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**A supervised market mechanism for
efficient airport slot allocation**

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Abstract

We provide a general procedure to deal with the airport slot allocation problem, which applies the principles underlying the Administered Incentive Pricing model for regulation of radio spectrum in electronic communications markets. In particular, we propose an incentive pricing mechanism that generates an efficient slot allocation, where prices are built on a measure of the best use of each slot in serving end users. Incentive prices are set by considering the structure of the air transport network (and thus interdependencies among slots at different airports) in a given region, and the effect on both quantity and quality of passenger air transport in the region. Therefore, incentive prices should better align private and social decisions over the use of slots compared with pure market mechanisms (auctions and trading).

Keywords: Airport slot allocation; Congestion; Administered incentive pricing; Market mechanisms

1 Introduction

In the last decades, airlines and passengers have been suffering from growing congestion at busy airports, and airport delays have become a major public policy issue. Large traffic volumes at peak travel periods relative to airport capacity are the major cause. Due to financial and environmental constraints to airport capacity expansion, airport slots have generally been recognized as a scarce resource. As stated in the March 2011 White Paper on transport of the European Commission (EC, 2011a), which is part of Europe 2020 Strategy, it is thus essential to pursue the optimal allocation and use of airport slots to foster competition and improve quality of air transport services.

In this paper, we focus on airport slot allocation and provide an incentive pricing mechanism to effectively manage scarce capacity. Slot allocation in the European Union (EU) is currently governed by the Slot Allocation Regulation (EC Regulation No. 95/93, as amended by Regulation No. 793/2004; see EC, 1993, 2004), which complies with the guidelines of the International Air Transport Association (IATA, 2013). Such regulation defines the rules that are mandatory for coordinated airports, namely, airports where slots are essential for using infrastructures.[1]

The granting of a slot at a coordinated airport means the airline may use the full range of infrastructure services necessary for operating a flight at a given time. To provide a slot, an airport should combine several airside and groundside elementary services. Airside services mainly relate to traffic control, meteorological services and the provision of airside facilities, such as apron, taxiway and runway. Groundside services relate to processing passengers (check-in, loading or unloading) and providing groundside facilities (aircraft parking, terminal gates and loading bays).

Although there are no property rights (in the sense that neither the airport nor the government, or the air carrier owns slots), there are *grandfather rights* in using airport slots. Thus, if an air carrier has used a series of slots for at least 80% of the time during a season, it will be entitled to use the same series of slots in the next corresponding season, otherwise slots become free. All free slots are grouped in a pool. Half of these available slots are allocated to new entrants, that is, carriers which own at this airport and on that specific

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[1] A coordinated airport is any airport where, in order to land or take off, an air carrier or any other aircraft operator should have been allocated a slot by a coordinator (except for State flights, emergency landings and humanitarian flights). Currently, there are 89 fully coordinated airports in countries where the Slot Allocation Regulation applies (the European Economic Area plus Switzerland), of which 62 are coordinated year-round and 27 are coordinated seasonally.

time period less than five slots altogether (*new entrant rule*). The remaining slots are allocated non-discriminatorily (EC, 1993, 2004).

A major drawback of this slot allocation mechanism is that the outcome can be very far from ensuring economic efficiency. Even the use-it-or-lose-it rule may have the effect of inducing airlines to use slots inefficiently, with carriers being reluctant to cede sub-optimally employed slots for fear of a competitor's entry (see e.g. Dempsey, 2001; Sieg, 2010; Starkie, 1998).

At congested airports, slots are valuable because they are scarce economic resources. It follows that market mechanisms, such as auctions and trading, may be efficient ways to allocate slots and ensure efficiency in their use, since the value of slots stems from market interaction (De Wit and Burghouwt, 2008; DotEcon Ltd, 2001, 2006; NERA, 2004; Whalen et al., 2007). Thus, the EC has envisaged introducing some changes to current regulation to enforce market mechanisms for slot allocation and use (EC, 2011b). Such mechanisms should provide airlines with suitable incentives, so that the available capacity is used by those being able to make the best economic use of it.

At one extreme, market mechanisms would imply withdrawing and auctioning historical slots. Auctions ensure that slots are assigned to carriers with the highest willingness to pay, which are prospectively the ones that will be able to generate the highest value from managing the asset. The implication is that, by assigning valuable slots through auctions, the airport authority might collect significant amounts of money. Nonetheless, these are not necessarily good news for society insofar as high private carriers' valuations for slots do not reflect the social value of slots. Despite the idea of auctioning off airport slots has been widely discussed (Brueckner, 2009; Button, 2008; Fukui, 2010; Grether et al., 1981; Rassenti et al., 1982; Verhoef, 2010), it seems far from being actually implemented, either inside or outside the EU.[2]

On the other hand, the Commission advocates secondary trading of slots between airlines at EU airports (EC, 2004). The 2008 interpretative Communication (EC, 2008) clarified certain points to increase the

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[2] In 2008, the US Federal Aviation Administration (FAA) initiated a proposal to auction off 10% of the slots at New York City's three major airports. This proposal was met with criticism from airlines and IATA as well as with legal challenges from the US Air Transport Association and port authorities. In 2009, the Obama Administration rescinded the plans for slot auctions after the US Court of Appeals stayed the proposal in December 2008 (IATA, 2010).

efficient use of the available capacity, including recourse to monetary exchanges of slots. As the Commission states, such trading of airport slots has already been in place in the UK.[3]

Trading shall enable the rights owners to resell the (rights of using) slots to other carriers, who may decide to employ the slots to serve different end users from that for which slots have been originally employed. Trading introduces flexibility in the management of slots, thereby impeding that such valuable resources remain assigned to inefficient uses.[4] Similar to auctions, as a result of trading slots may eventually be in the hands of those agents that plan to extract the highest value from them. However, there is the risk that dominant carriers have the ability to collect the majority of key slots, thereby foreclosing entrants. Furthermore, since exchanges of slots are the result of bilateral negotiations between carriers, secondary trading of slots might even amplify the divergence between private and social values of slots relative to auctions.

Pure market mechanisms for assigning slots at any airport may also yield inefficient outcomes since they cannot fully internalize the interdependence between slots at different airports. Indeed, for each flight an airline needs a feasible combination of slots at the origin and destination airports.[5]

Given the possibility of market failures (including the need for mitigating lack of coordination over using scarce resources), in this paper we define a supervised market mechanism to set out efficient prices for airport slots.[6] Such prices should provide long term signals to induce end users and carriers to take efficient decisions concerning the use of slots. For this purpose, these prices have to consider the interdependence between slots. Indeed, since any slot reserved for a route is subtracted to other possible routes, and thus to

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[3] In the UK, within the Guernsey Case in 1999, slot exchanges with monetary side payments were judged lawful by the English High Court, setting a precedent for further cases of slot trading at UK airports (DotEcon, 2001). In March 2008, Continental Airlines paid $ 209 million (about € 143 million) for four pairs of slots at London Heathrow (EC, 2011b).

[4] Madas and Zografos (2006) discuss a number of mixed strategies for slot allocation that embody various forms of decentralized auctions, centralized trading, and secondary trading.

[5] In principle, specific auction formats may consider the interdependence between slots, thereby allowing airlines to bid for packages of slots (Rassenti et al., 1982). Nonetheless, these formats suffer from severe implementation problems.

[6] Interestingly, Castelli et al. (2012) propose a slot allocation mechanism that simultaneously allocates slots at several airports considering the structure of the network and the airlines' requests in terms of origin-destination pairs. They also introduce the possibility to fairly redistribute the system disutility (i.e. the sum of the costs of individual airlines due to the imbalance between demand and capacity at airports) among airlines through monetary compensations.

other possible end users, then the incentive price of the slot should reflect an estimate of the marginal value of the slot to end users.

In particular, we derive an estimate of the marginal value of any specific slot by assessing the downgrade in the provision of the air transport service, both in terms of quantity (i.e. number of transported passengers) and quality (i.e. passenger travel times), should access to that slot be denied. Indeed, this reflects into the loss of utility which end users have to bear in the case where the slot gets unavailable (having the total costs of providing all other slots remained basically unchanged). Then, we set an incentive price for each slot that reflects an estimate of the marginal value of the slot, while preserving recovery of total costs of supplying all slots in the network. Such prices should be periodically updated to consider possible changes in the use of scarce resources.

The proposed mechanism relies on the principles of Administered Incentive Pricing (AIP), which has been adopted in electronic communications markets for spectrum use (see e.g. Ofcom, 2010). The AIP methodology leads to regulated charges to spectrum rights owners that reflect the opportunity cost of the spectrum, thereby promoting an efficient use of that scarce resource.

This paper is organized as follows. Section 2 introduces the AIP model and discusses how the underlying principles can be applied to airport slot allocation. Sections 3, 4 and 5 illustrate the different steps of the proposed procedure to determine incentive prices for slots. Finally, Section 6 provides some concluding remarks and perspectives on future work.

2   Incentive pricing for airport slots

It is widely recognized that market mechanisms, such as auctions and trading, are the most efficient way to allocate scarce economic resources and ensure efficiency in their use. As such, market mechanisms are claimed to achieve a better economic performance relative to alternative methods that have been historically employed to assign valuable resources, which consisted in 'Command & Control' centralized procedures that mainly pursued technical efficiency and service assurance.

For our purposes, it is worth considering for the moment electronic communications markets. In these markets, there are several examples of successful implementation of market mechanisms for spectrum assignment. Nonetheless, market mechanisms cannot be decisive in all circumstances. Indeed, some portions

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of the spectrum (such as those for defense, aviation, maritime services, or radio services) are not traded because of technical legacies, service coordination problems, and safety or security issues that are in charge of generating inefficient allocations (Cave et al., 2007).

In case of market failures, regulatory intervention in view of promoting an efficient use of the spectrum is warranted. In this framework, a number of regulatory authorities all over the world have suitably introduced spectrum fees, based on the so-called AIP methodology, which are aimed at reflecting the underlying marginal value of the spectrum (Cambini and Garelli, 2011).[7] Thus, incentive prices reflect the opportunity cost for the use of the spectrum, which is related to how the interchangeability of a complementary production resource varies in response to a change in the use of a marginal portion of spectrum.[8]

The AIP model operates by taking a unitary view of all the considered networks. In this sense, if any scarce resource (e.g. radio spectrum) is dedicated to providing a specific network service to end users, and not a different one, then this allocation must be suitably priced to take account of which alternative uses of the resource have been prevented. Incentive prices are periodically adjusted to consider changes in the use of the priced resources. For instance, these changes may be related to investing in a technology that uses the scarce resource more efficiently, to a shift of demand towards less congested resources, or to substituting priced resources with other production inputs.

The AIP methodology must be applied to spectrum that is currently, or expected in the near future to be in excess demand for existing and/or feasible alternative uses. AIP provides rights owners with adequate incentives to dispose of sub-optimally employed inputs. Thus, the AIP model is an effective tool to rationalize spectrum use. If the incentive price for a specific portion of spectrum is excessive, then the rights holder may conveniently release frequencies and give them back to the government or the national authority. Released frequencies are then reallocated to a different agent with a higher willingness to pay, who presumes to be able to use those frequencies more efficiently.

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[7] The AIP model was first introduced in the UK with the Wireless Telegraphy Act in 1998. Currently, it is estimated that implementing AIP generates yearly revenues to the UK government that are about equal to 185 million euro.

[8] Different assessments of the marginal value of radio spectrum have been proposed. For instance, yearly incentive prices can be set by measuring the reduction in network costs after assigning additional spectrum, or measuring the additional network costs of moving to a higher uncongested frequency band.

Ofcom (2009), the industry regulatory authority in the UK, has clarified that the AIP model well contributes to pursuing the optimal spectrum use, and is especially effective in the following cases:

- where potential excess demand for alternative uses of spectrum is significant, but secondary market trading mechanisms are not yet sufficiently mature to secure efficient reallocation;

- where the nature of the current use of spectrum requires the coordination of multiple users sharing frequencies, and the costs that would arise if multiple parties attempted to trade with each other directly would be prohibitive;

- where sunk costs and/or regulatory restrictions on the alternative use of the band mean that changes of use are constrained and so, in the medium term, efficiency gains are limited.

In this sense, the AIP model suitably complements market mechanisms for spectrum allocation.

Ofcom (2010) also argues that spectrum markets are still immature, with limited liquidity and without powerful market institutions. Thus, AIP may have a significant role in promoting efficiency in some markets where liberalization and trading are not effective enough, and in introducing complementary incentives in those markets where liberalization and trading do work. Note that incentive prices could also be used to determine reservation prices for spectrum auctions.

Although AIP has been proposed in the electronic communications markets, it is based on general principles that can be effectively applied to any network industry, and in particular to air transport. Indeed, the provision of any network-based service requires three distinct phases: origination phase (e.g. call generation in telecommunications, boarding and take-off in air transport), transmission phase (respectively, transport of data packages, flights), termination phase (respectively, call termination, landing and disembarking). Usually, distinct complementary resources are dynamically and continuously combined in each phase to provide the service to end users. However, provided that any resource is scarce (respectively, radio spectrum, airport slots), some effective combinations can be prevented since the allocation of scarce resources is fragmented among different operators with conflicting interests.[9] Applying AIP aims at mitigating this lack of coordination over the use of scarce resources by identifying (and applying as an allocation driver) the value which any scarce resource has for society (i.e. the social value of the resource).

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[9] For instance, mobile broadband access could be denied due to congestion of the radio spectrum available to the relevant mobile network, while a similar portion of spectrum, which has been reserved for the termination of a broadcasting television service in the same area, could be rarely used.

Evidence shows that five large airports in the EU are currently operating at full capacity (Düsseldorf, Frankfurt, London Gatwick, London Heathrow, Milan Linate), and their number is expected to grow at nineteen by 2030 (including e.g. Paris CDG). According to Eurocontrol, even considering currently planned infrastructure investments, as much as 12% of the demand for air transport will not be met in 2035 due to a shortage of airport capacity (Eurocontrol, 2013).

Since airport slots are affected by growing scarcity then defining incentive prices that reflect their social value, and requiring carriers to pay out such prices to airports to use the supplied slots, could be an efficient way to tackle the problem of slot scarcity.

To determine incentive prices for slots, we have to estimate the marginal value of slots. Different from radio spectrum, which can be sought-after by different networks, airport slots can be used only for providing air transport. Thus, the only costs which have to be considered are those underlying the provisioning of the air transport service. Therefore, the marginal value of a slot cannot be found by comparing the impact of the scarce resource allocation on the costs of alternative networks.[10] However, since any slot applied to serve a route is subtracted to other possible routes, and thus to other possible end users, the marginal value of the slot can be estimated through the best marginal contribution of the slot in the provision of the service to end users, both in terms of quantity (i.e. number of transported passengers) and quality (i.e. passenger travel times).

Hence, to assess the marginal value of a slot, first we consider the structure of the air transport network (and thereby interdependence among slots at different airports) in the selected region, and define any alternative use of the slot inside the network. Then, we choose a metric to measure the level of service, and determine how much a given slot can contribute to improve the service provided to end users in the network (i.e., the best marginal contribution of the slot to the level of service). Finally, we find the incentive price of any slot by allocating the total cost for supplying all slots in the network on the basis of the marginal contribution of the slot to the level of service.

In the following three sections, we discuss in detail each of the above steps.

3   Alternative uses of airport slots

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[10] Moreover, since in most cases airport capacity expansion is impracticable, we cannot figure out to invest in new infrastructures to study the incremental effect of new slots.

Let us consider the structure of the air transport network (and thereby interdependence among slots at different airports). Then, all alternative uses of any slot depend on those paths which connect a source with a destination by using that slot and which can actually be taken into account to serve the demand.[11] The first step consists of identifying the set of all paths which can link any pair of airports. To do this, let us introduce a bit of notation. Let A be the set of airports. Let $l_{a,b}^{max} \geq l_{a,b}^{min} > 0$ be the maximum and minimum times which on average a non-stop flight (i.e. with no intermediate stop) can take from a to b for any $a, b \in A$ with $a \neq b$. Let also $l_{a,a} > 0$ be the minimum time which an end user has to spend in a between the landing and the take-off of connecting flights. We denote a time band b by $[st_b ; en_b]$, where st_b is the starting minute (or on-block time) and en_b the ending minute (or off-block time) of b; given time band b, $st(b)$ and $en(b)$ returns, respectively, the starting and ending minute of b. For any given period (e.g. a week, a semester, an year), let B be the set of time bands which this period is partitioned into (e.g. $B = \{..., b_i = [day\ x, 08.01; day\ x, 08.30], b_{i+1} = [day\ x, 08.31; day\ x, 09.00], ..., b_{i+k} = [day\ x + y, 10.01; day\ x + y, 10.30], ...\}$).

An airport slot is the right to use the full range of the infrastructures of a given airport in a specific time band. Thus, we model any slot as a time band of B associated with a specific airport (thus any slot identifies a specific time band).[12] We will refer to an origination slot (take-off slot) and a termination slot (landing slot) as the airport slots which are involved during the origination and termination phase, respectively. Therefore, an origination slot represents the time band reserved by a specific carrier to use the suitable airport infrastructures to perform take-off and all the complementary required activities (such as, for instance,

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[11] In the network analysis literature, Freeman (1977, 1979) provided a formulation of the well-known betweenness centrality of a node of a network (in our case the nodes would be the slots), which is based on the assumption that shortest paths are the drivers to measure the centrality of a node, since the elements of a network are most efficiently used when the content of the linkages (e.g. traffic, information) follows shortest paths. Stephenson and Zelan (1989) relaxed the assumption that the content of the linkages has to spread exclusively along shortest paths. Following Stephenson and Zelan, we assume that specific paths (and not necessarily the shortest ones) can play a role in the provision of the air transport service.

[12] In principle, depending on the efficiency and the structural characteristics of an airport, different time bands for distinct airports could be considered to partition the selected period. However, with no loss of generality, to simplify the illustration we model each slot of any $a \in A$ as a time band of B (obviously, slot times are based on the planned starting and ending times, while actual times of arrival and departure can vary depending on several operational factors).

passenger and luggage boarding, fuel charging, catering boarding). A termination slot is the right of using at a specific time band the airport infrastructures necessary to carry out landing and all the complementary operations (such as, for example, air parking, passenger and baggage disembarkation, luggage delivery to passengers).

Let $\bar{O}_a$ and $\bar{T}_a$ be the set of origination and termination slots, respectively, which are available at airport $a \in A$ in the considered period. Sets $\bar{O}_a$ and $\bar{T}_a$ may contain multiple slots, that is, distinct slots which refer to the same time band (it depends on airport infrastructures, such as, for instance, the available number of runways). Given a slot $i \in \left(\bigcup_{a \in A} \bar{O}_a\right) \cup \left(\bigcup_{a \in A} \bar{T}_a\right)$, $a(i)$ returns the airport that provides slot i.

Let now O_a (T_a) be the set of origination (termination) slots of airport $a \in A$ derived from $\bar{O}_a$ $(\bar{T}_a)$ by removing, for any family of multiple slots in $\bar{O}_a$ $(\bar{T}_a)$, all but one of these identical slots. Let also $S = \left(\bigcup_{a \in A} O_a\right) \cup \left(\bigcup_{a \in A} T_a\right)$. With a slight abuse of notation, in the following we will refer to a slot $i \in S$ either as a single slot, or as a *multiple slot* in the case where $a(i)$ provides two or more identical slots with time band i. In particular, given any slot $i \in S$, let $no_i \geq 1$ $(nt_i \geq 1)$ be the number of origination (termination) slots with time band i provided by airport $a(i)$, that is, the number of flights that can be originated (terminated) in $a(i)$ during i, in the absence of unexpected hitches or contingencies.

We define a *path p* (or a *travel*) as an ordered sequence $(u, \dots, v)$ of slots of S such that the following conditions hold:

1) The first slot u (or *head* slot) is an origination slot.

2) The last slot v (or *tail* slot) is a termination slot.

3) Any origination slot i of p is followed by a termination slot j where $a(i) \neq a(j)$ and $l^{min}_{a(i),a(j)} \leq st(j) - en(i) \leq l^{max}_{a(i),a(j)}$ (i.e. i and j are supplied by different airports and the interval between the take-off in i and the landing in j is sufficiently large, but not too much).

4) Any termination slot j of p (different from the last one) is followed by an origination slot i where $a(j) = a(i)$ and $l_{a(j),a(i)} \leq st(i) - en(j)$ (i.e. slots i and j are supplied by the same airport and the interval between the landing in j and the take-off in i is sufficiently large).

5) For any airport, at most one of the origination slots and at most one of the termination slots can occur in the path.

Note that a path models a possible flow of end users, and does not necessarily coincide with a flight. Indeed, passengers on a given flight could be partitioned into flows associated with distinct paths. The airport of the head slot of a path is the *source* of the path, while the airport of the tail slot is the *destination* of the path. The *cardinality* of a path p is the number of slots occurring in the path (e.g. the cardinality of $p = (u, v, h, i, j, k)$ is 6). A path with cardinality equal to 2 is an *arc*. The *travel length $tl(p)$* (or *travel time*) of a path $p = (i, \dots, j)$ is the time required to connect the source to the destination of the path, that is, $st(j) - en(i)$ (e.g. the travel length of $p = (u, v, h, k)$ is $tl(p) = st(k) - en(u)$).

As said, to identify all alternative uses of any slot, we determine all paths which can actually be demanded by end users, which we will refer to as *feasible* paths. In particular, given two slots $i, j \in S$, we assume that any path $p = (i, \dots, j)$ from $a(i)$ to $a(j)$ is *feasible* when the following conditions simultaneously hold:

1) The cardinality of p is lower than or equal to integer $\varphi_1 \geq 2$, since paths with too many intermediate stops are not desired by end users. For instance, focusing on airports inside the EU, paths which involve more than two intermediate stops cannot be attractive to end users, and thus φ_1 could be set equal to 6.

2) If p is not an arc, the travel length of p is lower than or equal to $\varphi_2^p \cdot l_{a(i),a(j)}^{min}$, where $\varphi_2^p \geq 1$ for any p, since a path with one or more intermediate stops can be considered by end users only if it does not require too much additional time than the best non-stop connection (e.g. any φ_2^p could be set at a value that rises with $l_{a(i),a(j)}^{min}$).[13]

We consider any feasible path as a candidate to transport passengers while we discard all other paths (a feasible path can be attractive to some end users and not to others, while no end user can demand a path which is not feasible). Let us denote by P the set of all feasible paths (by construction, it does not contain multiple identical paths).

4 Airport slots and the level of service

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[13] In Redondi et al. (2011), travel times are applied to define a centrality measure to study the hub competition in the worldwide airport network.

As a first step, we need a metric to measure the level of the air transport service. For this purpose, we assign a weight to any feasible path measuring the benefit that the feasible path offers to society. We assume that: i) the social benefit of transporting end users from a source to a destination rises with the number of transported passengers; and ii) the benefit of transporting an end user from a source to a destination decreases with travel delay relative to the minimum time required by a non-stop flight. Therefore, to any path $p = (i, \dots, j) \in P$ we assign a weight equal to $\frac{l^{min}_{a(i),a(j)}}{tl(p)} \cdot w_p$, where $w_p \geq 0$ is the quantity of passengers who fly according to the program described by path p.

In network analysis, given a metric to measure the overall level of service provision, the contribution of an element to this level of provision can be estimated as in the network resilience analysis (or as in the computation of vitality measures). In such a case, the element is erased from the network to assess the marginal effect on the overall level of service provision (Koschützki et al. 2005, Everett and Borgatti 2010, Holme and Kim 2002). Thus, we can obtain a measure of the scarcity of a slot by assessing the impact on the level of service provision in the case where the slot is subtracted from the service (that is, removed from the network). Hence, the larger the degradation in the level of service provision, the higher the value of the resource.

Let now $d_{i,j} > 0$ be an estimate of the number of end users who are expected to travel by taking off from $a(i)$ in time band i and landing to $a(j)$ in time band j (for example, through one non-stop flight, or one direct flight, or two or more connecting flights). For instance, such an estimate can be obtained by using data related to flows that have been observed in an equivalent previous period (e.g. in the same period of the last year). For such end users, several feasible paths could represent attractive travel alternatives, while other feasible paths are of no interest. We assume that a feasible path can represent a valid alternative for users if it starts not too early relative to $st(i)$ and it ends not too late relative to $en(j)$. In particular, we define a feasible path $p = (u, \dots, v)$ as *compatible* with respect to arc (i, j) when: 1) $a(u) = a(i)$ and $a(v) = a(j)$, 2) $st(u) \geq st(i) - \varphi^p_3$ and $en(v) \leq en(j) + \varphi^p_3$ with $\varphi^p_3 \geq 0$ for any p (for instance, any φ^p_3 could rise with

$l_{a(i),a(j)}^{min}$).[14] Therefore, we denote by $P_{i,j} \subseteq P$ the set of feasible paths which are compatible with (i,j). Moreover, let $D = \{(i,j) : (i,j) \ is \ any \ arc, d_{i,j} > 0\}$.

Given a (multiple) origination slot $i \in \bigcup_{a \in A} O_a$, let $sc_i \geq 0$ be an estimate of the overall number of end users which can take off from airport $a(i)$ in time band i, boarded on distinct flights. Analogously, given a (multiple) termination slot $j \in \bigcup_{a \in A} T_a$, let $sc_j \geq 0$ be an estimate of the overall number of end users, distributed on distinct flights, which can land to airport $a(j)$ in time band j. Finally, let $fc_{ij} \geq 0$ be the average capacity of any non-stop flight which takes off from $a(i)$ in i and lands to $a(j)$ in j.

Let us now consider the problem Ψ of determining the maximum service level that can be provided by using all the (multiple) origination and termination slots of airports in A to serve the estimated demand (such problem is formally illustrated in the Appendix). We denote by $F \geq 0$ the value of an optimal solution to problem Ψ. It thus represents the maximum level of service that can be supplied by using all slots provided by airports in A. In the optimal solution, slots are used as effectively as possible, in the sense that the number of passengers allocated to any path is tuned in such a way as to maximize the overall benefit for society.

Given a (multiple) origination (termination) slot i, let us now remove from the network all origination (termination) slots with time band i supplied by $a(i)$ by substituting sc_i with 0 in Ψ.[15] Then, we can verify the impact of this removal on the level of service by solving the resulting problem, from now on denoted by Ψ_{-i}. Let F_{-i} be the optimal value of Ψ_{-i} (by construction $F_{-i} \leq F$) and let $\beta_i = F - F_{-i}$. In the case where $F_{-i} = F$, (multiple) slot i is not a valuable resource as it can be fully and effectively replaced when it is absent in the network. Indeed, when subtracted from $a(i)$, the relevant flows of passengers can be suitably rearranged in the network so that the level of the air transport service is not affected at all. On the contrary, the larger the quantity $F - F_{-i} \geq 0$, the higher the value of this (multiple) slot for society, as there is no way to fully compensate its absence in the provisioning of the air transport service. In other words, when the (multiple) slot is subtracted from the relative airport, there is no way of rearranging the flows of passengers without downgrading the air transport service level. Therefore, we can assume $F - F_{-i}$ as a measure of the

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[14] Actually, we should consider at least two classes of end users, such as business and economy, and define different parameters φb_3^p and φe_3^p. However, to simplify the analysis we consider just one class of end users.

[15] Or, equivalently, by substituting no_i (nt_i) with 0 in Ψ.

marginal contribution of the (multiple) slot in terms of the level of service.[16] Then, the social benefit

associated with each origination (termination) slot provided by $a(i)$ with time band i can be set equal to

$\frac{F-F_{-i}}{no_i}$ ($\frac{F-F_{-i}}{nt_i}$).[17] Let us denote by δ_i the so found marginal contribution of any single slot $i \in \left(\bigcup_{a \in A} \bar{O}_a\right) \cup$

$\left(\bigcup_{a \in A} \bar{T}_a\right)$.

5   Incentive prices for slots

In this section, we complete the procedure to determine incentive prices for slots. These prices are intended

to pursue an economically efficient usage of the full range of airport facilities necessary to operate an air

service, at a coordinated airport, on any specific date and time for the purpose of landing or take-off (while

preserving recovery of the total cost of supplying all slots in the considered airport network).

The first step consists of determining a suitable cost basis to derive incentive prices. For this purpose, it

is necessary to consider all the production factors that are involved in slot provision, and the relative costs

that need to be covered. Once the airport full cost has been defined, cost allocation criteria should be adopted

in order to properly allocate expenses to the different elementary services that must be combined to provide

any slot.

Slot prices may provide carriers with adequate incentives when the cost basis for their definition reflects

the costs of efficient airports. Thus, the costs of elementary services should not incorporate unjustified

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[16] Determining F (and F_{-i}) can require much computational effort because of integer constraints (7) in the formulation

in the Appendix. However, we can quickly get an (upper) approximation UF (UF_{-i}) of the optimal value of problem Ψ

(Ψ_{-i}) by determining an optimal value of the linear relaxation of problem Ψ (Ψ_{-i}), namely, problem Ψ (Ψ_{-i}) where

constraints (7) are removed. Moreover, it is easy to prove that $UF_{-i} \leq UF$. Therefore, from a practical point of view, to

estimate the marginal contribution of any (multiple) slot i, we could consider the value $UF - UF_{-i}$ instead of $F - F_{-i}$.

[17] In practice, the number of distinct F_{-i} to be computed can be greatly reduced by proceeding, for example, as follows.

First, consider a specific two-month period (e.g. March-April) of a year. Thus, set B is a partition of the considered

period in time bands. Then, assume that all slots in that period which are relative to the same time on the same day of

the week (e.g. all slots on 08.01 to 08.30 of every Monday in March-April) are fairly equivalent in terms of the demand

served. We can thus compute the aggregate marginal contribution of these equivalent slots by removing them all

together from problem Ψ. Finally, we can compute the (average) marginal contribution of any single slot by dividing

the aggregate marginal contribution by the number of such equivalent slots. The above described steps have to be

repeated for each two-month period of the year.

inefficiencies. In order to estimate the efficient cost basis, a suitable combination of top-down and/or bottom-up techniques can be applied. Bottom-up cost models predict that the relevant costs of a service or a facility are engineered from a production function based on efficient technologies. Top-down models, on the opposite, infer the costs of services and facilities from technical and economic data relative to a suitably defined population of airports.

In what follows, we provide a descriptive summary of cost categories, allocation criteria and the relevant cost basis for determining incentive prices for slots.

Cost categories

The categories of expenses to be included in the cost basis should consider operation and maintenance expenses, administrative and other overheads, and the cost of capital.

Operation and maintenance costs include: i) personnel costs, such as direct remuneration to the staff, the costs of health and social insurance, retirement funds, employee training and other costs; ii) the cost of spare parts and consumables that the airport incurs in the provision of services or facilities (including the operation and maintenance of fixed assets); iii) heating, air conditioning, lighting, water, cleaning, sanitation, CO_2 emissions;[18] iv) contracted services (i.e. payments made to third parties for the provision of some airport facilities and services).

Overhead, general and administrative costs include, among others, overall management, economic planning and control, and information systems.

To fully reward production factors, the cost basis must include the yearly reduction in value (i.e. depreciation and amortization) of fixed assets due to physical deterioration, obsolescence and other factors that limit their life. While assessing the correct economic value of fixed assets, we deem appropriate to refer to the current cost accounting approach. Current cost accounting is a valuation method whereby fixed assets used in production are valued at their actual or estimated current market prices at the time the production takes place.

Finally, the cost basis for incentive prices should consider the total cost of providing the elementary services, including the cost of capital. In other words, the airport revenue should generate a 'reasonable'

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[18] Negative environmental impacts, as CO_2 emissions, will impact on the costs, due to the inclusion of aviation CO_2 emissions in the general EU emissions trading system (ETS) from 2012.

return on assets, as appraised by an independent regulator. Whatever the airport governance, there are generally agreed principles to compute the cost of capital (see e.g. Damodaran, 2011). First, the financing costs of each source of capital (i.e. equity and debt) are calculated as rates of return. Then, the pre-tax weighted average cost of capital (WACC) is found on the basis of the proportion of equity and debt. Finally, the pre-tax WACC rate is applied to the capital employed to evaluate the cost of capital.

Criteria for cost allocation

Once the efficient total costs of the spending categories have been determined, they have to be allocated to the different elementary services. Cost allocation criteria are straightforward for the cost categories that are directly attributable to each elementary service. Conversely, for indirect cost categories, specific drivers of allocation must be applied depending on their specific nature. For example, the cost of personnel working in different elementary services can be divided according to the estimation of time worked in each of the services concerned. Administrative costs could be allocated on the basis of the operation and maintenance costs of elementary services. Electricity, water, heating and air conditioning, for instance, can be based on measured or estimated consumption of these utilities for each elementary service. Capital costs attributable to investments spanned on several assets (such as buildings) could be allocated among elementary services according to the volume of space, surface and/or area of movement where each service is provided.

Cost basis for slot provision

We are now in a position to estimate the cost basis for the provision of slots.[19] This cost basis should include a variety of costs related to the elementary services, and the following description is only indicative.[20] In particular, the cost basis for slot provision includes: i) landing or take-off costs, such as the cost of the aircraft movement areas and associated lighting, aircraft towing, fire and ambulance services, security services attributable to aircraft movement areas, air traffic control (including communications services) and meteorological services; ii) the costs of airport facilities for processing passengers, including the costs of security services and of ground access and terminal facilities; iii) the costs of noise monitoring and noise abatement measures; iv) the costs of measures preventing or mitigating air pollution directly attributable to civil aircraft operations.

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[19] It is worth to remark that only efficient costs (i.e. the costs that an efficient airport sustains for providing services and facilities) are recognized in the cost basis for slot provision.

[20] The cost elements that form the cost basis for slot provision can vary, depending on the cost structure of each airport.

Definition of incentive prices for slots

Given that we have assessed the total airport costs for providing all slots, we can now derive incentive prices for slots. For this purpose, we may follow either of two alternative approaches, namely, a global approach or a local approach.

In the global approach, we consider each airport inside a region (i.e. the EU) as part of a global network. Such global network can be characterized in terms of the full cost of slot provision, namely, the cost of supplying all of the slots pertaining to the network. In turn, the full cost for providing slots can be obtained by summing the efficient costs of all airports in the network (determined as explained in the previous paragraphs). Such a total cost TC is then allocated to single slots on the basis of the marginal contribution of each slot to the level of the service, that is, the incentive price ip_i of any slot $i \in \left(\bigcup_{a \in A} \bar{O}_a\right) \cup \left(\bigcup_{a \in A} \bar{T}_a\right)$ is equal to $\frac{TC \cdot \delta_i}{\sum_{j \in \left(\bigcup_{a \in A} \bar{O}_a\right) \cup \left(\bigcup_{a \in A} \bar{T}_a\right)} \delta_j}$. Under this global approach, we may have to implement an adjustment scheme in order to redistribute the extra-profits of some airports to those airports that cannot recover their actual costs on the basis of the resulting incentive prices for slots.[21] Indeed, it may occur that an airport with a low demand for slots may not recover the actual costs of supplying them, while a congested airport could be over-compensated from supplying slots.

Instead, the local approach considers each airport as a standalone entity, and determines incentive prices by allocating the total costs TC_a of airport $a \in A$ for supplying slots on the basis of the marginal contribution of each of the airport slots to the level of the service. In particular, for each airport $a \in A$, the incentive price ip_i of any slot $i \in \bar{O}_a \cup \bar{T}_a$ is equal to $\frac{TC_a \cdot \delta_i}{\sum_{j \in \bar{O}_a \cup \bar{T}_a} \delta_j}$. While considerably easier to implement than the global approach, the local approach cannot take full account of the social value of airport slots within the global network. Therefore, it cannot fully exploit the potential of the proposed method to improve efficiency in slot management and use. Hence, the local approach should be interpreted as a second-best solution that can be pursued whenever it is too cumbersome to manage the adjustment scheme under the global approach.

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[21] In many EU countries, adjustment schemes are applied in the distribution and transmission of energy given that operators are required to set uniform access charges to network infrastructures.

Once an incentive price has been determined for every slot provided by the airports inside a given region, then these slots can be allocated to carriers by applying for a last time the grandfather right criterion. For any assigned slot, carriers can choose among three alternative options: i) paying the corresponding incentive price to the airport[22] providing the slot and using it; ii) not paying the relative incentive price and returning the slot back to the airport coordinator (e.g. when the carrier is not able to efficiently use the slot and thus to adequately pay for it); or iii) exchanging the slot with another one handed over by a different carrier, thereby paying the incentive price for the acquired slot to the relevant airport while ceasing to pay for the released one (according to EC regulations, the exchange has to be authorized by the coordinator and might even imply money transfers between carriers). Returned slots could be reassigned according to criteria yet applied by the coordinator of the airport, but now requiring the payment of the corresponding incentive prices. Each and every year, incentive prices should be updated to respond to possible changes of the social value of the priced resources. In such a way, incentive prices could substitute for the grandfather right criterion in the allocation of slots to carriers, and provide long term signals which should induce end users and carriers to take efficient decisions concerning the use of slots.

6 Conclusions

We have provided a general procedure to deal with the airport slot allocation problem, which applies the principles underlying the AIP model for regulation of radio spectrum in electronic communications markets. In particular, we have proposed an incentive pricing mechanism that generates an efficient slot allocation, where prices are built on a measure of the best use of each slot in serving end users. In so doing, we have considered the structure of the air transport network (and thereby interdependence among slots at different airports) in a selected region, and we have defined a metric based on both quantity and quality of passenger air transport in that region. Therefore, the resulting incentive prices should better align private and social decisions over the use of slots compared with prices resulting from pure market interactions (such as auctions and trading).

It is worth noting that, to improve the effectiveness of market mechanisms, the Commission advocates higher cooperation between airports coordinators (EC, 2011b). Such enhanced cooperation can progressively

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[22] Obviously, incentive prices substitute for all payments that are currently required by the airport (such as take off and landing fees, among others) to allow carriers to use airport infrastructures associated with slots.

take place through developing a common slot allocation software (in the short run), merging the coordination activities for airports in different Member States (in the medium term), or even creating a European coordinator responsible for slot allocation at all EU airports (in the long run). Thus, this Commission's intent may prospectively provide the basis for the definition of an EU-wide system of incentive prices for airport slots.

Proposing incentive pricing for slot allocation also introduces some lines of future research. First, after acquiring economics and operative data relative to all airports inside a region, and to the served demand, we could estimate the actual incentive price of any provided slot under the global approach. Second, we could extend the procedure so as to determine the marginal value of all slots at any given airport. The resulting outcome could be of help for taking critical decisions about the opportunity of closing existing airports, or opening new ones. Finally, it could be interesting to study the problem of determining incentive prices in a wider framework where intermodal passenger transport is considered. In this case, different networks (e.g. air and rail transport) may compete for end users. Thus, the marginal contribution of a slot should be defined by taking into account the possibility of substituting the air transport service with other transport modes.

Appendix

Here follows the formulation of the problem Ψ of determining the maximum service level that can be provided by using all the origination and termination slots of airports in A in order to serve the estimated demand:

$$
\begin{cases}
\max \sum_{p=(i,\dots,j)\in P} \dfrac{l^{min}_{a(i),a(j)}}{tl(p)} w_p \\[2mm]
subject\ to \\[1mm]
\sum_{p\in P_{ij}} w_p \leq d_{ij} \qquad (i,j) \in D & (1) \\[2mm]
\sum_{p\in P: p=(\dots,i,\dots)} w_p \leq sc_i \qquad i \in \bigcup_{a\in A} O_a & (2) \\[2mm]
\sum_{p\in P: p=(\dots,j,\dots)} w_p \leq sc_j \qquad j \in \bigcup_{a\in A} T_a & (3) \\[2mm]
\sum_{p\in P: p=(\dots,i,j,\dots)} w_p \leq fc_{ij} \cdot nf_{ij} \qquad (i,j) \in P & (4) \\[2mm]
\sum_{j:(i,j)\in P} nf_{ij} \leq no_i \qquad i \in \bigcup_{a\in A} O_a & (5) \\[2mm]
\sum_{i:(i,j)\in P} nf_{ij} \leq nt_j \qquad j \in \bigcup_{a\in A} T_a & (6) \\[2mm]
nf_{ij} \in \mathbb{Z} \qquad (i,j) \in P & (7) \\[3mm]
w_p \geq 0 \qquad p \in P \\[1mm]
nf_{ij} \geq 0 \qquad (i,j) \in P
\end{cases}
$$

where $w_p \geq 0$ for any $p \in P$ represents the quantity of passengers who fly according to the program described by path p, and $nf_{ij} \geq 0$ for any $(i,j) \in P$ is the number of non-stop flights which take off from $a(i)$ in i and land to $a(j)$ in j.

In particular, any constraint (1) ensures that the number of passengers $d_{i,j}$ who would travel by taking off from $a(i)$ in i and landing to $a(j)$ in j can be (partially) rearranged among feasible paths which are compatible with arc (i,j). Each constraint (2) requires that the overall number of passengers who take off from $a(i)$ in i be subject to the capacity of the (multiple) origination slot i. Similarly, any constraint (3) requires that the overall number of passengers who land to $a(j)$ in j be subject to the capacity of the (multiple) termination slot j. Constraints (4) model that any non-stop flight which takes off from $a(i)$ in i and lands to $a(j)$ in j has a maximum capacity. Constraints (5) and (6) ensure that the number of flights which can be originated (terminated) in $a(i)$ ($a(j)$) during i (j) is limited. Finally, constraints (7) requires that any nf_{ij} be an integer.

Problem Ψ is formulated as an integer linear programming (ILP) problem. In the literature, many (computationally expensive) exact methods have been proposed to solve ILP problems (Bertsimas and Weismantel 2005). Alternatively, heuristic algorithms could be developed and applied to quickly identify a good solution to Ψ. Designing exact or heuristic methods to solve Ψ is not the goal of this work. However, let us remark that we are not interested in the details of an optimal solution to Ψ (i.e. in finding the optimal value of any variable in Ψ), but rather in finding just the optimal value of Ψ (i.e. the maximum level of the air transport service that can be supplied over the considered network). Therefore, there is more room for finding fast and effective heuristics that enable us to only determine approximations of the optimal value of Ψ (see e.g. footnote 16).

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