criteria are applied when allocating the available capacity: historical precedence (the so-called grandfather rights) and time adjustments of historical slots. Airlines can earn historic rights or grandfather rights to a series of slots, provided they operate the slots as allocated by the coordinator at least 80% of the time during a season (use-it-or-lose-it rule, also called 80-20 rule). Airlines can lose historic rights due to repeated and intentional slot misuse. Grandfather rights only apply to series of slots, never to single slots or other ways of slot groupings. Single slots and other groups of slots return to the slot pool the following season. There are exceptions to use-it-or-lose-it rule and an airline can justify a slot usage below 80% for one or more of the following reasons:

a) unforeseeable and unavoidable circumstances outside the airline’s control leading to the grounding of the aircraft type, closure of the airport or serious disturbance of operations at the airports concerned;
b) interruption of air services due to an action intended to affect them and which makes it practically and/or technically impossible to operate;
c) serious financial damage for a community airline;
d) judicial proceedings concerning the imposition of public service obligations resulting in a temporary suspension of the operation of such routes.
Additionally, in the case of certain extraordinary events, such as the terrorist acts of the 11th September, specific amendments to the regulation were made so as to relax the use-it-or-lose-it rule for one or more seasons, in order to mitigate the impact of such events on air transport operations.

Time adjustments of historical slots are made after historical precedence has been taken into account and before the allocation of the remaining slots from the pool to the other applicant air carriers. Re-timing of series of slots is carried out only for operational reasons or for improvement of the slot timing of the applicant air carrier with respect to the timing initially requested. If a requested slot cannot be accommodated, the coordinator informs the requesting air carrier of the reasons and indicates the nearest alternative slot. If no adequate alternative is available or acceptable, the slot request is rejected.

In those situations where all slot requests cannot be accommodated to the satisfaction of the airlines concerned, commercial air services — in particular scheduled services and programmed non-scheduled air services — have preference over the others. In the case of competing requests within the same category of services, year-round operations are prioritised.

When there are public service obligations (PSO) imposed on a route, the State may reserve the slots required for the operations envisaged on that route, in accordance with Article 4 of Regulation (EEC) No 2408/92.

**Figure 2. Allocation of slots process**

After this first assignment to incumbent airlines and the slot reservation for PSO, a slot pool is created with the remaining slots. Fifty percent of this slot pool is allocated free of charge by the slot coordinator to new entrant airlines. An airline is considered a new entrant at an airport on a particular day if, upon allocation,

- it would hold fewer than five slots in total on that day; or
- for an intra-EU route with less than three competitors, it would hold fewer than five slots for that route on that day.

The remaining slots in the pool are allocated giving priority to year-round commercial air services. Within each category (changes to historic slots, allocations to new entrants and other allocations from the slot pool), a request to extend an existing operation to operate on a year round basis should have priority over a new slot request.
Coordinators allocate the available capacity based on the following priorities:

1. a series of scheduled services;
2. ad hoc services;
3. other operations.

Other criteria to be applied when slots cannot be allocated based on the above mentioned rules are:

- Effective Period of Operation: the schedule that will be effective for a longer period of operation in the same season should have priority;
- Type of Service and Market: the balance of the different types of services (scheduled, charter and cargo) and markets (domestic, regional and long haul), and the development of the airport route network should be considered;
- Competition: coordinators should try to ensure that due account is taken of competitive factors in the allocation of available slots;
- Curfews: when a curfew at one airport creates a slot problem elsewhere, priority should be given to the airline whose schedule is constrained by the curfew;
- Requirements of the Travelling Public and Other Users: coordinators should try to ensure that the needs of the travelling public and shippers are met as far as possible;
- Frequency of Operation: higher frequency such as more flights per week should not in itself imply higher priority for airport slot allocation;
- Local Guidelines: the coordinator must take local guidelines into account if they exist. Such guidelines should be approved by the Coordination Committee or its equivalent.

Slots are allocated in scheduling seasons — summer starting in late March and winter starting in late October. The initial allocation of slots occurs before the biannual IATA Slot Conferences, the international forum for the allocation of slots which is held twice per year. Conferences are held in November (for the Summer season) and June (for the Winter season). The purpose of the IATA Slot Conference is to provide an international forum in which both IATA and non-IATA airlines can participate to adjust slots mainly through bilateral discussions between airlines and coordinators when it involves alternatives offered, or between airlines to exchange slots.

As a slot change at one airport could affect one or more other airports, the conference provides a unique forum in which all such repercussive changes can be quickly and efficiently processed and all airlines can leave the conference with slots which they consider are the best compromise between what is wanted and what is available.

**Administrative allocation using mathematical optimisation**

Exact and heuristic algorithms are mathematical tools used to obtain the best (or close to best) solutions with respect to defined objective function and constraints. These approaches, also referred to as mathematical optimisation, are usually applied when the problems at hand become intractable empirically. To our knowledge, currently, the slot coordinators do not use exact or heuristics approaches in the slot allocation process.

On the academic side, Zografos et al. [10] formulate the optimisation model of the current primary allocation as a binary linear programming problem. The model is developed at a strategic level, for a single airport. Furthermore, the EU/IATA slot allocation rules in effect are implemented in the model, as well as coordination procedures and other operational constraints. The objective of the model is to distribute the slots (series of slots) in a more efficient way “and better accommodate airlines’ preferences at schedule coordinated airports [10].” The objective function seeks to minimise the difference between “the requested slot time and the slot time allocated to airlines 2-6 months before the start of the scheduling season (initial coordination or pre-conference activity)” [10]. The model takes into account the slot priorities, and it is solved for the entire season. Thus, the slot series are taken into account as opposed to the individual, non-dependent slots (that do
not have basis for grandfather rights). The results of the optimisation are compared to the outcome of the primary allocation process by slot coordinators at Heraklion, Chania and Rhodes airports (Greece).

The motivation for using the optimisation model in the primary allocation process stems from the assumption that the efficiency of the process can be greatly improved, as in the current coordination process [10]:

i. “coordinators have to deal with a rather complicated allocation process with multiple criteria, rules, and priorities,

ii. there is limited decision support available to coordinators mainly through rule-driven slot management applications or visualisation tools, and

iii. the problem size even for medium-sized, non-congested airports makes it practically impossible to manage empirically.”

Koesters [11] addresses a similar objective function, taking into account the difference between requested and allocated slot times, but applying a heuristics approach. The heuristics procedure matches the airline demand and airport capacity by computing the differences between the requested and allocated slot times, or so called scheduled delays. The procedure is applied at the strategic level, for different levels of capacity, demand and slot utilisation. However, the model does not take into account the slot priorities (grandfather rights and similar), nor the concept of slot series.

2.2.2 Market mechanisms

Exchange

Both the IATA guidelines and the European regulation encourage slot exchanges, as it is often the last instrument the airlines have to create better schedules. The slot exchanges are a part of the secondary slot allocation, as they happen after the primary allocation is finished. All the slot exchanges have to be submitted to the airport coordinator that needs to approve the exchange, taking into account competition and similar requirements.

Trade

Slot trade is the slot exchange or transfer accompanied by monetary or non-monetary compensation. Slot trade happens during the secondary slot allocation. According to IATA guidelines [1], “the exchanges for compensation or consideration may only take place where they are not prohibited by the laws of the relevant country”. So far, the slot trade is explicitly allowed only in the USA (only at Washington Ronald Reagan National Airport), and in the UK [12].

The Buy/Sell Rule of 1985 in the USA allowed the airlines to sell, buy or lease slots at the slot controlled airports (Chicago O’Hare, Washington National, LaGuardia, Newark, and JFK). The immediate impact of the rule was that “between December 1985 and December 1988, the eight major airlines increased their control of slots from 70 percent to 96 percent” [13]. The only way to obtain the slots for new entrants was to lease the slots from the incumbents, which would leave the incumbent in the control of the slot and the new entrant would not have a reliable long-term access to the airport.

At the moment, the trades are allowed only at the Washington National airport, as the slots at New York area airports are under the FAA temporary orders, and as such are not considered to be the permanent solution, so these slots can be only exchanged or leased. Furthermore, the FAA is of the opinion that [14] “the Buy/Sell Rule also failed to foster a robust secondary market because it did not require any transparency”.

As the applicable European regulation is unclear on slot trading, the Commission issued a communication in 2008 [15] stating that it does not intend to “pursue infringement proceedings against Member States where such exchanges take place in a transparent manner”. To our knowledge, in Europe, secondary trading is legally
established only in UK, mainly for Heathrow and Gatwick airports. At the time of the SDG report [12], some fake slot exchanges were identified by the coordinators, but all the involved airlines denied that the payment occurred. The fake slot exchange is done through an airline asking for a useless slot available through the slot pool (for example at 5 am), and then exchanging it for a slot in a peak hour. Furthermore, the airline that gave up the “more useful” slot does not use the 5 am slot and often returns it to the slot pool.

Airport Coordination Limited (ACL), the UK slot coordinator opened the slottrade.aero website, which is the service they offer for facilitation of slot trades. According to the data on the website, 291 slot trades occurred at Heathrow and Gatwick since 2008. The transparency requirements (versus public) on a trade operation are limited to the aggregate information on the airlines buying/selling, the number of weekly slots and the description of the trade. The price disclosure is not mandatory. However, even here, where the slot trade is allowed, the slots are traded by means of a slot exchange, as it is a “tried and tested method that is fully compatible with the Slot Regulation” [16].

The slot trade produced the expected benefits at Heathrow: increased aircraft size, increased competition, improved slot mobility; that mostly offset the negative impact of the reduction of regional accessibility [12]. However, the same benefits were not reached at Gatwick. It also need to be taken into account that according to SDG report [12] there are only a few coordinated airports in Europe where the demand for slots exceeds the capacity for most of the day. Those airports are the best candidates for the efficient secondary slot trade markets. At all other coordinated airports, slots are available in the off-peak hours.

**Auctions**

Airport slot allocation is a combinatorial allocation problem (CAP) that can be solved by means of auctions. To our knowledge, to-date, auctions have not been applied in the airport slot allocation process, even though many researchers and economists are advocating auctions as a more efficient means to allocate slots.

The FAA attempted to introduce auctions in the slot allocation process in 2008, through the Congestion Management Rules for LaGuardia, Newark and JFK airports [17]. The rule proposed to establish a secondary market by auctioning a limited number of slots each year. The auction type proposed was second-placed-price sealed bid. The proposed rule covered, among other things, the auction design, the economic assessment of the auction impact and the proposal for the use of the proceeds from auctions. However, the rule was withdrawn in May of 2009 because it caused heavy litigation from different opponents to the rule (both airlines and port authorities), and last but not least, the US Government Accountability Office (GAO) concluded [18] that “FAA currently lacks authority to auction arrival and departure slots, and thus also lacks the authority to retain and use auction proceeds.”

As an introductory first step, the primary slot allocation problem can be described and formulated within a single airport with its capacity constraints. This process is illustrated in Figure 3, where several airlines place their bids for the available slots of a certain airport. Each of these airlines has its own interests, which are represented by their objective functions. The auctioneer might be the airport authority, a slot coordinator or an organism designated to the effect. The auctioneer is in charge of the auction management, consisting mainly in establishing the prices for each slot according to certain criteria, through the different iterations of the process.
This model is easily extended conceptually for several airports. In this case, for each airline’s flight, an arrival slot at a destination airport will be dependent on a departure slot at origin airport. The number of possible combinations increases, and with it the complexity of the problem. Additionally, a strong dependency between the items appears, being this a key aspect influencing the way to solve the problem and the characteristics of the feasible solutions.

Figure 4 shows an illustration of a multi-airport slot auction. The airports offer their capacity, which is known by the other actors. The airlines place their bids for the combination of slots in several airports that maximise their objectives, depending on the price of each slot. The coordinator, knowing the capacities and restrictions at every airport, processes all the bids and examines which timeframes would be congested and which ones not. A timeframe would be the period of time comprising several slots existent in an airport at a single time.

Several approaches can be taken to modify the price through the iterations of the auction, such as ascending clock, descending, Walrasian or adaptive, mainly based on the deviation between supply and demand. Within the ACCESS project, computational tests will be used to analyse which one of them works better. The advantage is that the price profile generated by the algorithm can provide managerial insights for airports and/or authorities, and it helps manage the scarcity of the slots more efficiently.

The objective function of each actor is a key aspect of the design, since a slight difference may lead to a completely different market situation. The design of these objective functions may answer to different
considerations such as economic profit, market competence, historical background, socio-political or geographical issues, etc. The formulation that will be developed by ACCESS will try to represent some of this variety, and it will be evaluated by means of simulation with multiple scenarios.

Figure 4. Outline of a multi-airport slot auction

The situation in a secondary market is slightly different because the agents can be both buyers and sellers at the same time. Additionally, there could be the case where an airline could be interested in some non-allocated slots in a pool. The rules established for the exchange, such as whether it has to be one-for-one, or whether a monetary exchange is allowed or not, will create markets of different nature where the best approach to find a solution may not be the same. In this situation, a central coordinator could gather all the
airlines' requests to exchange or sell slots, and then publish them in an aggregated way so all the airlines can make their requests for this offer. Figure 5 illustrates this general scenario for the secondary market. The number of possible combinations in a secondary market is much lower than in a primary allocation, but depending on the case, it could also be difficult to get to a solution because there may not exist a combination of the offer that satisfies the demand.

The starting point for the mathematical formalisation of the slot allocation problem can be seen as an integer programming model. Traditionally, this type of integer programming problems have been tackled offline and simultaneously by a centralised decision-maker that uses a global optimisation function, but the complexity of the problem can make it unaffordable in this way. The advantage of the combinatorial auction approach is that it allows the decentralisation of the process by using the paradigm of multi-agent systems, to distribute the complexity of the overall problem among the actors involved: the airports (as suppliers), the airlines (as bidders) and a coordination organism (as auctioneer). Each of them must solve a decision optimisation problem according to their preferences (their own objective functions), which is less complex than the overall
problem. The joint interaction of agents over several iterations eventually leads to a solution to the overall problem.

The mathematical formulation of the auction problem presents an interesting analogy with the application of “Lagrangian Relaxation” to the original integer programming model [19], [20]. The Lagrangian relaxation, a decomposition technique for mathematical programming problems, provides a mathematical model of the auction process and guarantees an equilibrium price, and it also helps to avoid the complexity of the capacity constraints. In the original combinatorial problem there is no guarantee of the existence of equilibrium prices because of the complementarity between slots, but the Lagrangian relaxation formulates the problem in a different way that allows obtaining an equilibrium price, although it may not be the optimum solution. This reformulation of the problem can be resolved by applying a “sub-gradient search” [21], [22], [23], hence eventually solving at the same time the CAP for all the requested slots in an auction.

Congestion pricing

Economists have long been advocating the use of pricing of public resources in the presence of negative externalities such as congestion, wherein each user of the public resource is required to pay a price equal to the marginal cost imposed by that user on all the other users of the resource [24]. Airlines operating at congested airports automatically internalise a part of the congestion costs they impose [25] [7], but also impose additional delay costs on the other airlines operating at the same airport. Congestion pricing consists of surcharging airspace users for the use of scarce capacity to regulate demand, by establishing different prices along the day based on marginal congestion costs [26].

As auctions, congestion pricing relies on the ability of the airlines to assess the economic value of airport slots, while bidding for slots in the case of auctions and for determining the demand for slots at a given level of prices in the case of congestion pricing [26]. The main drawback of congestion pricing is that — unlike auctions, which automatically reveal information about relevant parameters as well as acting as allocation mechanisms — congestion charges need to be set by an external body that needs to calculate their appropriate level by estimating demand elasticity and marginal congestion costs [27]. The difficulty to dynamically set the optimal structure and level of airport charges would most likely lead to efficiency losses [28]. This is probably the main reason why, despite being conceptually well developed in the economics literature, congestion pricing has found limited practical application.

Additionally, practical experiences indicate that institutional barriers may prevent the effective use of peak pricing. In Europe, the British Airport Authority introduced peak pricing in 1972 in the UK Airports it managed. The peak element of the pricing strategy initially charged £20 (the equivalent of around $50 at that time) per operation between the hours of 8:00 and 11:59 a.m. and only applied from May through October, while in May and June it was only in effect on weekdays. Changes to this initial pricing structure have been made every year since its implementation [29]. However US carriers complained about these charges since the beginning and a “British Airport Users’ Action Group” was formed by 18 airlines (larger aircraft operators who felt discriminated and refused to pay the fee) to sue the BAA. The suit was eventually settled out of court with a memorandum of understanding and the peak charge was eliminated in 1980, replaced by fixed element in weight charge. In the US Boston Logan Airport has proposed at least five pricing schemes since the 1980’s and implemented two of them [29]. In this case it was the smaller aircraft users (commuter carriers and General Aviation) who challenged the rule in court on the base of being unfair and discriminatory and the fee structure was ultimately rescinded.

At least in a first stage, ACCESS will set aside congestion pricing, focusing on the analysis of auctions (see section 4).
Hybrid mechanisms

Congestion pricing is normally proposed as an alternative to slot constraints, but there is also some theoretical work that combines slot constraints with congestion pricing.

Theoretically, under conditions of certainty, both congestion pricing and slot auctioning can generate optimal results from the point of view of social welfare. However, under demand uncertainty, the welfare performance of each instrument can differ according to the structure of demand and congestion costs [30]. To address demand uncertainty, Czerny [30] proposes a solution based on the combination of lower/upper limits for congestion charges and slot constraints, consisting of:

- a sealed-bid, one price auction;
- a system in which slots are numbered and each slot has an associated congestion charge (to be paid only if the slot is used) equal to the marginal external congestion costs of operations given that all slots with a number smaller than or equal to the number of the respective slot are used; and
- a secondary market, in order to ensure that only the cheapest slots are used.
3. Description of stakeholders

A description of all stakeholders can be found in ACCESS Working Paper 1 [3], where 5 groups of stakeholders are described in detail:

- Regulation group (in Europe): includes those stakeholders that play a role in establishing the legal framework for slot allocation process: IATA, European Commission, European Parliament, European Council and Member States.
- Coordination group: those that coordinate slot allocation, monitor the process and ensure the compliance of allocated slots. That group includes airport coordinators and coordination committees.
- Airspace Users group: the companies that will request and operate the slots: airspace users. This group is quite heterogeneous as airspace users are of different sizes, have different fleets and commercial strategies.
- Airport Operators group: includes airport operators. Different types of operators exist as there are several different models of ownership.
- Final users group: finally, one can identify a stakeholder that does not have a direct role in the allocation process but is the final customer of airspace users: passengers.

![Diagram showing characteristics of main stakeholders](image)

Figure 6. Characteristics of main stakeholders
3.1 Airports

There are different characteristics of an airport that may vary their attitude towards slot allocation and the different types of mechanisms.

Business model

Different airport business models may change the airport’s attitude towards different solutions to capacity scarcity due to the different weights that the aeronautical incomes and costs will have in the airport charges.

- single till: all revenues of an airport are directly considered for setting airport charges;
- dual till: splits the aeronautical and non-aeronautical business into distinct income and expenditure accounts, therefore only the aeronautical account is considered for setting airport charges.

The single till principle provides lower airport fees at those airports where commercial activity is a very meaningful share of the airport revenues, while dual till principle is independent from the commercial activity of the airport. Both principles have supporters and detractors providing many arguments in favour and against them. As an example, the IATA defends the single till principle, indicating that lower fees mean an increase of traffic and passengers which ends up with higher commercial revenues for the airport, creating a win-win situation for the airline and the airport [31], while ACI invokes that the inclusion of non-aeronautical revenues in the cost base for airport charge calculations creates an artificial constraint on the airport company, obligating the airport to focus heavily on non-aeronautical revenues in order to meet reasonable returns and providing an unjustified subsidy for the aeronautical activities which effectively becomes a subsidy for the airlines [32].

Due to the nature of each principle, it is often argued that the single till principle would contradict the so-called economically efficient congestion prices, due to the fact that congested airports would have a high non-aviation income, which would lead to lower landing fees and would make the congestion even more serious. However, the dual till principle creates incentives to keep capacity to a minimum, transferring scarcity into yields. As competition between airports is limited, they are in a position to push through their prices and earn monopoly yield. In the long run, it is again the passenger who would have to pay higher prices for tickets [33].

Ownership

The airport may have a different point of view regarding slot allocation criteria depending on the airport ownership. Interest from private investors may be quite different from publicly owned airports. Publicly owned airports will have a strategy not only focused on obtaining revenues from direct airport activities but may also consider indirect benefits to the local economy. Private investors will probably focus on maximising direct airport activities revenues.

There might also be the case of these private investors being other interested stakeholders, such as airlines. For example, the airline Deutsche Lufthansa is present in the shareholder structure of Fraport with 8.46% of the share [34].

Management unit

There are companies managing more than one airport at a time, creating an airports’ system. When these airports are located nearby, competition between them may be eliminated since the company strategy will be to maximise the benefits from a global unit formed by all airports within the system. A relevant example was back in 2009 when BAA owned London Heathrow, Gatwick and Stansted airports, which ended up with the Competition Commission requiring BAA to sell both Gatwick and Stansted [35]. This may vary the attitude that one airport will have regarding the slot allocation process, since the aim of the company will not only be to improve operations at that specific airport but looking at the overall outcome of the system, using surplus
from the highly profitable airports to subsidise the unprofitable ones. Therefore, the airport strategy towards slot allocation will depend on whether the airport stands alone or is part of an airport system and, of course, on the intrinsic details of that airport system.

3.2 Airspace Users

There are different characteristics of an airline that may vary their attitude towards slot allocation and different types of mechanisms.

Business model

In the airlines industry, one can differentiate 3 strategic groups of airlines of importance for slot allocation mechanisms [36]:

- Traditional or network carriers;
- Low Cost Carriers;
- Charter companies.

Other types of airspace users in the ATM system are General Aviation, Business Aviation and Military. However they are only partially affected (or not at all as Military) by slot allocation and their share in the total European air traffic figures is negligible for the purpose of this study. Therefore they are not specifically taken into account.

It must be noted, though, that meaningful definitions of and distinctions between airline business models are not easily formulated. The following picture shows an application of a product and organisational architecture approach to airline business models proposed by Mason and Morrison [37].

![Figure 7. Product and organisational architecture of airlines](image)
Within the organisational architecture the size and composition of the fleet along with the organisational design are elements that follow on primarily from the product architecture. In particular, the decision on network structure is key because the complexity of operating a hub-and-spoke network requires certain functions relating to coordination, yield management, etc., which implies a more vertically integrated organisation. In contrast, an airline operating a point-to-point network has relatively more opportunities to form a ‘nexus of contracts’ organisational structure in which many functions are contracted out. In terms of distribution, all airlines now take advantage of Internet-based booking systems, yet even here point-to-point network carriers can offer more simplicity in the process with implications for both cost and benefit drivers.

**Network carriers** can be characterised by the following elements:

- they schedule flights at the optimum departure travel times;
- they were usually created before the advent of the Internet;
- most of them were national or flag carriers;
- they are usually big companies, with well-known brands;
- they usually operate via international alliances with shared codes, and are strong on quality and reliability;
- they usually operate at the biggest and best airports;
- they focus on business trips, international and long-haul routes, where hub services and connections are far more significant; and
- they use loyalty programs and relationship management techniques.

Network carriers usually operate according to hub-and-spoke systems through which they funnel passengers from different locations into central hubs at major airports and sort the passengers onto connecting flights to their final destinations. They usually belong to international airline alliances, through which they benefit from other airlines linking airports outside their network with their hub or other airports, increasing its network without needing to invest in new routes. This type of carrier usually holds a large share of slots in its hub due to grandfather rights, having some flexibility in its hub to adapt its routes to other airports’ slot constraints. Their slot dominance in their hub is key for their strategy planning, which together with the fact that the current system gives little incentive to release slots brings network carriers to keep the slots even if they cannot use them efficiently (slot hoarding) in order to prevent competition from entering in their hub airport.

The second group is the **low cost airlines (LCC)**. The definition of an European LCC is rather ambiguous: the sector includes airlines ranging from the Irish national carrier, Aer Lingus (which has transformed itself into a “superior” LCC), through former charter airlines such as Air Berlin which have now entered the scheduled market, to the dedicated low-cost operators such as the market leaders, Ryanair and EasyJet. All LCCs share a commitment to the “cult of cost reduction”, a business model that offers low fares, reduces overall costs and leverages assets (both human and material) to the full. Their main characteristics are:

- they operate a standardised fleet to lower training and maintenance costs;
- they remove non-essential features (free meals, frequent flyer schemes, non-reclining seats, etc.)
- they usually schedule flights out of the busiest time-windows (early in the morning or late at night);
- they usually operate from regional or secondary airports, following a point-to-point network structure;
- they are relatively young companies that entered the market thanks to the liberalisation of EU air transport industry implemented between 1988 and 1997;
- they operate independently, without using alliances and hardly providing connection flights;
- they almost exclusively use the Internet to interact with customers (ticket sales and check-in);
- they usually focus on regional or short-haul international flights for European tourism;
- they have high load factors;
- they try to minimise costs, maximising the use of assets;
- they predominantly use yield or revenue management techniques.
One of the main characteristics of Low Cost Carriers (LCCs) is the type of airport they operate to/from, which is usually a regional one, providing short to medium haul flights. There are cases in which LCCs fly to/from major airports under capacity restrictions where they need to be allocated a slot to operate, but there are two main points that ease their scheduling:

- LCCs don’t usually fly from one congested airport to another one, but they usually have one non-congested airport at the origin/destination, meaning that they do not need to fit 2 different slots, but can adjust their arriving/departing time to/from the non-congested airport to their convenience;
- LCCs often operate at congested airports during non-busy hours (i.e. very early in the morning or very late in the evening), so that they do not have much difficulty getting the desired slots.

For these reasons, the need that LCC have for slots is significantly smaller than that from network carriers.

Even though some characteristics have been listed above, there are important differences in the business models of airlines that are all commonly referred to as Low Cost Carriers [37]. These differences in business model may also affect their attitude towards slot allocation.

The third group of companies operating in the airline industry are the charter companies. Their main characteristics are:

- normally they do not fly scheduled flights. Their departure times are more adapted to demand, flying usually with a single class;
- they are usually small companies, many of them belonging to vertically integrated tour operators;
- they operate 24 hours a day in high season;
- they fly on demand, with negotiated prices, adapted to the intermediary firm;
- their flights are characterised by high load factors;
- although there is a great variety of charter companies, most of them, especially the ones covering tourist destinations, usually operate with very low costs; and
- they also choose to fly to regional airports, instead of big hubs.

However, some charter companies, as they grow and concentrate on tourist destinations, try to compete and act in a similar way to the LCCS, by operating mainly with short-haul flights for European tourism, especially when they offer their seats to the final customers.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Business model</th>
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<td><strong>Network Carriers</strong></td>
<td><strong>Low Cost Carriers</strong></td>
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<tr>
<td>Network</td>
<td>Hub-and-spoke</td>
</tr>
<tr>
<td>Flights</td>
<td>Business trips, international and long-haul</td>
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<td>Airports</td>
<td>Biggest and best</td>
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<td>Departure times</td>
<td>Optimum</td>
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<tr>
<td>Company</td>
<td>Big, with well-known brands. Most of them were national or flag carriers</td>
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Table 7. Summary of the main characteristics of each type of airline business model
Alliances

The development of alliances requires the timetables of members to be planned at least in conjunction with each other and preferably as an overall system. Some airlines operate at their hub in a scheduling pattern. An example of this is KLM in Amsterdam Schiphol, where KLM has a wave pattern with four major peaks each day. A flight arriving at Schiphol in one of the waves, e.g. at 18.00, will connect to more than 70 outbound flights in the period 19.00-19.59, where most of those connections are operated by KLM or one of its allies. This means that an airline joining this alliance should first of all move their flights to KLM waves. This should be easy if this airline connects Amsterdam Schiphol with different regional airports where no capacity constraints exist, but when these connections are instead from/to capacity constrained airports, the retiming of their slots may not be easy [38]. Therefore, the attitude of the airlines towards slot allocation criteria and its allocation mechanism may change due to an overall alliance strategy instead of a single airline. In this case, an airline with grandfather rights over some series of slots which this airline is not planning to operate, may still request to retain the series of slots in order to transfer them to a partner airline which would have been unlikely to obtain these slots in its own right, monopolising the airport usage by one alliance and reducing the possibilities of having slots allocated to new competitor entrants in the current allocation system.

A network carrier may prefer to acquire a regional carrier instead of allying with them, but sometimes alliances provide more advantages than acquisitions. As an example, when British Airways took over the regional airline CityFlyer Express, regulatory authorities demanded a cap on the combined slot holdings of BA and its franchise partner at London Gatwick, not only on an overall basis but within each hour, thus in practice not allowing them hubbing activity at that airport [38]. In contrast, currently there is no competition problem for an alliance to have a high percentage of slots in one airport.

Regarding different mechanisms of slot allocation, airline alliances will also influence the attitude of individual airlines, since the overall alliance strategy may also prevail over individual interests. This attitude modification due to alliances may sometimes be subject to anti-trust considerations.

3.3 Airline-airport alliances

Currently, there are not only horizontal alliances between airlines (airline alliances) or airports (being part of the same management unit), but also vertical alliances involving an airline and an airport. This is mainly the case of hub airports, where a major airline commits to the airport to exploit the infrastructure as much as possible and the airport provides the airline with special dedicated services. This collaboration goes from joint airline-airport marketing, such as sharing a customer fidelity program, to airport infrastructure investments such as new terminal constructions dedicated to that airline or airline alliance. This is the case of, for example, the Munich airport, which was partially financed by Lufthansa. This financial participation of the airline in the terminal construction entitled Lufthansa to significantly influence and determine the planning and realisation of the terminal [39]. Lufthansa goes a step further in Frankfurt, where it owns part of Fraport.

This type of alliances can only very limitedly help airlines in terms of slot allocation, due to the current administrative mechanism for slot allocation, but are rather a consequence of an airline’s dominance in an airport due to its grandfather rights. However, airline-airport alliances may be of much importance when applying other mechanisms for slot allocation as their attitude may vary due to a joint strategy.
4. Formalisation of slot allocation mechanisms

Primary allocation is currently performed in accordance with a set of administrative rules, while market-based mechanisms have only been proposed but not yet adopted nor implemented. On the contrary, secondary allocation relies only on trading mechanisms and no administrative rules to govern it have been envisaged so far. In this context, the ACCESS project investigates possible modifications to the design of the current secondary trading and, as for the primary allocation, provides novel single and multi-airport approaches.

4.1 Primary slot allocation

As introduced in section 2, primary allocation is currently performed separately at each individual airport, based on the administrative rules set out by IATA and complemented by EU regulation. The initial, pre-conference allocation is rather poor as distributed slots fail to match well the requested slots. One of the reasons is that the problem posed to slot coordinators, which they need to solve empirically, is rather complicated. Consequently, “the problem size and complexity give rise to serious allocation inefficiencies that are initially reflected on substantial deviations between requested and allocated slots” [10].

In the ACCESS project, we propose to formulate the current administrative rules for primary slot allocation through a mathematical optimisation approach (also referred to as “mathematical programming” or simply “optimisation” approach), as described in section 4.1.1. The proposed modelling extends the formulations introduced by, inter alia, Castelli et al. [40], Pellegrini et al. [41] and Zografos et al. [10], which show that such an approach provides several advantages over the current empirical way of allocating slots by national coordinators (see also section 2.2.1.1). ACCESS expected advances with respect to this literature are:

- mathematical formulation will consider additional performance criteria (see section 5);
- benefits of the mathematical approach will be tested on real data (thanks to access to the SlotAnalyser tool) and on medium to large European airports (Zografos et al. [10] only consider three minor Greek airports);
- primary slot allocation will not only be performed independently at each airport, but a simultaneous allocation for a group of airports is proposed. The aim is to verify if the implementation of such a simultaneous primary slot allocation may limit the need for bilateral negotiations leading to slot exchanges after the IATA conference (i.e., the so called “secondary trading”).

The slot allocation at each individual airport is performed according to a centralised perspective, meaning that a unique decision maker is assumed to run such a task. This assumption replicates the current role of national slot coordinators. In addition, the ACCESS project will address the case where a unique decision maker at the European level allocates slots to all (or most) airports simultaneously. Unfortunately, centralised allocations may become computationally cumbersome and may require the disclosure of confidential information from airlines. To overcome such weaknesses, the ACCESS project also proposes to model the primary allocation through market-based mechanisms such as auctions (section 4.1.2). In such a case, a decentralised perspective is easily obtained and airlines may take decisions on which slots to acquire relying on private information that does not need to be disclosed. These market approaches can be applied for one or several airports, the latter one being one of the advances beyond the state of the art provided by ACCESS.

Generally, the proposed auction mechanisms are coordinated by a central auctioneer, which is some organisation designated to this effect. The auctions consist of an iterative process where the airlines make their requests based on their interests and the auctioneer processes them taking into account the existing capacity of each airport and any other constraint. At every iteration the auctioneer updates the prices for each
slot, based on the calculations, until certain stopping criterion is met. In the end, the auctioneer informs all airlines on the allocated slots and the price set for each of these slots.

This decentralised approach splits the logic of the overall allocation problem and spreads it over the different actors involved, so that each of them has to solve a simpler problem. With respect to the centralised approach, decentralised formulations are usually faster to reach the final, although suboptimal, solution.

4.1.1 Administrative approach

Due to commercial and operational reasons, an airline requests a specific pair of departure and arrival slots for each of its flights, hereafter referred to simply as ideal (or requested) slots. When this ideal pair is not available, the airline has to advance or delay the departure and corresponding arrival time and this shift (also called scheduled delay [11]) induces an undesired cost, hereafter referred to as shift cost. We assume that each airline can indicate the maximum shift cost it can bear for each of its flights.

Costs for executing flights (such as fuel, crew and aircraft maintenance costs) may be considered independent from the exact schedule. Thus, costs due to a shift of departure and arrival slots correspond to potential revenue losses; potential customers that would have bought a ticket for the ideal schedule may not do it if the schedule is different.

The objective is to seek a slot allocation that minimises either the total shift (i.e., the scheduled delay) or the total shift cost. Alternatively, among all feasible allocations, the objective is to identify the allocation that considers two hierarchically ordered objectives: first it maximises the number of flights to which slots are allocated (‘accommodated flights’); second it minimises the cost of receiving slots different from the originally requested ones (‘ideal slots’). Other forms of the cost function are also possible, imposing, for example [10]:

- quadratic penalties for deviation from requested time, and
- different penalties for various ranges of slot allocation times which are somewhat equally desirable by airlines in the form of a “window of tolerance”.

Constraints

To adequately describe the slot allocation process, a set of constraints needs to be defined, such as:

- capacity requirements: airport capacity must never be exceeded, for each day and time interval;
- time requirements: slots allocated to a flight, if any, must be within an acceptable time period indicated by the airline: for example, a slot cannot be allocated to an airline if it is more than 30 min later than the airline’s ideal slot;
- turnaround requirements: turnaround time constraints are also considered for requests for which both an arrival and a departure time have been stipulated.

Additional administrative rules, such as grandfather rights, can be modelled either by explicitly imposing ad-hoc constraints (see, e.g., [40] and [41]) or by using a lexicographic approach, as in [10]. In this latter case, airlines’ slot requests fall in three general priority classes: (i) requests with historical rights, (ii) requests with new entrant status, and (iii) all remaining requests. Within each of these classes, additional (sub)criteria may also apply. IATA defines 16 subclasses with different priority for historical requests and a further 9 for new entrant and other requests [1]. Slot requests are optimally allocated to minimise the total absolute difference between the requested and allocated time interval. The model is then applied hierarchically for each priority class: after solving the model for a specific priority class, capacities must be updated for each allocated movement, before applying it to the next class; the problem turns increasingly constrained.
Mathematical optimisation approaches allow analysing:

- important aspects of the slot allocation mechanisms, such as fairness, which are addressed by running the system through very complex administrative rules (the optimal allocation may penalise just a few airlines to the benefit of the whole system, as it may happen that all flights whose slots are shifted belong only to a subset of airlines);
- the impact on costs imposed by the enforcement of administrative rules, such as the grandfather rights (in principle, the efficiency of the slot allocation should increase by removing the restrictions enforcing these historical rights).

Fairness can be improved and the impact of the modification of administrative rules (such as the relaxation or removal of grandfather rights) on incumbent airlines can be mitigated by the introduction of (monetary) compensation mechanisms, which have to meet two properties [42]:

- budget balance: the overall amount paid and received by the airlines participating in the mechanism sums up to 0. In such a way no subsidies are needed to run the mechanism, nor can gains be obtained from it;
- individual rationality: airline utility does not decrease without compensation through an appropriate side payment. In other words, each airline must have no disadvantage in participating in the mechanism. The amount paid as compensation plus the shift cost must be at most equal to the maximum cost the airline is ready to bear.

Since several combinations of payments can satisfy the budget balance and individual rationality properties, to achieve a fair allocation Castelli et al. [40] add a set of constraints ensuring that an airline $a$ bears no more than a share $s_a$ of the total cost. Three different ways of computing $s_a$ are envisaged:

1. **Contribution to infeasibility.** One choice is to penalise airlines proportionally to their contribution to the infeasibility of the ideal solution. If an airline $a$ asks only for slots in periods with no excess of demand and it must bear a time shift to create a feasible schedule, the consequent cost must be completely compensated. If, instead, an airline lands at a main airport in the peak time. then even if it is allowed to do so, it must be ready to refund competitors that do not have the same opportunity.

2. **Equal flights.** $s_a$ is equal to the ratio between the number of flights requested by airline $a$ and the total number of flights in the system.

3. **Equal airlines.** The total cost is equally divided among airlines. Hence $s_a$ is equal to the inverse of the number of airlines.

Furthermore, if new and incumbent airlines compete for the same slots, both types of airlines may accept the removal of grandfather rights provided that an appropriate compensation scheme is implemented.

The ACCESS project will implement and validate on real data this and possibly other compensation mechanisms that take into account the performance scheme described in section 5.

**Simultaneous allocation**

An additional feature of the mathematical modelling proposed by the ACCESS project is the opportunity to solve the primary slot allocation problem at all (or most) airports simultaneously, taking into account the structure of the air route network. In this way, an airline obtains for each flight a departure (arrival) slot, if it receives a departure slot compatible with the flight duration on one of the possible routes connecting the two

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Even though they might share some properties such as budget balance and individual rationality, the compensation mechanism described here is not a market-based mechanism (as described for instance in section 4.2.1) because no item (or good) is sold or bought. The outcome of the compensation mechanism is the (positive or negative) amount that has to be transferred among airlines to make acceptable for all of them the result of the central administrative slot allocation.
airports. Hence, a (simplified) representation of the route network is needed. In its simplest version, we may assume that:

- the time required to cross every sector is fixed (no speed control);
- en-route sectors always have enough capacity;
- only one route exists between departure and arrival airports, i.e., the time required to connect them is fixed.

More complex formulations relaxing any combination of these assumptions can be easily derived, such as considering different routes connecting origin and destination airports or assuming varying flight time, variation to be within a fixed interval.

With respect to the individual allocation, the simultaneous allocation requires some additional specifications in terms of:

- Constraints. Besides the time requirements that remain unchanged, additional constraints need to be defined:
  - capacity requirements: neither airport nor sector capacity must ever be exceeded, in each day and time interval;
  - route requirements: slots must be allocated so that, for each accommodated flight, a route of the appropriate duration exists for connecting the origin and destination airports at the allocated time;
  - duration requirements: route duration cannot be longer than a predefined value, for example, slots cannot be allocated to an airline if they imply that the flight must be rerouted, adding, e.g., 1 hour to its shortest route.

- Sharing of information. To make a simultaneous slot allocation properly run, some additional sharing of information is needed in terms of disclosure of airlines’ preferences, requirements and costs. For coping with the airlines’ reluctance to disclose their costs and requirements to competitors, in accordance with Soomer and Franx [43] the mechanism could be regulated by an independent coordinator that is in charge of managing sensitive data, like the foreseen costs of a flight. The independent coordinator has the role of collecting the requests of each airline to verify that a feasible solution exists and ensure that the optimal slot allocation is implemented. If a feasible solution does not exist, the coordinator should report the failure to the airlines and ask for new requests and/or updated information.

The ACCESS project will assess whether the introduction of a simultaneous primary slot allocation may reduce scheduled delay and/or the number of slots to be exchanged in the secondary allocation, as some of the inconsistencies currently addressed in the secondary allocation are anticipated and solved during the primary phase. This assessment will be performed for both the secondary bilateral trading and single market trading (see section 4.2).

### 4.1.2 Market-based mechanisms

This section provides a high level formalisation of the implementation of an auction process for the primary slot allocation problem. The main objective is to design the process that would support the simultaneous allocation of slots at several airports, that is, a combinatorial auction for several airports at the same time. As a first step, to introduce the problem, an auction process for just one airport is presented, so that the explanation is progressive and the extension to several airports can be more easily understood by the reader. Second, we describe the auction mechanism proposed for several airports, which is the most general case for primary slot auctioning. Particular scenarios, such as auctioning part of the capacity, different price update mechanisms, etc., can be detailed in different implementations (or sets of parameters) of certain blocks of this more general process.
This high level formalisation of auction mechanisms will detail the following aspects:

- the actors involved,
- the flow of the overall process,
- the information exchanged between actors,
- decision points,
- the input and output of the process.

**Single airport problem**

The actors involved in the slot auction process for a single airport are:

- the airport, which acts as the auctioneer (though it could be a different organisation or authority),
- and the airlines, which act as the bidders for the different slots (the goods auctioned).

The flow of the overall process can be observed in Figure 8. In the first step, all the airlines involved in the auction make their requests for slots to the airport (bids). The airport, as auctioneer, will process these requests taking into account the available capacity (may depend on the declared capacity, grandfather rights, etc.) and all other constraints (arrivals, departures, sector, etc.). The auctioneer processes the received data by means of a set of calculations that also depend on the price update mechanism implemented, and thus obtains a preliminary set of arrival and departure slot prices, and a preliminary general allocation for the airport.

The price update (or pricing) mechanism can be formalised through several approaches, the most appropriate ones being the Walrasian, the adaptive, the ascending clock and the descending ones. The pricing mechanism modifies the prices of the slots so that price is raised for slots with excess of demand, and it is lowered for those where the supply is greater than the demand. Due to the fact that airports may have different values of arrival and departure capacity restrictions for a same time span, the surplus of different slots at the same time might be different depending on whether they are for arrival or departure, so the pricing mechanism has to provide different prices for arrival and departure slots.

The provisional slot allocation and prices, together with the other criteria such as the number of iterations, can be then combined to analyse the stopping criteria. If the established rules are matched (e.g., prices for the next iteration do not vary more than a threshold, a certain threshold of the overall capacity has been allocated, and/or a certain number of iterations have been run), the preliminary outputs become definitive, and all actors are informed. If not, the new prices for the next auction iteration are communicated to the airlines and the bidding process starts again. The preliminary schedule is not communicated to the airlines.

The main decision points in the overall process are:

- the airlines have to decide where to place their bids to maximise their benefit,
- the auctioneer/airport has to decide:
  - how to modify prices according to a previously established criteria (overall utility, auction profit, fairness, etc.),
  - when to stop the auction.

Other aspects of this auction process, such as its frequency, the objective functions of the actors, etc., can be parameterised and studied in the simulation through different scenarios.
To illustrate the difference with a fully centralised implementation, as in section 0, we can compare Figure 8 with Figure 9, where the mathematical formalisation of the slot allocation problem is solved with a mixed-integer linear programming model (MILP). The problem has to be tackled offline and simultaneously by a centralised decision-maker that uses a global optimisation function, and the airlines lose great part of their decision capacity in the process.

One notable advantage of using an auction mechanism instead of the central allocation is that the former does not require airlines to reveal to the system their cost of delay, but simply to place bids according to current prices of slots compared with their cost functions, which remain private. This entails two main features of interest of airlines: (i) they do not have to directly reveal confidential information to potential competitor airlines and (ii) they do not have to exactly estimate their costs, but just the relation between cost and slot prices.
Multi-airport problem

Although the multi-airport (or simultaneous) allocation problem presents a much more complex situation in combinatorial terms, the conceptual design does not differ much from the single airport problem. The flow of the overall process can be observed in Figure 10.

The actors involved in this process are:

- the airlines, which act as the bidders for the different slots (the goods auctioned),
- the set of airports involved in the auction, which provide their available capacity and their constraints (the supply),
- the auctioneer or coordinator of this auction process.

Generally, in this situation the auction coordinator has to be an independent organisation/authority, so that the privacy of the information and the fairness of the process can be guaranteed.

As in the single airport problem, all of them provide their inputs to the auctioneer in the initial step:

- the airports provide their capacities and constraints,
- and the airlines place their initial requests for slots depending on their interests.

Again, through a set of calculations depending on the price update mechanism, the coordinator will obtain a preliminary schedule for all the airports and a set of arrival and departure slot prices for each of them. The provisional allocation will not be published and will only be used by the auctioneer to evaluate its objective function and the stop criteria. These criteria are established in the same way as in the single airport problem, but they are more complex because they have to take into account another dimension (the set of airports).
If the stop criteria is not matched, the preliminary prices for the next round are communicated to the airlines and a new auction iteration starts. If it is matched, the preliminary output becomes final:

- the slot allocation for each airline is published,
- the overall schedule for each airport is known, and
- the arrival and departure prices for each slot are communicated.

The total complexity increases, but the main decision points in this process are the same as in the single airport case. It has to be noticed that:

- the complexity of the bids the airlines have to place is much higher and it will depend on the number of airports involved: there are many more possible combinations for the requests, and the dependency between items is very important;
- the complexity of the problem the auctioneer has to face is also much higher: the objective function will depend on the schedules achieved for each airport, but it might also depend on some other criteria such as fairness, market growth, societal factors or policies for certain regions, fostering the entrance of new airlines, etc.

The advantage of using a distributed auction process to solve this problem is that this overall complexity is spread over different actors, and the overall problem does not have to be solved just by one of them. As in the previous case, aspects such as its frequency, objective functions, complexity depending on the number of airports/airlines, number of iterations needed, etc. can be parameterised and studied through simulation.

![Flow diagram of the slot auction process for a multi-airport problem](image-url)
Again, we can compare the process described in Figure 10 with a fully centralised implementation, represented in Figure 11, which tries to resolve directly the mathematical formalisation of the slot allocation problem for multiple airports as a MILP model. The complexity of the MILP problem has to be analysed when lots of airlines and airports are involved, because computational limitations can make it unaffordable. Again cost deviation for airlines is information requested in the centralised method, and not in the auction.

![Centralised Method for the Slot Allocation Problem in Multiple Airports](image)

**Figure 11.** Flow diagram of the centralised slot allocation process for a multi-airport problem

### 4.2 Secondary slot allocation

ACCESS will consider a single market for slot trading, formulated as a centralised combinatorial exchange and modelled as a mixed integer linear programming problem. This formulation allows the exact identification of the optimal solution, i.e., the slot trading that minimises the sum of scheduled delays (or their associated costs) over all airlines (section 0). However, combinatorial exchanges usually are NP-hard problems, hence their exact formulations may become unpractical to solve when the size of the instances significantly grows. For this reason, we also propose a decentralised agent-based and heuristic approach that allows tackling large sets of data, as the single market approach over the whole Europe would likely require (see section 0).

#### 4.2.1 Centralised approach

In the current slot allocation process, at the end of the primary slot allocation a set of slots is allocated to each airline. After this phase, bilateral negotiations leading to slot exchanges may continue among airlines. In other words, slots that are allocated to an airline may be exchanged for slots held by another airline, on a strict one-for-one basis. Such bilateral exchanges are usually non-monetary, even though more recently slot exchanges with monetary considerations (trade) were explicitly recognised by the European Commission [15] as a legitimate option in the secondary slot allocation. Such exchanges may occur because, inter alia:

- the outcome of the primary allocation is unsatisfactory for some flights because of the severe constraints upon matching slots at different airports, and routes all over the world;
- conditions that led to requesting a particular slot at the moment of primary allocation have changed, leading in turn to a change in the utility of a certain slot for a certain airline.
The trade option allows better matching of airlines’ requests, i.e., reducing the scheduled delay [11].

ACCESS proposes to extend the current mechanism to a framework where airlines trade in a single market rather than on a bilateral basis. This single market approach implies that a wider set of choices is available to each airline and then the total scheduled delay and the associated shift costs are expected to be reduced. Since an airline owns a set of slots and may wish to exchange (some of) these slots for other slots, bundles of these can be traded. A market mechanism where bundles of items are traded is usually referred to as combinatorial exchange and its main characteristics [44] are:

1. the price of an item is a function of the seller’s willingness to gain and the buyer’s willingness to pay;
2. multiple sellers and multiple buyers participate in the trade;
3. a single bid can express the willingness to buy (sell) a bundle of items.

The implementation of secondary trading as a combinatorial exchange requires some additional features that are similar to those needed to effectively run a simultaneous primary slot allocation:

- the combinatorial exchange should meet the budget balance and individual rationality properties. Indeed, if budget balance is not guaranteed, it would be required to decide what the gain coming from the market should be used for, and who should pay if the market needed to be subsidised. On the other hand, if individual rationality is not guaranteed, it would be very difficult, if not even impossible, to ensure airlines’ participation;
- the combinatorial exchange needs to be managed by an independent coordinator, which is in charge of managing sensitive data, collects all bids and unused slots, and finds the optimal solution;
- capacity, time, route and duration requirements need to be respected as hard constraints;
- a possible objective is to minimise either the total shift (i.e., scheduled delay) or the total shift cost.

The combinatorial exchange governed by an independent coordinator that identifies the optimal slot trading for all airlines can be formulated through a mixed-integer linear programming model. Unfortunately, such an approach may not be able to provide good solutions in reasonable time in the case of implementations involving a large number of flights, due to the heavy computational burden. For this reason, an alternative and viable way is to formulate the single market by allowing some of the actors to take their own local decisions. This decentralised agent-based perspective may however lead to sub-optimal solutions, as de-facto does not solve the problem exactly, but heuristically.

4.2.2 Decentralised approach

This section provides a high level formalisation of the implementation of an auction process for the secondary slot allocation problem. The main objective is to design the process that would support the simultaneous exchange and/or trading of slots between airlines at several airports, that is, a combinatorial auction for several airports at the same time. This process will take place in periods between primary allocations and will involve some of the slots in possession of an airline.

Particular scenarios, such as auctioning only the offered slots or all the slots, different price update mechanisms, monetary exchange allowed or not, etc., can be detailed in different implementations (or sets of parameters) of certain blocks of this more general process.

This high level formalisation of auction mechanism will detail the following aspects:

- the actors involved,
- the flow of the overall process,
- the information exchanged between actors,
- decision points,
- the input and output of the process.
The actors involved in the slot auction process are:

- all or part of the airlines, which act as the auctioneers for the different slots offered (the goods auctioned),
- all or part of the airlines, which act as the bidders for the different slots requested,
- the auction coordinator of this auction process.

Generally, in this situation the auction coordinator has to be an independent organisation/authority, so that the privacy of the information and the fairness of the process is guaranteed.

An airline can act as a seller, offering some of its held slots, or as a bidder, requesting slots from other airlines, or both at the same time. In a more general version of the problem, all the airlines’ slots could enter in the auction process, accepting or rejecting the bids received for their slots, either in the form of exchange for other slots, by a monetary amount, or through a mix of both, depending on the type of exchange allowed. The flow of the overall process is shown in Figure 12.

Figure 12. Flow diagram of the slot auction process for the secondary allocation

The inputs provided to the auction coordinator in the initial step will be:

- the airlines, as sellers, provide their offered slots at certain timeframes. In the mentioned general case, all the slots held by airlines enter in the process;
- the airlines, as bidders, provide their initial requested slots at certain timeframes.
The auction coordinator will process all these requests. Two cases can be considered at this point:

- the exchanged slots must retain their original use after the exchange, or in other words, arrival slots must only be used for this purpose by the new owner airline, and the same for departure slots;
- it is allowed to change the use so that, for example, an original departure slot can be used as an arrival slot.

In the first case, the coordinator would not need to re-evaluate the capacity constraints of the airports involved (already evaluated in the primary allocation of these slots) and the submitted requests must consider the restrictions to be valid.

In the second case, in addition to the already assigned slots that airports are willing to trade, the coordinator has to be aware of the capacity constraints of each airport because it has to re-evaluate them depending on the requests (particularly, depending on the specific use requested for a slot: departure or arrival). Airlines will request slots at certain timeframes (for departure or arrival), and the coordinator will evaluate these requests to check if they can match the overall capacity constraints. This makes the resulting combinatorial decision problem much more complex than in the first case.

As it is mentioned above, the exchange options have to be regulated in advance. It is possible to consider at the same time one or more of the following situations:

- Non-monetary exchanges:
  - direct slot exchange is allowed in a one-for-one basis;
  - direct exchange is allowed in a one-for-many basis;
  - while having the right to use certain slot for certain part of the season (or the whole season), an airline may be interested in using it only partially (less weeks/months than expected), and therefore be willing to exchange the use of the corresponding slots for some weeks for an equal or different amount of slots of another airline.

- Monetary exchanges:
  - direct slot buy/sell operations are allowed, based on the prices established in a primary auction;
  - an airline is willing to trade the use of a slot only for part of the time where it has the rights, according to the price established in a primary auction;
  - direct buy/sell operations of full/partial rights over slots are allowed, without a pre-established price over them, therefore involving a new bargaining process that will create new prices for some slots.

It is necessary to define, once the airlines put their offered slots in the market, whether they can reject the exchanges or if they are forced to accept the exchange.

The auction coordinator processes the received data by means of a set of calculations that also depend on the price update mechanism, and thus obtains a preliminary set of arrival and departure slot prices for all the involved slots, and a preliminary general allocation of possible direct exchanged slots between airlines at each involved airport.

The price update scheme can be formalised through several approaches, the most appropriate ones being the Walrasian, the adaptive, the ascending clock and the descending ones. The pricing mechanism modifies the prices of the slots in a way that price is raised for slots with excess of demand, and it is lowered for those where the supply is greater than the demand.

The provisional allocation is published and, depending on the allowed exchange options, the airlines evaluate if they accept or reject the possible exchanges and/or trades received through the auction coordinator. Then the auction coordinator has to evaluate all the provisionally accepted exchanges and/or trades and select a feasible combination to maximise its objective function and evaluate the stop criteria.
If the stop criteria is met (e.g. prices for the next iteration do not vary more than a threshold, preliminary schedule covers more than a threshold of the overall capacity, etc.), the combinatorial auction winners bids will be the final exchanges that will be closed. If the stop criteria is not met, the bidder airlines could change their request and/or offered slots for the next iteration as a function of their preferences and the resulting prices of the previous iteration, and the process is repeated in a new iteration.

The main decision points in the overall process are:

- the airlines have to decide which slots they request and which ones they offer to maximise their benefit (depending on the existent exchange rules),
- the auction coordinator has to decide:
  - how to modify prices (if it is allowed) according to a previously established criteria (overall utility, auction profit, fairness, etc.),
  - when to stop the auction.

Other aspects of this auction process, such as its frequency, the particular objective functions of the actors, etc. can be parameterised and studied in the simulation.

To illustrate the difference with a fully centralised implementation (see section 0), we can compare Figure 12 with Figure 13, where the central authority is trying to resolve directly the mathematical formalisation of the slot allocation problem as a mixed-integer linear programming model (MILP). Here, the whole problem has to be tackled offline and simultaneously by a centralised decision-maker that uses a global optimisation function, and the airlines lose great part of their decision capacity in the process. Also, the complexity of the MILP problem with lots of airlines, airports and slots has to be analysed because computational limitations could make it unaffordable.

**Figure 13. Flow diagram of the centralised slot allocation process for the secondary allocation**
4.3 Summary of slot allocation mechanisms considered by ACCESS

Primary allocation

- Administrative approach
  - MILP formulation extending [40] and [41] (section 4.1.1)
- Market-based approach as a Combinatorial Auction
  - Agent-based approach (section 4.1.2)

All models for primary slot allocation consider a multi-airport (or simultaneous) allocation, the currently single-airport allocation just being a particular case.

Secondary trading

As a combinatorial exchange:

- Centralised
  - MILP formulation extending [45] (section 4.2.1)
- Decentralised
  - Agent-based approach (section 4.2.2)

All models for secondary trading consider a single market for trading slots, and not just bilateral trades as it happens today. The implementation of a single market can be easily extended to a multi-airport (or simultaneous) setting, the current trading of slots belonging to the same airport being a particular case.
5. Assessment criteria: performance framework

5.1 Required properties

There is abundant literature on the requirements to be met by a performance framework to properly achieve its intended functions. Ill-defined indicators can result in misinterpretations or inconsistencies, preventing a comprehensive comparison of policy alternatives. In the case of airport slot allocation, we consider that a performance framework should have the following properties:

- the framework should be comprehensive, i.e. encompass the full range of economic, social and environmental impacts of the slot allocation system;
- it should be target relevant, i.e. outcome indicators should be relevant to the target they intend to measure;
- it should be understandable to all stakeholders;
- outcome indicators should be independent of each other.

When using indicators for the ex-post evaluation of real-world situations, a fifth desirable property often cited in the literature is that indicators should be measurable based on available and reliable data. In what follows we will somewhat relax this constraint, on the assumption that simulation models allow the estimation of relevant indicators that are very difficult or impossible to be measured in practice, but are however of vital importance for properly accounting for the inherent uncertainty about the future in the ex-ante assessment of different policy options.

5.2 Performance framework for airport slot allocation mechanisms

A comprehensive evaluation of capacity allocation mechanisms requires an analysis of impact along several performance areas. The same performance area being often referred by several different names in the literature, here we aim at establishing a common understanding of a set of relevant concepts. We have tried to be as consistent as possible with the concepts and terminology used by the SES II Performance Scheme and the SESAR Performance Framework. Nevertheless we also include other dimensions that fall outside the scope of SES II and SESAR performance schemes, but are considered necessary for a sound and comprehensive impact assessment.

Taking account these guiding principles, we propose the categorisation of the impacts of capacity allocation mechanisms according to the following performance areas:

- Economic Efficiency;
- Equity and Distributional Issues;
- Access and Competition;
- Flexibility, Resilience and Adaptability;
- Interoperability;
- Capacity and Delay.

Different approaches are possible to identify and deal with potential trade-offs across KPAs/KPIs and facilitate eventual choice of preferred mechanism(s). The final decision involves addressing a multi-criteria decision problem: for such type of problem, there is not a unique optimal solution and it is necessary to use decision maker’s preferences. Multi-criteria decision methods can be used to weight the different performance targets and define one metric for aggregated performance. An example of such methods is Analytic Hierarchy Process (AHP), which evaluates the relative importance of the different KPAs/KPIs by pair wise comparisons and
converts these evaluations to numerical values (weights) that are then used to calculate a score for each alternative. Additional criteria can be established, such as setting a minimum level of required performance within each KPA.

Another possible approach is to carry out a Cost-Benefit Analysis (CBA). CBA calculates benefits net of policy costs for determining the improvement in society’s net well-being associated with a policy option. This requires that benefits of policy be calculated in monetary terms, making costs and benefits directly comparable, in order to translate the different KPIs into the same “measurement unit” (euros). Monetisation of impacts is however a challenging task and it involves some political choices (e.g. valuing inequality). It shall also be taken into account that benefits and costs may not be fairly distributed among stakeholders with conflicting objectives. Therefore, it is also important to carry out a distributional analysis to assess which stakeholders would receive the benefits and which segments bear the costs (see section 5.2.2 below).

5.2.1 Economic efficiency

Economic efficiency measures the ratio between the total social welfare created and the maximum welfare that could be created. Social welfare is the sum of consumer and producer surplus (i.e., the sum of the effects on airlines, airports and passengers) and net benefits to third parties (externalities). The property of maximising economic efficiency is often referred to as social optimality [46]. According to economic theory, maximum efficiency is achieved only if a good is produced by the lowest cost producers and the products are consumed by the consumers with the highest willingness-to-pay.

When regarding capacity as a limited resource, economic efficiency is arguably the most adequate measure to evaluate its efficient use. Slots would be efficiently allocated when used by those carriers able to generate the greatest social value. It seems therefore appropriate to use as outcome indicator the ratio between the total social welfare created and the maximum welfare that could be created.

The determination of the social value of a slot and thus the evaluation of economic efficiency is not an easy task. Economic efficiency includes all allocative and productive efficiencies, and finding the optimal trade-off poses a number of theoretical and practical challenges. Below we discuss several key dimensions that should be taken into account for a sound evaluation of economic efficiency, as well as possible intermediate indicators associated to these dimensions.

Allocative efficiency measures the capability of the strategy to allocate slots to those with the greatest willingness to pay. One of the main criticisms of the current system is that it does not allocate capacity in an efficient manner: since it makes no explicit consideration of the value that carriers attach to a slot, services may not be allocated to those with the greatest willingness to pay and therefore slots may be operated inefficiently by carriers who do not make the most efficient use of the capacity. It is generally accepted that market mechanisms, such as auctioning of slots or secondary trading, would improve allocative efficiency by bringing appropriate incentives so that the available scarce capacity is used by those airlines able to make best economic use of it [47], [48], [49], [50].

By buying tickets, customers would indicate their willingness to pay for the utility derived from a particular service [51]. Most literature on air transport economics argues that, given the sophisticated price discrimination strategies used by most airlines today, it is reasonable to take the value that an airline places on a slot as a proxy for consumer and producer surplus. In a situation of allocative efficiency, the prices paid for the tickets would be equal to the marginal costs. However, due to the network nature of the air transport system, the calculation of revenues collected from passengers can become very complex, e.g. a small aircraft feeder flight could use slots more efficiently than a charter flight with more passengers, but less total revenue once network effects are taken into account [47]. Assuming that airlines are able to correctly calculate the value of a slot, we can alternatively say that allocative efficiency is reached when the total shift costs (scheduled delay) is minimised.
Productive efficiency. On the other hand, market mechanisms increasing allocative efficiency could have an impact on productive efficiency that should not be underestimated. Productive efficiency shall account appropriate amounts for cost of capital and depreciation of assets, as well as the cost of maintenance, operation, management and administration. In the case of capacity allocation, different capacity allocation mechanisms may affect productive efficiency in several manners:

- **Cost of operating the system.** One of the arguments in favor of the current system is that it is relatively simple and inexpensive [52]. This is also one of the arguments against the use of auctions for primary slot allocation: even if economic theory indicates that auctions should be a more effective way of achieving allocative efficiency than other alternatives, there is considerable concern about the cost of designing and operating the system, due to the complexity created by the interdependencies between the value of different slots. For an auction system to allocate access rights efficiently, the simultaneous auctioning of slots at all slot-constrained airports is required, and carriers shall be able to submit package bids, which leads to a complex auction and therefore to the need for sophisticated software and bidding facilities, resulting in high costs on both auctioneers and bidders. Even if auctions were used to allocate slots, a secondary slot market would still be necessary to ensure that slot allocation remains efficient by dynamically reallocating slots to their highest valued uses. Secondary trading should be significantly easier and cheaper to operate, so many authors argue that the most effective measure for the efficient allocation of scarce capacity would be the extended use of secondary markets [48]. These authors argue that, as long as slots could be traded in a secondary market and in the absence of market imperfections, the initial allocation of slots should make no difference in terms of efficiency [49]. The initial allocation will nevertheless affect wealth distribution; equity and distributional issues are discussed in section 5.2.2.

- **Dynamic efficiency (cost of uncertainty).** Dynamic efficiency is concerned with the productive efficiency of a firm over a period of time. There may be a trade-off between static and dynamic efficiencies over different periods of time, and it is thus reasonable to argue that sacrificing efficiency in the short run is justified, for example, to reduce the cost of managing uncertainty in the long run. The argument of schedule continuity could be seen as a particular instance of this type of trade-off: incumbent carriers argue that grandfather rights maintain stability and continuity in scheduling, thus facilitating long term planning, operational stability and economic viability to airlines and airports; on the other hand, new entrants claim that grandfather rights deny them opportunities to enter the market, often leading to an inefficient use of capacity.

- **Cost of delay.** Another issue identified in the literature is that different slot allocation mechanisms may change not only the use of capacity at congested airports, but also lead to different route structures. Both factors may in turn affect delay distribution. We address delays more in detail within the section dedicated to Capacity and Delays, but we will point out here that a lot of modelling work remains to be done for a proper quantification of the cost of delay for airlines and passengers [46], [53].

**Externalities.** In the presence of externalities, the value of a slot for an airline will not be the same as the social value of a slot. Examples of externalities are the impact on environment or on the accessibility of European regions, which have been discussed e.g. in [47].

The ACCESS modelling and simulation work will focus on allocative efficiency. Dynamic efficiency and cost of delay, on the other hand, should in principle be embedded in the modelling of airlines’ objective functions when bidding for a (set of) slot(s). Concerning externalities, the impact on the accessibility of European regions will be evaluated at a very coarse level; modelling environmental impact would require coupling the ACCESS model should to an environmental performance model — this is also out the scope of the ACCESS modelling work, but in principle it should be unnecessary if proper mechanisms were in place for the internalisation of environmental costs.
5.2.2 Equity and distributional issues

The performance framework should not only address the total social welfare, but also the distributional impacts of different mechanisms, as they will alter how different stakeholders gain or lose.

Equity implies that all parties are treated equally by the system, independently from their identities and characteristics. Therefore it is intimately related with the distributional impacts of different mechanisms. For example, due to commercial and operational reasons, an airline will have an ideal pair of departure and arrival slots (ideal slots) for each of its flights. When this ideal pair is not available, the airline has to advance or delay its flight, which induces an undesired cost (shift cost) [40]. From the airline’s point of view, the main objective is the minimisation of its shift costs. A system-wide efficiency indicator instead may look for optimising the social welfare, which, in this case, could be approximated by the minimisation of the sum of the shift costs imposed to all flights. However, this minimum overall cost could be achieved at the expense of some individual airlines or flights that can be enormously more penalised than others, thus negatively affecting equity.

A proper outcome indicator for equity and distributional issues would be one stating whether each stakeholder gets a non-negative utility. The property of a mechanism such that each stakeholder is expected to get a non-negative utility is referred to in the literature as individual rationality [40]. To compute such indicator, it is in turn necessary to measure stakeholder-specific indicators which account for the utility per stakeholder (i.e. revenues minus costs per stakeholder), so that they can then be used to assess the fairness of a certain mechanism.

Assuming that a certain mechanism is individual rational, one can still pose the question of how evenly shift costs are distributed among airlines, as already discussed in section 4.1.1. A proper indicator to assess this is e.g. the ratio between the average shift cost per slot for each airline and the average total shift cost per slot, i.e. (Airline shift costs/No of Slots of Airline)/(Total shift costs/Total No of Slots)

While secondary trading should in theory improve equity, as both the seller and the buyer will only carry out a transaction if it increases their utility, this is not the case for other potential reforms, such as auctions. The opposition from certain stakeholders to these mechanisms can be understood from this perspective. Incumbent airlines, for example, oppose slot auctions because they would reduce the slot rents they are currently obtaining thanks to grandfather rights. Reference [41] introduces some monetary compensation mechanisms in the airport slot allocation process for redistributing among airlines the surplus deriving from the elimination of grandfather rights. Another example is the question of who receives the revenues in the case of slot auctioning; it has been suggested, for example, that they could be earmarked for airport expansion. Generally speaking, mechanisms that could in principle have the potential of increasing social welfare may raise distributional issues if they don’t include appropriate compensation mechanisms or certain constraints.

5.2.3 Access and competition

A competitive market environment should allow new airlines to challenge incumbents, efficient airlines to grow, and inefficient ones to exit, ensuring an equitable treatment for all airspace users, except where special considerations (e.g. significant overall safety or efficiency considerations, national defence, etc.) advise to establish priority on a different basis. Two main policy ingredients are generally recognised as necessary for a competition environment: first, market regulation should be set in a way that does not hamper competition [54]; second, anticompetitive behaviours that hinder the functioning of markets should be prohibited and punished within an effective antitrust framework, and mergers that may reduce competition should be blocked or at least remedied.

The issue of competition and access of new entrants is, together with that of economic efficiency (to which it is intimately and intricately linked), the other major criticism of the current system. In order to effectively compete with the dominant carrier at a given airport, a new entrant needs to build up a sustainable slot
portfolio. Under the current rules, airlines quickly fall outside the definition of new entrant, which obstructs the growth of efficient competition [12]. At the same time, there is little incentive for incumbents to release slots even if they cannot use them efficiently (slot hoarding or babysitting). Moreover, the slot pool is usually made of slots at less commercially attractive times than those assigned due to grandfathering. This aspect is also sometimes referred as competitive efficiency, i.e. the capability of promoting competition through the elimination of entry barriers to newcomers and discriminatory practices in favour of established carriers. It must also be pointed out that, even if the new entrant rule has not been overall extremely successful at promoting sustainable competition, it has made it possible for low cost airlines such as Ryanair and especially EasyJet to achieve significant growth at some congested airports. Schemes to provide equal opportunities to new entrants have been addressed in two recent studies. Reference [41] compares airlines’ costs when grandfather rights are either enforced or not. Reference [55] introduces five types of airport slot allocation strategies consisting of different combinations of grandfather rights, central coordination and free market and characterised by an increasing level of differentiation with respect to the current system.

The definition of suitable outcome indicators to measure competition is not a trivial task: there is a need for indicators able to grasp whether the output is being deliberately restrained below capacity, i.e. whether the airport slot allocation system prevents the entry of new competitors with a higher willingness-to-pay than those airlines operating the available slots. Institutions like the OECD have developed indicators that measure the institutional quality of product market regulation [56] and competition regimes [57]. In the air transport literature, one can find indicators like the ratio between the number of slots allocated to new entrants and the total number of allocated slots, or the level of slot concentration. Some authors argue that measuring slot concentration as an indicator of competition could be misleading, as it may happen that the maximisation of social welfare occurs for a high level of concentration of slots at certain airports and there is some evidence that concentration of slots may increase when slot trading is allowed, which could be due to the value of slots in a hub and spoke network, so that large carriers could have a higher willingness-to-pay [58]. Reference [59] argues that higher fares at slot constrained airports do not necessarily constitute a case for abuse of market power, and that other reasons may exist, such as the cost of providing for passenger connections and operating at a bigger airport. On the other hand, slot concentration naturally increases the risk of anticompetitive behaviours such as exclusionary conducts and mergers, which has sometimes led regulators to take measures to limit such concentration.

Other aspects related to access and competition, which should be taken into consideration, are discussed below.

**Access costs:** one could think that if a primary airport slot allocation based on auctions were established, it would be more difficult for small carriers with lower purchasing power to get slots at the busiest airports. That airport slot allocation in the current system is free of charge is sometimes seen as a positive feature from the point of view of competition, though it would not necessarily imply more economic efficiency.

**Public Service Obligations:** PSO is an arrangement to operate a specified service of public transport for a specified period of time for a given subsidy. Article 9 of Regulation EC 95/93 as amended in 2004 provides that slots may be reserved for PSO routes. This guarantees that services to regional communities are operated regularly even in those cases in which they are not profitable for airlines.

**Independence of the coordinator:** according to the Regulation the coordinator must be a qualified natural or legal person, acting in an independent, neutral, non-discriminatory and transparent manner. But the limits of this independence are sometimes vague and may not be clear at first sight.

**Transparency of slot information:** the transparency and adequacy of slot information provided by coordinators to the different stakeholders could be improved. According to [12], several airlines believe that they should receive more information on actual coordination parameters, local rules and sanctions systems, and most stakeholders believe that standardisation of online formats across coordinators would be beneficial.
Some airlines complain about the fact that, when slots become available, not all coordinators make this publicly known, which reduces the competition for these slots. The level of transparency may be characterised by means of a qualitative indicator, as a desirable feature from the point of view of institutional quality. Additionally, the question of what information is shared (and when) is a key design parameter for market mechanisms that will have an impact on the way the market develops.

The evaluation of aspects related to institutional quality, such as the independence of the coordinator or the transparency of slot information, is out of the scope of the ACCESS modelling work, which will be focused on simulating and detecting possible anti-competitive behaviours under different slot allocation mechanisms and scenarios.

### 5.2.4 Flexibility, resilience and adaptability

Flexibility, as defined by ICAO, addresses the ability of all airspace users to modify flight trajectories dynamically and adjust departure and arrival times to exploit operational opportunities as they occur. While the ICAO concept is restricted to operations at the tactical or flight execution stages, herein we will use flexibility in a wider sense, covering the ability to modify the trajectory at its different instantiations, from the strategic phase across the collaborative layered planning process, to the tactical phase. Flexibility will be thus understood as the ability provided by the system to modify the allocation and use of slots in order to cater for a changing environment. Flexibility can be analysed at different temporal and spatial scales.

**Flexibility of allocation:** ability of the system to modify the airport slot allocation to match airlines request. The current system provides some flexibility of allocation to both airlines and coordinators. After the initial allocation, each slot may be allocated as desired, rejected, or allocated but rescheduled. In the last two cases, negotiations can be carried out at the IATA conferences to find a proper solution and, if that is not possible, airlines can hand-back the unusable slots and possibly benefit from the slots returned by another airline. On the other hand, the rejection of the proposal of the coordinator involves no allocation of that slot in the next season, limiting the flexibility for airlines of being assigned in each season the slots they are interested in. Additionally, no mechanism is implemented to link dependent (origin-destination) requests. Airlines can use overbidding as a hedging strategy to mitigate the risk of not being allocated certain slots, e.g. the risk of not getting the relevant complementary slot(s) [51]. In summary, even though it provides some flexibility during the airport slot allocation phase, the current system tends to be reactionary rather than proactive. Different instruments have been suggested to improve this aspect of the system, from optimisation techniques to minimise the difference between requested and allocated slot time [55] and mechanisms for linking requests at dependent airports during the slot request process [40], [41], to the use of combinatorial auctions in conjunction with secondary trading. Defining a suitable outcome indicator to evaluate flexibility of allocation is again a non-trivial task. Such indicator should measure how close the resulting airport slot allocation is from that which would minimise shift costs, possibly under certain equity constraints. Intermediate indicators such as the percentage of slot requests rejected by the coordinator with respect to the total slot requests for a given level of capacity usage (i.e. for a given percentage of allocation of the declared capacity) can provide useful hints about the performance of the system in this respect, but should be carefully used as they don’t allow the extraction of direct conclusions about the flexibility of allocation provided by the system.

**Flexibility of use (in normal conditions):** the current system gives some flexibility for air carriers to adapt their offer to the actual demand. The 80-20 rule gives some margin to change the schedule once slots are allocated, allowing airlines to make certain decisions based on the commercial viability of individual flights, such as cancelling some flights on “cold” days (e.g. Christmas Day). On the other hand, some European airports have become so congested that some airlines are willing to pay other airlines to give up their slots, often for cash, but sometimes in exchange for other slots. According to [12], over 10% of the slots allocated in Europe in the 2008-2010 period were not used; unused slots are taken into account for the application of the 80-20 rule, but do not involve a fine or penalty to the carrier. Uncertain factors that may lead to late return include changes in
travel demand, traffic rights, availability of the right aircraft type for each particular route, or last minute problems [12]. Here again, secondary slot trading in a transparent market would arguably increase the flexibility of slot use. Regarding indicators, similar considerations to those previously made for flexibility of allocation can be made: a suitable outcome indicator should measure how close the resulting slot use is from that which would minimise shift costs. The level of slot mobility, measured as the number of exchanges/transfers accepted against the total number of exchange/transfers requests, can also be useful to evaluate the performance of the system in this dimension.

**Flexibility of adaptation to disturbances:** ability of the system to adapt the final airport slot allocation to temporal, force majeure circumstances. The concept is closely linked to that of resilience, which has received much attention during the past few years, and can be loosely defined as the ability of a system to absorb disturbances and then to re-organise so as to retain its basic structure and functions [60]. The allocation rules under the current system are not adaptable to special circumstances. When these have occurred, the regulator has made temporal amendments to the law, such the suspension of the 80-20 rule due to a decrease in air traffic demand in 2002, after the 11/9 terrorist attacks [61], in 2003 due to the Iraq war [62], or in 2009 as a consequence of the global economic crisis [63]. It is expected that under a more liberalised framework (e.g. auctions, secondary trading), the market would be able to self-adapt to these circumstances. Resilience indicators could be a particular instance of flexibility of use indicators in the case of disruptive events.

**Flexibility of adaptation to local geographical conditions:** ability to adapt to specific local needs. The current system leaves some space for local rules, especially regarding the definition of coordination parameters, the acceptance of a secondary market and the imposition of PSOs according to local needs. In principle, the reforms under consideration, in particular the introduction of market-based mechanisms, would still be compatible with providing for this type of flexibility at local level.

Flexibility, resilience and adaptability can therefore be seen as a “metaperformance area”, which measures the ability (performance) of the system to retain its performance vis-à-vis changing conditions. ACCESS will evaluate the flexibility of different slot allocation mechanisms by simulating the performance of the system under different scenarios (e.g. drops in demand due disturbances) and measuring the economic efficiency, equity, and a competition indicators described in the previous sections. Flexibility, resilience and adaptability will be provided as a (set of) ratio(s) between the performance achieved through each slot allocation mechanism and the maximum attainable performance in a set of reference scenarios.

### 5.2.5 Interoperability

It is generally accepted that the air navigation system should be based on global standards and uniform principles to ensure technical and operational interoperability and facilitate homogeneous and non-discriminatory global and regional traffic flows. As far as airport slot allocation mechanisms are concerned, two dimensions are considered particularly relevant:

**Interoperability of airport slot allocation systems:** the European slot allocation system is based on IATA Guidelines, which have an international scope and are used almost all around the world except for the US. Each country or airport may add local rules, but the principle is the same. This homogenisation eases planning for carriers that operate flights between Europe and other territories where IATA Guidelines apply. This is one of the arguments used by legacy carriers against the modification of the airport slot allocation system. This performance aspect could be qualitatively expressed as the level of commonality/compatibility with the IATA guidelines.

**Interoperability of flight information:** currently there is a lack of consistency between slots and flight plans. Flight plans are validated by the Network Manager (the NMOC), whereas airport slots are assigned by the coordinator of that airport. Historically there has been very little information sharing, if any, between these organisations, and airlines have often operated their flights according to a flight plan with departure and/or
arrival time differing notably from the slots schedule. According to the Single European Sky principle of adopting a gate-to-gate perspective, airports need to be integrated into network planning. A common network planning, with slot assignment information available would increase the consistency between slot times and flight plans. This issue is addressed in [64], which aims to integrate slot allocation with the reform of the European ATM system (Single European Sky) by associating the European Network Manager with the slot allocation process, and advocates the improvement of the information flow between slot coordinators, airports, airlines, national authorities and organisations providing air traffic control, in order to inform decisions on airport coordination. The SESAR Concept of Operations, which is expected to bring a radical change in the way operations are conducted, may have an impact on the way slot allocations are conducted in the future. The problem is tackled by the Operation Improvement OI DCB-0301 in the SESAR Master Plan [65]. SESAR Step 2 includes the integration of Airport Operations Plan (AOP) into the Network Operation Plan (NOP), with airport slots being managed dynamically by new processes, using access to current and accurate information and enabling greater timing precision. A suitable indicator to measure the level of interoperability of flight information could be the difference between slot times and take-off and arrival times in flight plans.

5.2.6 Capacity and delay

To respond to future growth, along with corresponding increases in other performance areas, capacity must increase. The design of the airport slot allocation system may influence capacity and delays in several respects, which we briefly discuss below.

**Capacity specification:** while the question of whether airport slot allocation mechanisms are efficient has been the subject of different research efforts, less attention has been paid to the previous step, i.e. the optimal choice of the number of slots at a given airport or, in other words, what level of scheduled flight demand, in the presence of different sources of uncertainty, provides the right trade-off between the costs of additional delays (and possibly, environmental costs) and the benefits from additional throughput. The current practice has been criticised based on a number of arguments, such as the ample room for local interpretation or the empirical ad-hoc processes often applied. Some studies on the topic, mainly related to the US, are illustrated in [2].

**Incentives for capacity expansion:** another aspect that shall be taken into account in relation to capacity is the ability of a certain airport slot allocation system to create the right incentives for investment. Increases in airport capacity devalue slots. Some authors argue that auctions or congestion pricing could create perverse incentives for airports to underinvest in new capacity if they make profits from pricing or auctioning of scarce capacity [28]. On the other hand, it is also reasonable to argue that, with the current system, incumbent airlines that have very valuable slots at busy airports have an incentive to moderate their requests for capacity expansion [50].

**Delay:** with respect to a congestion-based, first-come first-served system like the one adopted in almost all US airports, a slot system not only reduces congestion through reduced throughput, but it also reduces congestion at any level of throughput by means of a more ordered, less random traffic. Additionally, the reform of the airport slot allocation system, e.g. through the introduction of market mechanisms, may lead to changes in airlines’ route structures [47], which may in turn modify the level and distribution of delay. To model (even if in a very crude manner) incentives for capacity expansion, the horizon of the simulation should be extended to several years, while the modelling of the level and distribution of delays resulting from a particular slot allocation would require coupling the ACCESS model to a traffic model simulating up to the day of operation. The issue of capacity specification is out of the scope of the ACCESS project.
5.3 Summary table

The following table summarises the performance areas and indicators discussed in the previous section. The indicators that will be addressed by the ACCESS modelling work (or by extending the ACCESS modelling work with other models) are highlighted in bold font.

<table>
<thead>
<tr>
<th>Performance area</th>
<th>Outcome indicators</th>
<th>Type</th>
<th>Intermediate indicators</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic Efficiency</td>
<td>Social welfare = consumer and producer surplus (sum of the effects on airlines, airports and passengers) + net benefits to third parties (externalities)</td>
<td>Quantitative Global System-wide</td>
<td>Allocative efficiency</td>
<td>Price equal to marginal cost</td>
</tr>
<tr>
<td></td>
<td>Economic efficiency = Total social welfare created / Maximum attainable social welfare = Allocative efficiency + Productive efficiency</td>
<td></td>
<td>Total shift costs (scheduled delay)</td>
<td>Quantitative Global System-wide</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Productive efficiency</td>
<td>Quantitative Global System-wide</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dynamic efficiency (Cost of uncertainty)</td>
<td>Quantitative Global System-wide</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cost of delay</td>
<td>Quantitative Global System-wide</td>
</tr>
<tr>
<td>Externalities</td>
<td>Individual rationality = All stakeholders get a non-negative utility-</td>
<td>Qualitative (Yes / No) Global System-wide</td>
<td>Utility per stakeholder = (Benefit - Cost) per stakeholder (airlines, airports, passengers)</td>
<td>Quantitative Global Stakeholder-specific</td>
</tr>
<tr>
<td></td>
<td>(Airline Shift Costs / No of Slots of Airline) / (Total Shift Costs / Total No of Slots)</td>
<td></td>
<td>Consensus among stakeholders</td>
<td>Qualitative (e.g. High / Medium / Low) Global System-wide</td>
</tr>
<tr>
<td>Equity and Distributional Issues</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
## Market-Based Mechanisms for Airport Slot Allocation: Formalisation and Assessment Criteria

<table>
<thead>
<tr>
<th>Performance area</th>
<th>Outcome indicators</th>
<th>Type</th>
<th>Intermediate indicators</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access and Competition</td>
<td>Ability to discover, stop and punish anticompetitive behaviours</td>
<td>Qualitative</td>
<td>Concentration of slots</td>
<td>Quantitative</td>
</tr>
<tr>
<td></td>
<td>Independence of the coordinators</td>
<td>Qualitative</td>
<td>No slots allocated to new entrants / Total number of allocated slots</td>
<td>Quantitative</td>
</tr>
<tr>
<td></td>
<td>Transparency of information</td>
<td>Qualitative</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Flexibility / Resilience / Adaptability</td>
<td>Flexibility of allocation</td>
<td>Qualitative</td>
<td>No of slots requests accepted / No of slot requests</td>
<td>Quantitative</td>
</tr>
<tr>
<td></td>
<td>Flexibility of use (in normal conditions) = Ability to achieve economic efficiency, equity and competition in normal operating conditions</td>
<td>Qualitative</td>
<td>No of slots exchanges/transfers accepted / No of slot exchanges/transfers requested</td>
<td>Quantitative</td>
</tr>
<tr>
<td></td>
<td>Flexibility of adaptation to disturbances (resilience) = Ability to achieve economic efficiency, equity and competition under external disturbances</td>
<td>Qualitative</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Flexibility of adaptation to local geographical conditions: compatibility with particular rules at local level</td>
<td>Qualitative</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Interoperability</td>
<td>Harmonisation at worldwide level - Level of commonality/compatibility with the IATA guidelines</td>
<td>Qualitative</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Consistency with flight plans - Difference between slot times and take-off/arrival times in flight plans</td>
<td>Quantitative</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
### Table 8. Performance framework – Summary table

<table>
<thead>
<tr>
<th>Performance area</th>
<th>Outcome indicators</th>
<th>Type</th>
<th>Intermediate indicators</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity and Delay</td>
<td><strong>Airport capacity</strong></td>
<td>Quantitative</td>
<td></td>
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</tr>
<tr>
<td></td>
<td><strong>Delay indicators: average number of delayed flights, average delay per flight, cost of delay, etc.</strong></td>
<td>Quantitative</td>
<td></td>
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<td>Global / Local System-wide</td>
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6. Conclusions

This document describes the stakeholders participating in the slot allocation process, the methods and approaches that will be further modelled by the ACCESS project, and the performance framework to be used for an effective comparison of advantages and drawbacks of current and proposed mechanisms.

The stakeholders involved in airport slot allocation can be classified into five groups: regulators, airport coordinators, airspace users, airport operators, and end users (passengers). Each of these stakeholders plays a role in the system and has its own interests and strategies, which need to be taken into account for the design of the slot allocation system. Airports’ objectives and attitude towards slot allocation may vary depending on the airport business model (single till vs dual till), the airport ownership (privately owned vs publicly owned), or the airport management unit (e.g. for companies managing more than one airport at a time, the company strategy will be to maximise the benefits from a global unit formed by all airports within the system). The interests and strategies of airspace users are strongly dependent on factors such as the airlines route structure, scheduling strategies, airport network or pricing policies, which are in turn conditioned by the airline business model (network carriers, low cost carriers, charter operators). The attitude of individual airlines may also be influenced by airline alliances, whose strategy often prevails over individual interests; airlines’ attitude modification due to alliances may sometimes be subject to anti-trust considerations. Finally, there are not only horizontal alliances between airlines (airline alliances) or airports (being part of the same management unit), but also vertical alliances involving an airline and an airport. This is mainly the case of hub airports, where a major airline commits to exploit the airport infrastructure as much as possible and the airport provides the airline with special dedicated services. Collaboration goes from joint airline-airport marketing to investments in new airport infrastructure. This type of alliances cannot really help airlines in terms of slot allocation, due to the current administrative mechanism, but is rather a consequence of an airline’s dominance at an airport due to grandfather rights. However, airline-airport alliances may be of much importance when applying other mechanisms for slot allocation as their behaviour may vary due to a joint strategy.

Slot allocation process consists of primary and secondary slot allocation. The primary allocation is currently performed in accordance with a set of administrative rules, while market-based mechanisms have been proposed but not yet adopted nor implemented. On the contrary, the secondary allocation relies only on trading mechanisms and no administrative rules to govern it have been envisaged so far. In this context, the ACCESS project proposes a single and multi-airport approach to implement and solve the primary slot allocation as well as different design of the current secondary trading. All models for primary and secondary slot allocation consider a multi-airport (or simultaneous) allocation, the current single-airport allocation being a particular case of the former.

The ACCESS project will model, simulate and compare different slot allocation mechanisms: we will first model the current administrative approach to primary slot allocation, and will investigate how it can be improved through a mathematical optimisation approach. This approach will be compared to a market approach based on auctions. As for secondary allocation, we will consider a single market for slot trading, formulated as a centralised combinatorial exchange and modelled as a mixed integer linear programming problem. This formulation allows the exact identification of the optimal solution, but may become unpractical to solve when the size of the instances significantly grows. For this reason, ACCESS also proposes a decentralised agent-based approach that allows tackling large sets of data, as the single market approach over the whole Europe would likely require.

Auctions are a decentralised market mechanism that can be applied to solve the slot allocation problem for several airports at the same time, both for a primary or a secondary slot allocation. The auctions split the complexity of the problem’s logic, so it is spread among the different actors involved (airlines, airports, and coordinator). Several types of iterative price-setting auctions (ascending, descending, Walrasian and adaptive)
will be modelled and simulated, one of their advantages being that they provide a value (the price paid) for each slot at the end of the auction process. Despite the facts that depending on the market situation the solutions achieved can be sub-optimal, these solutions can be applied in complex situations with a large number of actors where other centralised methods may not be computationally feasible.

Auctions are not an exclusive mechanism, and they can be combined with other centralised approaches (i.e., auctioning only part of an airport’s capacity, while keeping other centralised mechanisms for the rest). It is possible to compare the results of an auction process with other centralised approaches, as long as the case studies have a common definition and rules, which is the goal ACCESS is setting for the future modelling efforts.

To summarise, ACCESS will model the following approaches:

**Primary allocation**

- Administrative approach
  - MILP formulation extending [40] and [41]
- Market-based approach as a Combinatorial Auction
  - Agent-based approach

All models for primary slot allocation consider a multi-airport (or simultaneous) allocation, the currently single-airport allocation just being a particular case.

**Secondary trading**

- Centralised
  - MILP formulation extending [45]
- Decentralised
  - Agent-based approach

Finally, we have introduced some considerations about the conditions to be met by a performance framework to allow a sound comparative evaluation of different slot allocation mechanisms, and we have proposed a set of performance areas and indicators. Administrative slot allocation has its drawbacks and advantages: the process is simple and predictable, and is implemented throughout the world in one form or the other; on the other hand, different studies conclude that administrative slot controls lead to inefficiencies and, despite the provisions for new entrants, often prevent competition by creating barriers to entry. Market mechanisms are expected to provide the right incentives for a more efficient use of the available capacity, but they also raise a number of concerns, from the potentially negative impact on airline operating costs to market failures. There is therefore a need for a comprehensive assessment of different market designs. We propose a comprehensive performance framework encompassing six performance areas: economic efficiency; equity and distributional aspects; access and competition; flexibility; resilience and adaptability; interoperability; capacity and delay.
Annex I. References


