An incentive pricing mechanism for efficient airport slot allocation in Europe

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Abstract

We define a supervised market mechanism to deal with the airport slot allocation problem. This mechanism is based on the principles underlying the AIP model for regulation of radio spectrum. Incentive prices for airport slots should reflect an estimate of the marginal value of each slot to end users. We compute this value 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 any given slot be denied. Incentive prices consider interdependencies among slots at different airports. We argue that, in principle, incentive prices may better align private and social decisions over the use of slots compared with the outcomes of pure market interactions (such as auctions and trading).

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

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1 Introduction

In the last decades, airlines and passengers have been suffering from growing congestion at busy airports. Evidence shows that several large airports in the European Union (EU) are currently operating at full capacity. According to Eurocontrol (2013), as much as 12% of the demand for air transport will not be accommodated by 2035 because of a shortage of airport capacity.

Due to severe constraints to capacity expansion, airport slots are a scarce resource. Thus, the European Commission (EC) pursues the optimal allocation and use of slots to foster competition and improve quality of air transport services (EC, 2011a). In this paper, we focus on airport slot allocation and provide an incentive pricing mechanism to effectively manage scarce capacity.

Currently, in the EU, the Slot Allocation Regulation (EC Regulation 95/93, as amended by Regulation 793/2004) defines the mandatory rules for coordinated airports, namely, airports where slots are essential for using infrastructures (EC, 1993, 2004).[1] Although there are no property rights, there are *grandfather rights* in using slots. If an air carrier has used some slots for at least 80% of the time during a season, then it is entitled to use the same slots in the next corresponding season, otherwise slots become free and may be allocated to new entrants (see also IATA, 2013).

Unfortunately, the outcome of this slot allocation mechanism can be far from economic efficiency. Even the *use-it-or-lose-it* rule may induce airlines to use slots inefficiently, since airlines are reluctant to cede slots for fear of rivals' entry (Dempsey, 2001; Starkie, 1998).[2] Thus, the EC has planned to amend current regulation to enforce market mechanisms for slot allocation and use (EC, 2011b).

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[1] In order to land or take off in a coordinated airport, 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). The granting of a slot at a coordinated airport means the airline may use the full range of elementary infrastructure services (both airside and groundside) that are necessary for operating a flight at a given time. In the European Economic Area plus Switzerland, where the Slot Allocation Regulation applies, there are currently 89 fully coordinated airports.

[2] Incumbents may have incentives to opt for inefficient schedules and aircraft sizes to dampen competition. In practice, a few carriers hold a large amount of available slots and operate several flights merely to comply with the use-it-or-lose-it rule (Madas and Zografos, 2008). Sieg (2010) stresses that, since air carriers may have better information than airports on passenger demand, the use-it-or-lose-it rule may increase slot use. However, social welfare decreases under that rule.

At one extreme, market mechanisms would imply withdrawing and auctioning historical slots. Auctions may 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 assets. Despite the idea of auctioning off airport slots has been widely discussed (Brueckner, 2009; Button, 2008; Verhoef, 2010), it seems far from being actually implemented, either inside or outside the EU.[3]

On the other hand, following the UK practice,[4] the EC promotes secondary trading of slots between airlines at EU airports. Trading introduces flexibility in the management of slots, since slots may serve different end users from those for which they have been originally employed. This in turn may impede that slots remain assigned to inefficient uses.[5]

Despite their benefits, market mechanisms have some important drawbacks.[6] Indeed, high private carriers' valuations of slots may not reflect their social value. Moreover, there is the risk that dominant carriers collect the majority of prominent slots and thereby foreclose entrants. Finally, assigning slots locally (i.e. at any given airport) fails to internalize interdependencies among slots at different airports (e.g. at the origin and at the destination of a flight).[7] Thus, there is the need for mitigating the issue of lack of coordination over using scarce resources such as airport slots.[8]

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[3] 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, but it was met with criticism from airlines and IATA. 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).

[4] In 1999, slot exchanges with monetary side payments were judged lawful by the English High Court. In March 2008, Continental Airlines paid $ 209 million (about € 143 million) for four pairs of slots at London Heathrow (EC, 2011b).

[5] 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.

[6] In Section 6, we discuss in detail the main drawbacks of pure market mechanisms for allocating scarce resources, and provide some relevant examples of radio spectrum auctions.

[7] Castelli *et al*. (2012) propose a mechanism that simultaneously allocates slots at several airports considering the structure of the network. They also allow for fairly redistributing 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.

[8] In principle, specific auction formats may consider the interdependence among slots, thereby allowing airlines to bid for packages of slots (see e.g. Rassenti *et al*., 1982). However, these formats suffer from severe implementation problems. Indeed, the problem of determining the winning bids is NP-hard, so that solving it to optimality is very difficult. Moreover,

In this paper, we define a supervised market mechanism that aims at overcoming market failures by introducing incentive prices for airport slots. Incentive prices consider the interdependence among slots, and thereby may induce carriers to take efficient decisions concerning the use of slots. Since any slot reserved for a route is subtracted to other possible routes, and thus to other possible end users, then we derive an incentive price for each slot that reflects an estimate of the marginal value of the slot to end users, while preserving recovery of total costs of supplying all slots in the network.

We compute the marginal value of any 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. This reflects into the loss of utility for end users in the case where the slot gets unavailable (total costs of providing all other slots being unaffected). Incentive prices should be periodically updated to consider changes in slot use.

The mechanism relies on the principles of Administered Incentive Pricing (AIP) for spectrum use in electronic communications markets (Ofcom, 2010). The AIP model leads to regulated charges that reflect the social opportunity cost of the spectrum, thereby inducing an efficient use of that resource.

This paper is organized as follows. Section 2 applies the principles of the AIP model to airport slot allocation. Sections 3 to 5 explain the procedure to derive incentive prices for slots. Section 6 discusses the main drawbacks of pure market mechanisms. Finally, Section 7 concludes.

2 Incentive pricing for airport slots

In the last two decades, a number of regulatory authorities in electronic communications markets have introduced radio spectrum fees, based on the AIP model, which reflect the underlying marginal value of the spectrum. The AIP model was first introduced in the UK with the Wireless Telegraphy Act in 1998. Current estimates assess that applying AIP generates yearly revenues to the UK government about equal to 185 million euro (see e.g. Cambini and Garelli, 2011).

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the high level of complexity of these auction formats may even prevent bidders from formulating optimal strategies (see e.g. Pekeč and Rothkopf, 2003).

The AIP model considers all alternative uses of congested spectrum. If spectrum is used to provide a given network service to end users, then it must be suitably priced to account for the alternative uses of spectrum that have been prevented. Thus, incentive prices reflect the social opportunity cost for spectrum use. If the incentive price is excessive, then the rights holder may release the allocated spectrum and give it back to the government for reallocation. Hence, the AIP model rationalizes the resource use.[9] Incentive prices are then periodically updated to consider changes due to a technology that uses scarce resources more efficiently, or to a shift in demand towards less congested resources.

Ofcom, the industry regulatory authority in the UK, has clarified that the AIP model can be suitably employed both as a substitute for and as a complement to market mechanisms (e.g., incentive prices could be set as reservation prices for spectrum auctions). According to Ofcom (2009), AIP well contributes to pursuing the optimal spectrum use, and is especially effective in the following cases:

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

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[9] Incidentally, the AIP model shares the idea of assessing the marginal contribution of an element in a given setting with the well-known Vickrey-Clarke-Groves (VCG) mechanism. In fact, the VCG mechanism aims at evaluating the externalities caused by the participation of an element (e.g. an agent) on the other elements in a setting (e.g. an auction), namely, revenues and costs imposed on the other elements, given that there is not a market where the element participation can be negotiated and priced (Ausubel and Milgrom, 2002). For this purpose, the VCG rule removes the element from the setting and measures the change in some metric of the outcome (e.g. the optimal allocation in an auction). On the other hand, the AIP model has been implemented in the UK on the basis of two different assessments of the marginal value of radio spectrum. Indeed, incentive prices have been set by measuring the additional network costs due to subtracting a portion of radio spectrum from a given service (e.g. for moving to a higher uncongested frequency band). Alternatively, incentive prices have been set by measuring the decrease in network costs due to adding a portion of spectrum to a given service (e.g. when technology innovation yields some digital dividend). Future work may investigate whether these alternative assessments could be considered equivalent. More generally, it may study the relationship between AIP and the VCG rule. In particular, since the VCG rule is affected by some drawbacks (Ausubel and Milgrom, 2002; Avenali, 2009), it is worth verifying whether AIP suffers from similar drawbacks.

- where sunk costs and/or regulatory restrictions on the alternative use of the band mean that changes of use are constrained and thereby, in the medium term, efficiency gains are limited.[10]

We argue that policy makers can suitably convey the underlying principles of AIP to the air transport industry for airport slot allocation. Indeed, slots are affected by growing scarcity. Moreover, the allocation of slots at congested airports is fragmented among different operators with conflicting interests. This in turn may prevent some efficient uses of slots (e.g. due to unbalanced schedules or the use of small aircrafts in congested slots). Therefore, to effectively deal with the issue of lack of coordination over slot use, it is appropriate to define incentive prices that reflect the social value of slots, and require carriers to pay out such prices to airports to use the supplied slots.

To highlight the potential benefits of introducing incentive prices for airport slots, we discuss a stylized example (see Appendix 1). This example shows how suitable incentive prices may increase efficiency in using airport slots, particularly when incentive prices are compared with a regulatory regime where capacity is allocated on the basis of grandfather rights.

We derive incentive prices for slots from their marginal value. Since radio spectrum is sought-after by different networks, then we can find the marginal value of spectrum by comparing the impact of spectrum allocation on the costs of those networks. Conversely, we only use airport slots to provide air transport. Thus, the only relevant costs are incurred for the air transport service.[11] However, when a slot serves any route, it is subtracted from other possible routes and end users. Hence, the marginal value of the slot stems from the highest contribution of the slot to the air transport service, both in terms of quantity (i.e. number of transported passengers) and quality (i.e. passenger travel times).

Thus, to assess the marginal value of a slot in a given air transport network, first we identify all alternative uses of the slot inside the network. Then, we choose a metric to measure the level of the air transport service, and assess how much the slot may contribute to improve the service to end users

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[10] For instance, mobile broadband access may suffer from congestion of available spectrum to that use, while a similar portion of spectrum, which has been reserved for broadcasting television services in the same area, may be poorly used.

[11] Moreover, due to constraints to airport capacity expansion, we cannot assess the incremental effect of additional slots.

(i.e., the highest marginal contribution of the slot). Finally, we find the incentive price for the slot by allocating the total cost for supplying all slots in the network based on the marginal contribution of the slot to the level of service. In the following sections, we discuss in detail each of the above steps.

3 Alternative uses of airport slots

Let us consider the structure of the air transport network (and thereby interdependencies among slots at different airports). In order to assess the marginal contribution of each slot to the level of service at the time incentive prices are set, we should identify any alternative use of the slot at that time, by considering the most accurate network model. Indeed, the alternative uses of any slot depend on those paths that connect a source with a destination by using that slot, which can actually be taken into account to serve the demand.[12] In what follows, we will make some simplifying assumptions (to be discussed throughout the paper) that allow us to focus on the main ideas.

The first step consists of identifying the set of all paths that can link any pair of airports. For this purpose, let us introduce some 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 that on average a non-stop flight (i.e. with no intermediate stops) can take from a to b, for any $a, b \in A$ with $a \neq b$.[13] Let also $l_{a,a} > 0$ be the minimum time that an end user has to spend in a between landing and the take-off of a connecting flight.[14] 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 the time band b, $st(b)$ and $en(b)$ return, respectively, the starting and

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[12] In network analysis, Freeman (1977, 1979) formulate the well-known concept of betweenness centrality of a node (in our model, nodes are airport slots), which assume that shortest paths are the drivers to measure the centrality of a node. Thus, the elements of a network are efficiently used when the content of the linkages (e.g. traffic, information) follows shortest paths. In line with Stephenson and Zelan (1989), we relax the assumption that the content of the linkages has to spread exclusively along shortest paths, and assume that further specific paths play a role in the provision of air transport.

[13] We will use minimum and maximum times to discard unreasonable paths. Given a pair of airports, the minimum (respectively, maximum) time of a non-stop flight can be defined, for instance, by the time required for the flight by the fastest (slowest) type of aircraft that is used to connect the airports.

[14] We restrict our analysis to passenger transport. For simplicity, we assume that the minimum time an end user has to spend in an airport before taking a connecting flight depends only on the airport features, and not on the type of aircrafts.

the ending minute of b. For any given period (e.g. a week, a semester, a year), let B be the set of time bands which this period is partitioned into (e.g. $B = \{\dots, b_i = [day\ x, 08.01; day\ x, 08.30], b_{i+1} = [day\ x, 08.31; day\ x, 09.00], \dots, b_{i+k} = [day\ x + y, 10.01; day\ x + y, 10.30], \dots\}$).

An airport slot is the right to use the full range of infrastructures of a given airport in a specific time band. We model a slot as a time band of B associated with a given airport (thus, any slot identifies a specific time band).[15] We refer to an origination slot (or take-off slot) and a termination slot (landing slot) as the airport slots that are involved during the origination and termination phase, respectively. Hence, an origination slot represents the time band reserved by any carrier to use the suitable airport infrastructures to perform take-off and all the complementary activities (such as passenger, luggage, and catering boarding, and fuel charging). 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 aircraft parking, passenger and baggage disembarkation, and 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 that refer to the same time band (depending on airport infrastructures, such as the number of runways). Let $\bar{S} = \left(\bigcup_{a \in A} \bar{O}_a\right) \cup \left(\bigcup_{a \in A} \bar{T}_a\right)$ denote the slot population (namely, the set of all origination and termination slots available at all airports in A in the selected period). Given a slot $i \in \bar{S}$, $a(i)$ 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, we will refer to a slot $i \in S$

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[15] In principle, depending on the efficiency and the structural characteristics of airports, we could partition the selected period in different time bands for distinct airports. Without loss of generality, to simplify the analysis 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).

either as a *single* slot, or as a *multiple* slot in the case where $a(i)$ provides two or more identical slots in time band i. Given any slot $i \in S$, let $no_i \geq 1$ ($nt_i \geq 1$) be the number of origination (termination) slots in 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:[16]

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 origination slot and one termination slot can occur in the path.

Note that a path models a possible *flow* of end users, namely, a set of passengers who follow the same travel. Observe also that a path does not necessarily coincide with a flight. Indeed, we could partition passengers on a given flight into flows associated with distinct paths.[17]

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[16] For instance, $([OSL\text{: }15.15; 15.30], [LHR\text{: }16.45; 17.00])$ is a travel from Oslo Airport (OSL) to London Heathrow (LHR), and $([OSL\text{: }15.00; 15\text{: }15], [FRA\text{: }17.00; 17.15], [FRA\text{: }18.00; 18.15], [LHR\text{: }18.45; 19.00])$ is a travel from OSL to LHR with one intermediate stop at Frankfurt Airport (FRA) —for brevity, we omit the day of the travel from notation.

[17] For example, a non-stop flight operated by an Airbus A321-200 from Frankfurt Airport (FRA) to London Heathrow (LHR), taking off from FRA at 18.05 and landing to LHR at 18.55, with about 200 passengers, can serve two distinct travels. For instance, 110 out of 200 passengers might be flying from FRA to LHR because their travel is $([MUC\text{: }14.00; 14\text{: }15], [FRA\text{: }15.00; 15.15], [FRA\text{: }18.00; 18.15], [LHR\text{: }18.45; 19.00])$, where MUC stands for Munich Airport, while the remaining 90 passengers might be transported from FRA to LHR as complying with their travel $([OSL\text{: }15.00; 15\text{: }15], [FRA\text{: }17.00; 17.15], [FRA\text{: }18.00; 18.15], [LHR\text{: }18.45; 19.00])$.

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 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 time* $tl(p)$ of 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 time of $p = (u, v, h, k)$ is $tl(p) = st(k) - en(u)$).[18]

We refer to all paths that can actually be demanded by end users as *feasible* paths. Given any two slots $i, j \in S$, we assume that a 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 not higher than integer $\varphi_1^p \geq 2$, since paths with too many intermediate stops are not attractive to end users. For instance, for airports inside the EU, paths with more than two intermediate stops are not appealing, and thus φ_1^p could be set equal to 6. The upper bound φ_1^p is exogenously given (e.g. set by a public authority based on relevant studies and simulations).
2) If p is not an arc, the travel time of p is not higher than $\varphi_2^p \cdot l_{a(i),a(j)}^{min}$, where $\varphi_2^p \geq 1$ for any p, since end users consider a path with one or more intermediate stops only if it does not require too much additional time than the fastest non-stop flight (where the value of φ_2^p could rise with $l_{a(i),a(j)}^{min}$). The upper bound φ_2^p is also exogenously given.

We consider any feasible path as a candidate to transport passengers, while we discard all other paths (a feasible path could be attractive to some end users but not to others, while no end user can demand a path that 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

Let us now select a metric to measure the level of the air transport service. For this purpose, we assign a weight to any feasible path measuring the social benefit of the path. We assume that the social

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[18] Redondi *et al.* (2011) use travel times to derive a centrality measure to study hub competition worldwide.

benefit of transporting end users from a source to a destination: i) rises with the number of transported passengers; and ii) decreases with the travel delay relative to the minimum time of a non-stop flight (defined as the ratio between the minimum time that on average a non-stop flight can take from the source to the destination of the path, and the travel time of the path). Therefore, to any path $p = (i, \ldots, j) \in P$ 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 number of passengers who fly according to the program described by path p.[19]

Given a metric for the level of service provision, we estimate the contribution of an element to the level of service as in the network resilience analysis (or as in the computation of vitality measures). This implies removing the element from the network and assessing the marginal effect on the level of service (Everett and Borgatti, 2010). Thus, we measure the scarcity of a slot by assessing the impact on the level of service should that slot be subtracted from the service (i.e. removed from the network). Hence, the larger the downgrade in the level of service provision, the higher the value of the slot.

Let now $d_{i,j} > 0$ be 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 j (by a non-stop flight, a direct flight, or two or more connecting flights). We can assess this number through data on observed flows in a similar previous period (e.g. in the same period of the previous year). For such end users, some feasible paths are attractive travel alternatives, while other feasible paths are of no interest. We assume that a feasible path is a valid alternative for users if it starts not too early relative to $st(i)$ and it ends not too late relative to $en(j)$.

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[19] The proposed metric considers just one class of passengers for any path. In principle, a few passengers may receive a high aggregate utility from flying relative to a large number of passengers. There is a rough way to deal with this issue, which slightly increases the complexity of the model. Assume that there are two distinct classes of passengers (e.g. business and economy). For any path, we should identify the number of passengers in each class who fly along the path, and then assign a different unit mass to passengers of different classes (for instance, one of those passengers receiving a high utility from flying may count as two of the other passengers). Alternatively, we could design a more fine-tuned metric by considering two or more classes of passengers for any path, and then assigning to each class an estimate of the average willingness to pay of any passenger in the class for flying along that path. However, this solution would be more demanding in terms of data, since it requires estimating the willingness to pay of passengers for each path.

We define a feasible path $p = (u, \dots, v)$ as *compatible* with respect to arc (i, j) when: i) $a(u) = a(i)$ and $a(v) = a(j)$; and ii) $st(u) \geq st(i) - \varphi_3^p$ (i.e. path p starts not too early relative to $st(i)$) and $en(v) \leq en(j) + \varphi_3^p$ (path p ends not too late relative to $en(j)$) with $\varphi_3^p \geq 0$ for any p. Parameter φ_3^p is exogenously set (for instance, φ_3^p could rise with $l_{a(i),a(j)}^{min}$).[20] We denote by $P_{i,j} \subseteq P$ the set of feasible paths that are compatible with (i, j). Moreover, let $D = \{(i,j) \colon (i,j)\ is\ any\ arc, d_{i,j} > 0\}$.

Given a (multiple) origination slot $i \in \bigcup_{a \in A} O_a$, let $sc_i \geq 0$ be the estimated number of end users that can take off on distinct flights from airport $a(i)$ in time band i. Similarly, given a (multiple) termination slot $j \in \bigcup_{a \in A} T_a$, let $sc_j \geq 0$ be the estimated number of end users that can land from distinct flights to airport $a(j)$ in time band j. Finally, let $fc_{ij} \geq 0$ be the capacity of a non-stop flight that takes off from $a(i)$ in i and lands to $a(j)$ in j (for instance, it could be the average capacity of the most used aircrafts for that flight).[21]

Consider now the problem Ψ of determining the highest level of service that can be provided by using all the (multiple) origination and termination slots of airports in A to serve the estimated demand (we formulate this problem in Appendix 2). Let $F \geq 0$ be the value of an optimal solution to problem Ψ. 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 so as to maximize the overall benefit for society.

Given a (multiple) origination (respectively, termination) slot i, let us remove from the network all origination (termination) slots in time band i supplied by $a(i)$, by substituting 0 for sc_i in Ψ.[22] We can assess 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

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[20] Actually, we should consider at least two classes of end users (business and economy), and define distinct parameters φb_3^p and φe_3^p. However, to simplify the analysis, we consider just one class of end users (as yet observed in Footnote 19).

[21] While our model may consider aircrafts with different capacities operating non-stop flights between two airports, for simplicity we assume that non-stop flights taking off from $a(i)$ in i and landing to $a(j)$ in j entail only one type of aircraft.

[22] Or, equivalently, by substituting 0 for no_i (nt_i) in Ψ.

$\beta_i = F - F_{-i}$. If $F_{-i} = F$, then (multiple) slot i is not a valuable resource as it can be effectively replaced when it is removed from the network (i.e. passenger flows can be rearranged so that the level of service is not affected at all).

Conversely, the higher the difference $\beta_i = F - F_{-i} \geq 0$, the higher the value of (multiple) slot i for society. Indeed, when (multiple) slot i is removed from the network, there is no way of rearranging passenger flows without downgrading the air transport service level. Thus, we can take β_i as a measure of the marginal contribution of (multiple) slot i in terms of the level of service.[23] Then, the social benefit δ_i of each single origination (termination) slot $i \in \bar{S}$ at airport $a(i)$ in time band i can be set equal to $\frac{\beta_i}{no_i}$ $(\frac{\beta_i}{nt_i})$, namely, equal to the ratio between the marginal contribution of multiple slot i and the number of origination (termination) slots in time band i provided by airport $a(i)$.[24]

5 Incentive prices for slots

In this section, we complete the procedure to find incentive prices for slots. These prices are intended to pursue an economically efficient use of the full range of airport facilities necessary to operate an

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[23] Determining F (and F_{-i}) may require much computational effort, because of integer constraints (7) in the formulation in Appendix 2. However, we can quickly get an 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. On the one hand, solving the linear relaxation requires less computational effort, while, on the other hand, UF (UF_{-i}) is an upper bound of the optimal value of problem Ψ (Ψ_{-i}). We can easily prove that $UF_{-i} \leq UF$. Thus, it is worth studying in future work whether we may suitably use the value $UF - UF_{-i}$ (instead of $F - F_{-i}$) to assess the marginal contribution of (multiple) slot i in real cases.

[24] In practice, we can restrict the number of distinct F_{-i} to be computed by proceeding as follows. First, consider a specific two-month period (e.g. March-April) of a year. Set B is thus a partition of the considered period in time bands. Then, assume that all slots in the period on the same time on the same day of the week (e.g. all slots on 08.01 to 08.30 on every Monday in March-April) are 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. Clearly, we have to repeat the above described steps for each two-month period of the year.

air transport service[25] at a coordinated airport on any specific date and time, for the purpose of landing or take-off (while saving recovery of the total cost of supplying all slots in the whole airport network).

The first step consists of finding a suitable cost basis to derive incentive prices. For this purpose, we have to consider all the production factors involved in slot provision, and the relative costs to be covered. Having found the airport full cost, we should use suitable cost allocation criteria to 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 inefficiencies. We may use a combination of bottom-up and top-down techniques to derive the efficient cost basis. Bottom-up cost models predict that the relevant costs of services and facilities are engineered from a production function based on efficient technologies. Top-down models infer the costs of services and facilities from technical and economic data of a 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, health and social insurance, retirement funds, employee training and other costs; ii) spare parts and consumables that the airport uses to provide services or facilities (including the operation and maintenance of fixed assets); iii) heating, air conditioning, lighting, water, cleaning, sanitation, CO2 emissions;[26] iv) contracted services to third parties.

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[25] 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 the provision of groundside facilities (aircraft parking, terminal gates and loading bays).

[26] Negative environmental impacts, as CO2 emissions, will impact on the costs due to the inclusion of aviation CO2 emissions in the general EU emissions trading system (ETS) since 2012.

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

To fully reward production factors, we include in the cost basis depreciation and amortization of fixed assets. We assess the economic value of fixed assets by using current cost accounting, which is a valuation method whereby fixed assets are valued at their actual or estimated current market prices.

A proper cost basis for incentive prices should also include the cost of capital. Airport revenues should thus yield a ‘reasonable’ return on assets, as appraised by an independent regulator. Whatever the airport governance, there are generally agreed principles to compute the cost of capital (Damodaran, 2011). First, we assess the financing costs of each source of capital (equity and debt). Then, we find the pre-tax weighted average cost of capital (WACC) based on the proportion of equity and debt. Finally, to find the cost of capital we apply the pre-tax WACC rate to the capital employed.

Criteria for cost allocation

Once we have found the efficient total costs of the spending categories, we have to allocate them to the elementary services. Cost allocation criteria are simple for the cost categories directly attributable to each elementary service. Conversely, for indirect cost categories, we should apply specific drivers of allocation, depending on their nature. For instance, we can split the cost of personnel working in different elementary services based on the estimated time worked in each of the services concerned. Administrative costs can be allocated based on the operation and maintenance costs of elementary services. The costs of electricity, water, heating and air conditioning can be based on measured or estimated consumption of these resources for each elementary service. Capital costs attributable to investments spanned on several assets (such as buildings) can 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 able to find the cost basis for provisioning slots. This cost basis should include a variety of costs related to the elementary services, such as: i) landing or take-off costs, as the costs of 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 abatement measures; iv) the costs of measures for preventing or mitigating air pollution directly attributable to civil aircraft operations.[27]

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, which we characterize in terms of the full cost of slot provision (i.e. the cost of supplying all airport slots in the network). We can obtain this cost by summing the efficient costs of all airports in the network (as found in line with the previous paragraphs). Then, we allocate such a total cost TC to single slots on the basis of the marginal contribution δ_i of each slot $i \in \bar{S}$ to the level of service. It follows that the incentive price ip_i of any slot $i \in \bar{S}$ is equal to $\frac{TC \cdot \delta_i}{\sum_{j \in \bar{S}} \delta_j}$.

Under the global approach, we may have to define an adjustment scheme to redistribute the extra-profits of some airports to other airports that do not recover their costs based on the resulting incentive prices for slots.[28] In fact, 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 is over-compensated for supplying slots.

Instead, the local approach considers each airport as a standalone entity, and finds incentive prices by allocating the total costs TC_a of airport $a \in A$ for supplying slots on the basis of the marginal

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[27] The cost basis for slot provision includes only efficient costs (i.e. the costs incurred by an efficient airport to provide services and facilities). The cost elements that form the cost basis can vary, depending on the cost structure of each airport.

[28] Many EU countries make use of adjustment schemes in the regulation of energy distribution and transmission markets, given that network operators are required to set uniform access charges to essential infrastructures.

contribution of each of the airport slots to the level of service. Thus, 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 whole network (and thereby reduces the potential of the proposed method to improve efficiency in slot management). Hence, the local approach is a second-best solution to be pursued whenever it is too cumbersome to manage the adjustment scheme under the global approach.

Once we have found incentive prices, we can allocate airport slots to carriers by still applying the grandfather right criterion. For any assigned slot, a carrier can choose among three alternative options:

i) paying the relevant incentive price to the airport providing the slot[29] and using the slot;

ii) not paying the incentive price and returning the slot back to the airport coordinator (e.g. when the carrier cannot efficiently use the slot and thereby adequately pay for it); or

iii) exchanging slots with a different carrier, thereby paying the incentive price for the acquired slot to the relevant airport, while ceasing to pay for the released slot (according to EC regulation, the exchange has to be authorized by the coordinator, and may imply money transfers).

Returned slots may be reassigned based on some criteria set by the coordinator, including the payment of the relevant incentive prices. Every year, incentive prices should be updated to respond to changes in the social value of the priced resources.[30]

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[29] Clearly, incentive prices substitute for all current carriers' payments to the airport (such as take-off and landing fees, among others) for using the airport infrastructures associated with the slots.

[30] Since the demand for air transport is subject to seasonal fluctuations, we could divide a year in several periods (e.g. six two-month periods), and then compute incentive prices for slots in each period. This means that slots on the same time on the same day of the week (e.g. from 08.01 to 08.30 on every Monday) are priced differently, depending on the period of reference. Thus, demand fluctuations cause related fluctuations in slot prices. Demand for slots may also depend on short term trends. Hence, we should set slot prices for a specific period (e.g. March-April of year t) by considering the data for the same period of the previous year (e.g. March-April of $t-1$) and for some consecutive previous periods (e.g. November-December of $t-1$ and January-February of t). Thus, if an unpredictable radical change in demand occurs in a period, then it will be acknowledged in the slot prices for the next period (i.e., with one two-month period delay).

Incentive prices may thus prospectively substitute for the grandfather right criterion in the allocation of slots to carriers, and provide long term signals that should induce carriers to take efficient decisions concerning the use of slots.

6 Discussion

In this section, we discuss some experiences with market mechanisms for allocating scarce resources, such as auctions and trading. In so doing, we point out the main drawbacks of such mechanisms, and stress the potential benefits from using a supervised mechanism based on the concepts of AIP.

In principle, well-designed auctions may ensure that scarce resources are assigned to those bidders that will be able to generate the highest value from managing them. However, the literature highlights some risks in running auctions in specific contexts (Klemperer, 2002a). First, high private valuations do not necessarily reflect the social value of resources. Indeed, while there is the need to achieve economic efficiency in allocating valuable resources (thus maximizing a weighted sum of consumers' and producers' surplus), this goal can hardly be attained in practice, as consumers do not participate in auctions (in addition, measuring *ex ante* the expected consumers' surplus is very difficult). Hence, the outcome of an auction is primarily driven by bidders' profits rather than social welfare. Moreover, Hoppe *et al*. (2006) stress the importance of market structure as a determinant of bidders' valuations.

A relevant example is the weirdly different outcome of auctions for third-generation mobile licenses in Europe, where spectrum was sold for over 600 euros per person in Germany and the UK, but for 100 and 20 euros per person respectively in Austria and Switzerland (Klemperer, 2002b).[31]

Jehiel and Moldovanu (2003) argue that many allocation decisions arising from the wave of deregulation in network industries share some issues with spectrum auctions. As to airport slots, there are strong (time and space) complementarities between termination and origination slots, both at the

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[31] In Germany, the auction rules induced incumbents to continue bidding, in tens of rounds of increasing bids, for the only purpose of denying a license to new entrants. This conduct resulted in about Euro 20 Bn paid in vain, collectively, by the licensed firms, which eventually included entrants (Jehiel and Moldovanu, 2003). Thus, the winning bids likely reflect the incumbents' willingness to pay for achieving market dominance, rather than the social value of auctioned resources.

same and at different airports. Moreover, control over prominent slots affects both competition among existing airlines and new carriers' entry. Therefore, bids at an auction for airport slots would likely reflect issues of market power, instead of the social value of slots.

As regards secondary trading, some experiences are specific to airport slots. Secondary trading of slots may improve efficiency by creating an opportunity cost for holding slots, since airlines that use slots forego revenues from selling (the right to use) slots. In this sense, secondary trading is similar to our model, which also creates an opportunity cost for holding slots. Despite this similarity, trading may yield strikingly different outcomes. Indeed, trading creates a *private* opportunity cost for using slots that stems from negotiations between airlines, while our model weighs a *social* opportunity cost for using slots that stems from considering the structure of the whole air transport network in an area.

Thus, aside from the merits, secondary trading of slots has some potential pitfalls. Indeed, several factors limit the contestability of the secondary slot market, such as (de Wit and Burghouwt, 2008):

- airlines may keep slots to dampen competition, in order not to cede prominent slots to rivals;
- potential buyers and sellers do not meet each other due to lack of information and transparency;
- slots have the option value of giving airlines flexibility relative to future network developments;
- airlines may not trade because of uncertainty about the stability of the slot management regime.

While secondary trading aims at easing market entry, it may occur that market concentration rises as more slots get in the hands of a few dominant carriers, which could give rise to competition concerns.

According to de Wit and Burghouwt (2008), slot trading should not be overestimated. Empirical evidence in the UK shows that trading has had mixed effects, since it has helped the dominant carrier (i.e. British Airways) to increase the share of slots at Heathrow airport, but also some other strong carriers (such as Virgin Atlantic) to emerge. Moreover, traded slots at Heathrow are used for flights that bring about a more efficient use of airport capacity. Similar mixed results have been observed for secondary trading of slots at congested airports in the US (Fukui, 2010).

It is worth noting that, to improve the effectiveness of market mechanisms, the EC advocates higher cooperation among airport coordinators (EC, 2011b). Such cooperation can progressively 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), and even creating a single coordinator responsible for slot allocation at all EU airports (in the long run). This EC's intent may prospectively provide the basis for defining an EU-wide system of incentive prices for slots.

In this paper, we have proposed a model to build this price system. While we have tried to keep the model as simple as possible, we could fine-tune some simplifying assumptions in the case where we could perform simulations based on real data. In a first application of the method, we could conservatively set incentive prices at a fraction of the estimated opportunity cost for slots (for instance, spectrum fees have initially been set at around 50% of the full opportunity cost; see Ofcom, 2010). Then, incentive prices may gradually rise over time towards the full opportunity cost. This approach is especially appropriate in the case where the estimated opportunity cost would result in a high incentive price for the slot, thereby inducing a dramatic change relative to the *status quo*.

Indeed, the proposed model could be demanding in terms of operational and economic data, and may require a significant computational effort, particularly at the time of first implementation. However, regulatory authorities in network industries have already faced similar challenges. For instance, Ofcom (2010) explains that the computed estimates to implement AIP have been informed by the available market information and by economic studies of the value of spectrum in various uses.

7 Conclusions

We have proposed a supervised market mechanism 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. We have explained how to compute incentive prices for airport slots from a measure of the best use of each slot in serving end users. For this purpose, we have considered the structure of the air transport network (and thereby interdependencies among slots at different airports) in a given area, and we have defined a metric based on both the number of transported passengers and the quality of passenger air transport in that area. We have discussed how the resulting incentive prices could better align private and social decisions over slot use relative to prices resulting from pure market interactions (such as auctions and trading).

Finally, we discuss some directions for future work. First, we may use the global approach to compute the actual incentive price of any slot, based on the operational and economic data for all airports in an area, and on the demand served. In this framework, we may assess the sensitivity of the returned estimates to the main assumptions, thereby striking the right balance between improving the accuracy of estimates (by relaxing some assumptions) and managing a reasonable amount of data.

Second, we may extend our model to find the joint marginal value of the whole set of slots at any airport. The resulting outcome could be of help for taking critical decisions about closing some airports, or opening new ones. Third, we may study the problem of setting incentive prices in a wider framework where we allow for intermodal passenger transport. Since alternative networks (e.g. air and rail transport) would compete for end users, then the marginal value of a slot should be computed by considering the possibility of substituting air transport with other transport modes.

Appendix 1

Let us consider the simple network in Figure 1, with two carriers (X and Y) and four airports: a_i (e.g. Frankfurt Airport FRA), a_j (e.g. Munich Airport MUC), a_k (e.g. Ferenc Liszt International Airport BUD), and a_u (e.g. Roma Fiumicino FCO). Let us also consider the following slots: slot u_t (e.g. $[8.00; 8.15]$) that is provided at airport a_u; slots j_{t+1} (e.g. $[9.15; 9.30]$) and j_{t+2} (e.g. $[10.15; 10.30]$) at airport a_j; slot k_t ($[8.00; 8.15]$) at airport a_k; and, finally, slots i_{t+2} (e.g. $[10.15; 10.30]$) and i_{t+3} ($[11.15; 11.30]$) at airport a_i (for brevity, we omit the day of the slots from notation).

We assume that air travel demand is such that about $p_1 = 100$ passengers should be transported from a_u to a_i, about $p_2 = 90$ passengers from a_j to a_i, and about $p_3 = 40$ passengers from a_k to a_i.

Consider first Scenario 1 (i.e. the left panel in Figure 1). In this scenario, the following non-stop flights are operated on the network (in Figure 1, non-stop flights are denoted by large arrows, while passengers' travels are denoted by dotted arrows): (i) carrier X takes off with p_1 passengers from airport a_u at slot u_t, and lands to airport a_j at slot j_{t+1}; (ii) carrier Y takes off with $p_1 + p_2$ passengers from airport a_j at slot j_{t+2}, and lands to a_i at i_{t+3}; and (iii) carrier Y takes off with $p_3 \ll p_1$ passengers from airport a_k at slot k_t, and lands to a_i at i_{t+2}. Air travel demand is thus served along the following paths: p_1 passengers fly from a_u to a_i via a_j; p_2 passengers fly from a_j to a_i; and p_3 passengers fly from a_k to a_i.

For illustrative purposes, we assume that carrier Y controls the relevant slots at the congested airport a_i (e.g. because of grandfather rights), while carrier X is a new entrant that strategically aims at entering airport a_i, by taking control over some slot of a_i. Carrier Y has the incentive to keep out carrier X from airport a_i, thereby forcing passengers who travel from a_u to a_i to be served by Y's fleet (when flying from a_j to a_i). However, in so doing, carrier Y inefficiently uses slot i_{t+2}.

Indeed, consider Scenario 2 (i.e. the right panel in Figure 1). In this scenario, carrier Y no longer controls slot i_{t+2}, which has become available to the new entrant X. As a consequence, airport slots in the network are used more efficiently. On the one hand, the travel of p_3 passengers from a_k to a_i takes one hour more, because it now includes the intermediate stop at a_j. On the other hand, the travel of p_1 passengers from a_u to a_i takes one hour less, because it now avoids the intermediate stop at a_j. Since, by assumption, we have that $p_3 \ll p_1$, then the overall level of quality of the air transport service is higher in Scenario 2 than in Scenario 1.

Thus, how would Scenario 2 likely come up? As already noted, grandfather rights and the use-it-or-lose it rule may induce an inefficient use of slots (see EC, 2011b). In fact, they provide carriers with incentives to hold on slots to keep out competitors, with some flights being operated despite accounting losses. This may result in low load factors and/or using small aircrafts at busy airports. In our example, this regulatory regime would encourage carrier Y to inefficiently maintain slot i_{t+2}.

Let us now introduce a different regulatory regime, where carriers have to pay incentive prices for holding slots. If slots at airport a_i were consistently priced, carrier Y would likely find it profitable to leave slot i_{t+2}, because revenues from the few p_3 passengers would not cover the cost of holding the slot. On the other hand, carrier X would likely find it profitable to pay for using the newly available slot i_{t+2} (while leaving slot j_{t+1}), thanks to revenues from the higher number of transported passengers p_1. It follows that introducing suitable incentive prices for using airport slots may effectively serve the goal of converging towards Scenario 2.

[Insert Figure 1 about here.]

Appendix 2

We formulate here the problem Ψ of determining the highest service level that can be provided by using all the origination and termination slots of airports in A to serve the estimated demand:

$$
\left\{
\begin{array}{lr}
\max \sum_{p=(i,\ldots,j)\in P} \frac{l_{a(i),a(j)}^{min}}{tl(p)} w_p & \\
subject\ to & \\
\sum_{p\in P_{ij}} w_p \ \leq d_{ij} \qquad (i,j)\in D & (1) \\
\sum_{p\in P:p=(\ldots,i,\ldots)} w_p \ \leq sc_i \qquad i\in \bigcup_{a\in A} O_a & (2) \\
\sum_{p\in P:p=(\ldots,j,\ldots)} w_p \ \leq sc_j \qquad j\in \bigcup_{a\in A} T_a & (3) \\
\sum_{p\in P:p=(\ldots,i,j,\ldots)} w_p \ \leq fc_{ij}\cdot nf_{ij} \qquad (i,j)\in P & (4) \\
\sum_{j:(i,j)\in P} nf_{ij} \ \leq no_i \qquad i\in \bigcup_{a\in A} O_a & (5) \\
\sum_{i:(i,j)\in P} nf_{ij} \ \leq nt_j \qquad j\in \bigcup_{a\in A} T_a & (6) \\
nf_{ij} \ \in \mathbb{Z} \qquad (i,j)\in P & (7) \\
 & \\
w_p \ \geq 0 \qquad p\in P & \\
nf_{ij} \ \geq 0 \qquad (i,j)\in P &
\end{array}
\right.
$$

where $w_p \ \geq 0$ for any $p \in P$ denotes the number 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 that take off from $a(i)$ in i and land to $a(j)$ in j.

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 that 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 that 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 that can be originated (terminated) in $a(i)$ $(a(j))$ during i (j) is limited. Finally, constraints (7) require 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. Although designing exact or heuristic methods to solve Ψ is not the goal of this work, let us however 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 highest 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 determine good approximations of the optimal value of Ψ, which might be suitably applied, after further research, to provide an estimate of the marginal contribution of any (multiple) slot in real cases (see e.g. Footnote 23).

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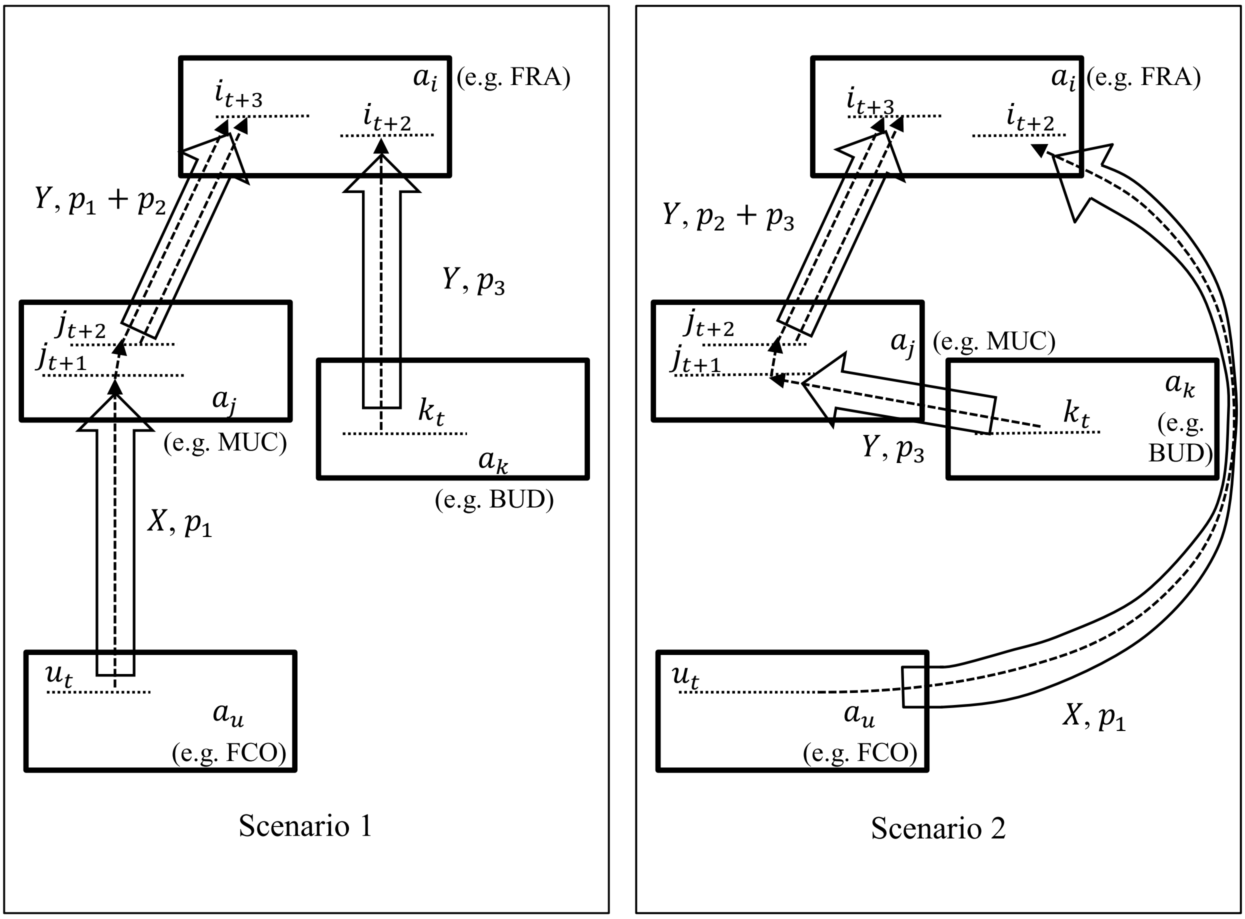

Scenario 1

Scenario 2

Figure 1. An example.