Department of Applied Mathematics, University of Venice

WORKING PAPER SERIES

Lorenzo Castelli, Paola Pellegrini, Raffaele Pesenti

Airport slot allocation in Europe: economic efficiency and fairness

Working Paper n. 197/2010
June 2010

ISSN: 1828-6887

Airport slot allocation in Europe: economic efficiency and fairness

LORENZO CASTELLI
castelli@units.it
DEEI, Università degli Studi di Trieste
Via A.Valerio 10, 34127, Trieste, Italy

PAOLA PELLEGRINI
paolap@unive.it
DMA, Università Ca' Foscari Venezia
Dorsoduro 3825/E, 30123, Venezia, Italy

RAFFAELE PESENTI
pesenti@unive.it
DMA, Università Ca' Foscari Venezia
Dorsoduro 3825/E, 30123, Venezia, Italy

(June 2010)

Abstract

We propose a mechanism for solving the airport slot allocation problem in Europe. We consider the interdependence of the slots at different airports, and we maximize the efficiency of the system. Through an experimental analysis we quantitatively assess the cost imposed by grandfather rights, which constitute one of the main principles of the current slot allocation mechanism. Moreover, we introduce the possibility to fairly redistribute costs among airlines through monetary compensations. Our results suggest that it is possible to remove grandfather rights without significantly penalizing airlines.

Keywords: Air Traffic Management, Airport slot allocation, Compensation mechanism, SESAR

JEL Classification Numbers: C61, C44

Correspondence to: Paola Pellegrini, paolap@unive.it

1 Introduction

The current European Air Traffic Management (ATM) system is not expected to be able to cope efficiently with the predicted growth of air traffic in Europe in the next ten to twenty years. In response of this challenge, in 2004 the European Commission launched the Single European Sky initiative whose technological dimension for promoting innovation in ATM is SESAR, the Single European Sky ATM Research Programme (SESAR Consortium 2008). A key concept in SESAR is the introduction of Collaborative Decision Making (CDM) tools for making the most of available resources (SESAR Consortium 2007).

An important area of implementation of possible ad-hoc CDM mechanisms is the strategic agreement during the flight planning phase to adjust traffic demand or individual flight trajectories if airports cannot provide sufficient capacity. In fact, the lack of airport capacity is a major constraint for the development of air traffic because the building of new runways is strongly limited. Then there is the need to design procedures which exploit as much as possible the available airport scarce resources. Formal procedures are implemented for allocating capacity and coordinate schedules. In Europe, these procedures comply with International Air Transport Association (IATA) and European Commission regulations (International Air Transport Association 2010, Council of the European Community 1993, 2004). In this framework, about six months before the starting of either the summer (April to October) or winter (November to March) season, representatives of airlines and airports meet at a IATA conference to allocate airport slots for the forthcoming season. A slot is a scheduled time of arrival or departure available for allocation for an aircraft movement on a specific date and airport. Currently, this *slot allocation problem* is solved in two steps. Initially, grandfather (or historical) rights are identified. An airline has a right to a slot if it has made use of the correspondent slot in the preceding equivalent season. Such right can be lost only as a consequence of the *use-it-or-loose-it* rule: a slot can be allocated to another airline if its usage on the preceding equivalent season has been lower than 80%. Then, the free slots are all grouped in a pool. Half of this pool is allocated to new entrants (*new entrant* rule). For being such, an airline requesting a series of slots at an airport on a day must have less than five slots at that airport at that day, if its request is accepted. The remaining slots are finally allocated in a non-discriminatory manner.

The first drawback of the above slot allocation mechanism is represented by the loss of economic efficiency due to the existence of grandfather rights: the *use-it-or-loose-it* rule has the effect of eventually inducing airlines to use slots inefficiently for not loosing them. Moreover, historical rights represent a strong entrance barrier for potential competitors notwithstanding the *new entrant* rule (DotEcon Ltd 2001, Maldoom 2003, Starkie 1998). Thus the current mechanism favors immobility in the market and prevents competition among airlines. As a result, scarce resources are often not used as efficiently as possible.

The ATM community emphasizes the need of a major modification of the current mechanism for overcoming these drawbacks. A new mechanism should allocate slots to whom values them the most. The need for this type of study is pointed out in a wide number of reports commissioned by the European Commission and other national institutions (DotEcon Ltd 2001, 2006, NERA Economic Consulting 2004). Also in the scientific literature several, authors investigate the opportunity of implementing auction mechanisms for managing slots, following the current practice at some US airports (Fukui 2010, Kleit & Kobayashi 1996, Maldoom 2003, Sentance 2003, Starkie 1998, Verhoef 2010). On the side of this rich branch of research, Madas & Zografos (2006) make an interesting qualitative analysis of the main strategies that may be implemented. In particular, the authors point out five type of strategies, characterized by an increasing level of differentiation with respect to the current slot allocation mechanism. The extreme scenarios correspond, on the one hand, to combining grandfather rights and the rationale of administrative coordination of slot allocation, and, on the other hand, to abandoning grandfather rights entirely and basing the allocation on decentralized auctions. The intermediate steps are characterized by different combination of grandfather rights, central coordination and free market.

In this paper, we quantitatively analyze the economic impact of grandfather rights by comparing airlines' costs when these rights are either enforced or not. We consider the cost due to the non-optimality of the final schedule allotted to each airline for respecting capacity constraints. We propose a slot allocation mechanism based on an integer programming model and we perform experimental tests on realistic instances that simulate air traffic demand over a portion of the European sky in a 5 hour time horizon. We show that the system disutility (i.e., the sum of the costs of the individual airlines) is higher when grandfather rights are present. Then we introduce some compensation mechanisms in the slot allocation process for fairly transferring the disutility of the system to each airline. The results of our experimental simulations show that compensations may help in redistributing among airlines the surplus deriving from the elimination of grandfather rights. In this way, it is possible to implement a mechanism in which social utility increases, without inevitably damaging the airlines that loose their grandfather rights.

In the current slot allocation mechanism airports are considered independent one of the other. It is not taken into account that, for each flight, an airline needs a feasible combination of slots at the origin and destination airports (NERA Economic Consulting 2004). Thus, an *a-posteriori* adjustments to the initial allocation may be necessary. Our slot allocation mechanism overcomes this weakness by simultaneously allocating slots at several airports and considering the structure of the network and the airlines requests in terms of origin-destination pairs. Thus, it provides a slot allocation that is coherent with the desired schedule from the very beginning. To the best of our knowledge, the interdependence among slots at different airports is formally considered only in Rassenti et al. (1982). The authors proposed a combinatorial auction mechanism for airport slot allocation. Still, the main focus was on the efficiency and robustness of the auction design in terms of demand revelation.

The rest of the paper is organized as follows. Section 2 introduces our slot allocation mechanism and details the integer programming model. In Section 3 we propose three compensation mechanisms that can be included in the model. In Section 4 we depict the structure of the experimental analysis and we report the results.

Finally, in Section 5 we draw some conclusions and define some future development of this research.

2 Slot Allocation Models

Our mechanism solves the slot allocation problem at all airports simultaneously, while considering the structure of the air route network. In this way, an airline obtains for each flight a departure (arrival) slot if at the destination (origin) airport it receives a slot which is compatible with the flight duration of one of the possible routes connecting the two airports. Moreover, we assume that, due to commercial and operations reasons, an airline has an ideal pair of departure and arrival slots, hereafter referred to simply as *ideal slots*, for each of its flights. When this ideal pair is not available, the airline has to anticipate or delay the departure and the corresponding arrival time and this shift induces an undesired cost, hereafter referred to as *shift cost*.

We model the problem of allocating airport slots to airlines while taking into account the air route network as a mathematical programming problem. In doing this, we rely on mathematical formulations which till now have been used in the Air Traffic Flow Management (ATFM) problem (Bertsimas et al. 2008, 2009, Bertsimas & Patterson 1998, 2000, Lulli & Odoni 2007, Sherali & Hill 2009).

ATFM models are used to prevent short-term demand-capacity imbalances by adjusting the flows of aircrafts combining actions such as the imposition of rerouting, ground holding, airborne holding and aircraft speed control. The most recent papers (such as Bertsimas et al. 2009) optimize the traffic flow on a short-term basis, i.e., a few hours before flight departures, taking into account the capacity of all elements (airports and en route sectors) of the ATM system. They consider details, such as whether conditions, that are not available in the planning phase, when the airport slot allocation is performed.

Our slot allocation model is a variant of the Bertsimas et al. (2009) one. Our formulation relies on a simplified representation of the route network, e.g., we assume that the time required to cross every sector is fixed (no speed control) and that the en-route sectors are uncapacitated. On the other hand, differently from the reference model, we consider airlines managing multiple flights and grandfather rights. In addition, the Bertsimas et al. (2009) model assumes that the schedule of each flight is already known. Any action to react to unforseen events necessarily leads to the introduction of either ground holding or airborne delay departure, when flight rerouting is not sufficient. On the contrary, our model, in trying to accommodate all the demand into the available slots, assumes that in the planning phase there is still room to both anticipating and delaying the departure and arrival times with respect to the ideal slots. As a consequence, we seek a solution that minimizes the shift costs while Bertsimas et al. (2009) minimize the delay costs. In this framework, our model allows each airline to indicate the maximum shift it can bear for each flight. To this aim some sharing of information is needed. For coping with the reluctance of airlines of making their costs and requirements transparent to competitors, in accordance with Soomer & Franks (2008), our mechanism is regulated by an independent coordinator that is in charge of managing sensible data.

2.1 The mathematical formulation

Notation

The model's formulation requires definition of the following notation:

$A \equiv$ set of airlines,
$F \equiv$ set of flights,
$F_a \subseteq F \equiv$ set of flights of airline a,
$K \equiv$ set of airports,
$S \equiv$ set of (en-route) sectors,
$S^f \subseteq S \cup K \equiv$ set of sectors that can be flown by flight f, including the origin and the destination airports,

$$\begin{array}{rcl}
T & \equiv & \text{set of time periods,} \\
P_i^f & \equiv & \text{set of sector } i\text{'s preceding sectors } (i \in S^f), \\
L_i^f & \equiv & \text{set of sector } i\text{'s subsequent sectors } (i \in S^f), \\
K_{j,t} & \equiv & \text{capacity of airport } j \text{ at time } t, \\
G_{j,t}^a & \equiv & \text{number of slots on which airline } a \text{ has grandfather right at airport } j \text{ at time } t \\
d_f & \equiv & \text{ideal departure slot of flight } f, \\
a_f & \equiv & \text{ideal arrival slot of flight } f, \\
orig_f & \equiv & \text{origin airport of flight } f, \\
dest_f & \equiv & \text{destination airport of flight } f, \\
l_{fjj'} & \equiv & \text{number of time units that flight } f \text{ must spend in sector } j \text{ before entering in sector } j', \\
end_f & \equiv & \text{maximum acceptable duration of flight } f, \\
T_{orig_f}^f = [\underline{T}_{orig_f}^f, \bar{T}_{orig_f}^f] & \equiv & \text{accepted departure slots for flight } f, \\
T_{dest_f}^f = [\underline{T}_{dest_f}^f, \bar{T}_{dest_f}^f] & \equiv & \text{accepted arrival slots for flight } f, \\
c^f(\hat{t}) & \equiv & \text{cost of deviating of } \hat{t} \text{ time intervals from the ideal arrival slot of flight } f, \\
c_{dur}^f(\hat{d}) & \equiv & \text{cost associated to an additional duration of } \hat{d} \text{ with respect to the ideal one for flight } f.
\end{array}$$

The decision variables

$$w_{j,t}^f = \begin{cases} 1 & \text{if flight } f \text{ is in airport or sector } j \text{ by time } t, \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

The objective function

Let

$$\begin{aligned} C_f = & \sum_{t \in T_{dest_f}^f} c^f(t - a_f)(w_{dest_f,t}^f - w_{dest_f,t-1}^f) + \\ & + c_{dur}^f \left(\sum_{t \in T_{dest_f}^f} t(w_{dest_f,t}^f - w_{dest_f,t-1}^f) - \sum_{t \in T_{orig_f}^f} t(w_{orig_f,t}^f - w_{orig_f,t-1}^f) - (a_f - d_f) \right) \end{aligned} \tag{2}$$

be the cost imposed to flight f. Note that the first part of the cost depends on the arrival time, while the second part depends on the flight duration, and hence, implicitly on the departure time. If no shift is assigned to the ideal arrival slot or to the ideal duration, this cost is null. Otherwise it is given by a function of such shift.

Costs for executing flights are considered independent from the exact schedule. Thus, costs due to a shift of departure and arrival slots correspond to revenue losses. If we consider a utility function that is directly (and linearly) proportional to revenue, minimizing costs, and thus revenue losses, is equivalent to maximizing utility.

In particular, in this paper we consider $c^f(\hat{t}) = \alpha \hat{t}^\beta$, $c_{dur}^f(\hat{d}) = \gamma \hat{d} \forall f \in F$, being α, β and γ nonnegative parameters.

The the overall objective function is

$$\min \sum_{f \in F} C_f, \tag{3}$$

that represents the sum of the cost imposed to all flights.

The Constraints

The model's constraints set is as follows:

$$\sum_{j\in\{orig_f,dest_f\}} w^f_{j,\bar{T}^f_j} = 2 \qquad \forall f \in F \tag{4}$$

$$w^f_{orig_f,\underline{T}^f_{orig_f}-1} = 0 \qquad \forall f \in F \tag{5}$$

$$\sum_{f\in F:dest_f=k\vee orig_f=k} w^f_{j,t} - w^f_{j,t-1} \leq K_{j,t} \qquad \forall j \in K,\, t \in T \tag{6}$$

$$\sum_{f\in F\setminus F_a:dest_f=k\vee orig_f=k} w^f_{j,t} - w^f_{j,t-1} \leq K_{j,t} - G^a_{j,t} \qquad \forall j \in K,\, t \in T,\, a \in A \tag{7}$$

$$w^f_{j,t} \leq \sum_{i\in L^f_j} w^f_{i,t+l_{fji}} \qquad \forall f \in F,\, j \in S^f \setminus \{dest_f\},\, t \in T \tag{8}$$

$$w^f_{j,t} \leq \sum_{i\in P^f_j} w^f_{i,t-l_{fij}} \qquad \forall f \in F,\, j \in S^f \setminus \{orig_f\},\, t \in T \tag{9}$$

$$w^f_{j,t} \leq \sum_{i\in L^f_j} w^f_{i,t} \qquad \forall f \in F,\, j \in S^f \setminus \{dest_f\},\, t = \max\{T\} \tag{10}$$

$$\sum_{i\in L^f_j} w^f_{i,t} \leq 1 \qquad \forall f \in F,\, j \in S^f \setminus \{dest_f\},\, t = \max\{T\} \tag{11}$$

$$w^f_{orig_f,t} - w^f_{dest_f,t+end_f} \leq 0 \qquad \forall f \in F,\, t \in T \tag{12}$$

$$w^f_{j,t-1} - w^f_{j,t} \leq 0 \qquad \forall f \in F,\, j \in S^f,\, t \in T \tag{13}$$

$$w^f_{j,t} \in \{0,1\} \qquad \forall f \in F,\, j \in S^f,\, t \in T \tag{14}$$

Constraints (4) and (5) ensure that all flights are executed in the time interval that is declared to be acceptable by the airline. Constraints (6) ensure that airport capacity is not exceeded at any time, and constraints (7) that grandfather rights are respected. Constraints (8) and (9), and (10), (11) and (13) represent routes' time and spatial coherence, respectively. As an example, constraints (9) ensure that an aircraft cannot enter a sector unless it has crossed a preceding one. According to constraints (12), each flight cannot last more than its maximum duration declared. Finally, constraints (14) impose the use of binary variables. Let us remark that constraints (7) and (8), are not present in the reference model (Bertsimas et al. 2009).

For speeding up the solution process, the following valid inequalities are implemented:

$$\sum_{i\in P^f_j:|L^f_i|=1} w_{i,\bar{T}^f_i} \leq 1 \qquad \forall f \in F,\, j \in S^f \setminus \{orig_f\} : |P^f_j| > 1 \tag{15}$$

$$\sum_{i\in L^f_j} w_{i,\bar{T}^f_i} \leq 1 \qquad \forall f \in F,\, j \in S^f \setminus \{dest_f\} : |L^f_j| > 1 \tag{16}$$

$$w^f_{j,t} \geq \sum_{i\in L^f_j:|P_i|^f=1} w^f_{i,t+l_{fji}} \qquad \forall f \in F,\, j \in S^f \setminus \{dest_f\},\, t \in Tf \tag{17}$$

$$w^f_{j,t} \geq \sum_{i\in P^f_j:|L_i|^f=1} w^f_{i,t-l_{fij}} \qquad \forall f \in F,\, j \in S^f \setminus \{orig_f\}, t \in T \tag{18}$$

Equations (17), (15) and (16) are presented by Bertsimas et al. (2009). Equation (18) is added following the introduction of constraints (8).

The efficiency in slot allocation can be increased by removing the restrictions enforcing the existence of grandfather rights (constraints (7)). The two models, where constraints (7) are either imposed or not, will be tested in Section 4, and they will be referred to as the *grandfather rights* model (GFR) and *free allocation* model (FA), respectively.

3 Compensation Mechanisms

In principle, GFR and FA may penalize just a few airlines to the benefit of the whole system. In fact, it may happen that all flights whose slots are shifted belong only to a subset of airlines. In this Section we propose further constraints to add to GFR and FA that increase the fairness of the final solution through a monetary compensation mechanism. Let p_a be an additional decision variable representing the amount of money received/payed by an airline $a \in A$. If p_a is greater than 0 then it is the compensation for the cost the airline must bear when its flights are shifted. If p_a is less than 0 it is the amount payed by the airline for compensating competitors subject to a high shift cost. In order to be effectively implemented the mechanism has to meet two properties: budget balance and individual rationality (?).

A mechanism is budget balanced if the overall amount paid and received by the airlines participating in it sums up to 0:

$$\sum_{a \in A} p_a = 0. \tag{19}$$

In such a way the independent coordinator neither subsidizes the market nor gains from it.

A mechanism is individual rational if it does not cause a decrement of the utility of any airline without compensating it by an appropriate side payment. In other words, each airline must have no disadvantage in participating to the mechanism. The amount payed as compensation plus the shift cost must be at most equal to the maximum cost the airline is ready to bear:

$$\sum_{f \in F_a} C_f - p_a \leq \sum_{f \in F_a} \{c^f(\max\{a_f - \underline{T}^f_{orig_f}, \bar{T}^f_{orig_f} - a_f\}) + c^f_{dur}(\bar{T}^f_{dest_f} - \underline{T}^f_{orig_f} - (a_f - d_f))\} \qquad \forall a \in A. \tag{20}$$

As previously mentioned, the airline itself declares this value when it announces the cost associated to the maximum acceptable variation with respect to the requested schedule.

Several combinations of payments can satisfy constraints (19) and (20). For example, a solution in which $p_a = 0$, for all $a \in A$ is feasible, although not achieving the desired fairness. Moreover, due to constraint (19) the objective function value is independent from the amount of the compensation:

$$\sum_{f \in F} C_f = \sum_{a \in A} \left(\sum_{f \in F_a} C_f - p_a \right). \tag{21}$$

For achieving a fair allocation, we may add to GFR and FA a further set of constraints ensuring that each airline bears no more than a share s_a of the total cost (22):

$$\sum_{f \in F_a} C_f - p_a \leq s_a \sum_{f \in F} C_f \qquad \forall a \in A, \tag{22}$$

where $0 \leq s_a \leq 1$ and $\sum_a s_a = 1$.

Several methods for computing these shares are possible. One choice is to penalize airlines proportionally to their contribution to the infeasibility of the ideal solution. In particular, let $\hat{KT}$ be the set of combination airport-time in which slot demand is greater than capacity:

$$\hat{KT} = \{(j,t), j \in K, t \in T : \sum_{f \in F} I(j,t,f) > K_{jt}\}, \tag{23}$$

where $I(j,t,f)$ is equal to 1 if the ideal slot either at arrival or at departure of flight f is at airport j at time t, and 0 otherwise. Then

$$s_a = \frac{|F_a : (orig_f, d_f) \in \hat{KT} \vee (dest_f, a_f) \in \hat{KT}|}{\sum_{(j,t) \in \hat{KT}} K_{j,t}} \qquad \forall a \in A. \tag{24}$$

In this way, if an airline a asks only for slots in periods with no excess demand (and hence $s_a = 0$) and it must bear a time shift for allowing a feasible schedule ($\sum_{f \in F_a} C_f > 0$), the consequent cost must be completely compensated. If, instead, an airline requires to land at a main airport in the peak time (and hence $s_a > 0$) then even if it is allowed to do so, it must be ready to refund competitors that do not have the same opportunity. In the following we will refer to this method as *contribution to infeasibility* (CI).

Two other possibilities consist in considering an equal distribution of costs to flights or to airlines. In the first case (*equal flights*, EF), each airline bears a share of the total cost that is equal to the ratio between the number of flights it requests and the total number of flights in the system. In the second case (*equal airlines*, EA), the total cost is just equally divided among airlines. These two methods can be enforced by computing s_a as shown in (25) and (26), respectively.

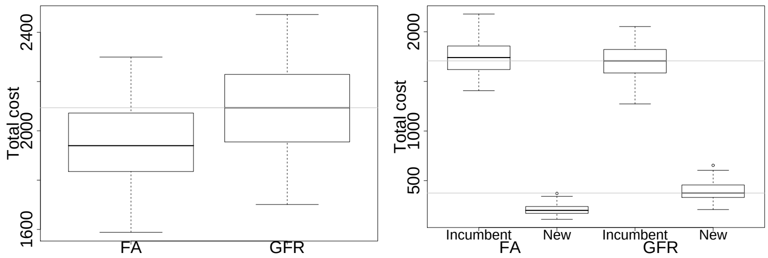
$$s_a = \frac{|F_a|}{|F|} \qquad \forall a \in A, \tag{25}$$

$$s_a = \frac{1}{|A|} \qquad \forall a \in A. \tag{26}$$

4 Computational Experience

In this Section, we analyze the different possibilities for enhancing the efficiency and the fairness of the slot allocation mechanism. In particular we compare GFR with the models that either eliminate simply the grandfather rights (FA), or also introduce one of the compensation mechanisms, i.e., FA+CI, or FA+EF, or FA+EA. The difference in the results are tested for statistical significance at the 95% confidence level, according to the Wilcoxon rank-sum test.

We run the experimental analysis on 100 randomly generated instances in which we simulate 5 hours traffic over a portion of the European sky. We consider 2200 flights of 20 airlines on a network of 60 airports, 4 of which hubs, and 300 sectors. The time horizon is divided in 20 fifteen-minute time intervals. Each flight spends one time interval in each sector it crosses, and it cannot exceed a 2-hour duration. Airport capacity is set to 28 for each time interval. Thus we have a set of 560 slots per airport. This value is consistent with Eurocontrol Experimental Centre (2009) considering the four larger European hubs. The same value is used for local airports, for representing the typical situation in which no capacity restrictions are imposed. At each hub, mimicking the situation at highly congested airports, as for example London Heathrow, 90% of slots are subject to grandfather rights, i.e. 504 out of 560 slots are pre-allocated. We partition the 20 airlines in 5 *new airlines*,



(a) Total cost (b) Cost per set of airlines

Figure 1: Total shift cost implied by the grandfather rights and free allocation models.

which do not have grandfather rights, and 15 *incumbent airlines*, which enjoy grandfather rights. The new airlines own in average about 37 flights, i.e., 1.69% of the flights considered. The incumbent airlines have their grandfather rights at the hubs assigned by randomly selecting some of their flights. Sectors are represented as a grid of square cells, and the location of airports is randomly distributed, imposing a minimum distance of three cells between each pair of airports. The maximum shift allowed is set equal to 2 time intervals for each flight, i.e., half an hour. The origin and the destination of each flight are randomly chosen, at least one of them being a hub. The ideal departure slot is randomly drawn and the arrival one is computed consequently, considering the shortest feasible route. Then, a check is done for seeking feasibility: both for origin and destination airports of each flight f, we check if, considering the ideal slots of all flights, total demand is lower than total capacity at that airport, within the maximum shift accepted for f. If this is not the case, then setting that slot as ideal one for flight f will turn into an infeasible instance. Thus, a new random selection is made. This procedure mimics the current practice, in which, if requests cannot be satisfied, the schedule coordinator asks airlines to change their requirements (International Air Transport Association 2010).

We set the parameters of the cost coefficients in the objective function equal for all flights: $\alpha = 10, \beta = 1.5, \gamma = 10$. By setting β greater than 1, shifting the arrival slot of 2 flights of $\hat{t}$ is less costly than shifting the arrival slot of one flight of $2\hat{t}$.

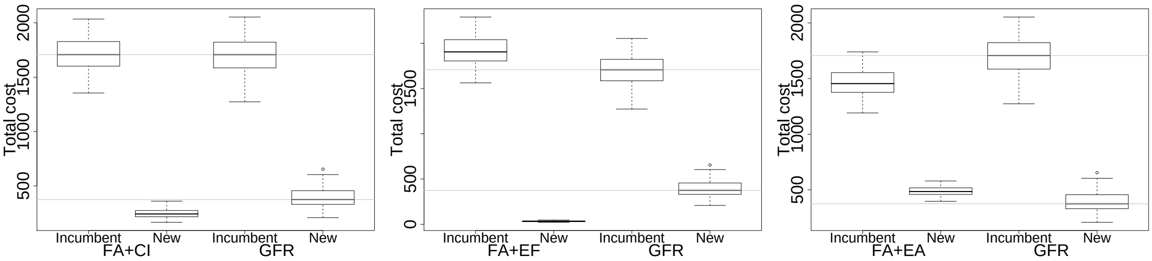
We solved these 100 instances with an optimality gap of 1%, using XPRESS optimizer version 20.00.11 on a Intel Core 2 Duo CPU at 1.86 GHz and with 2.00Gb of Ram. The CPU time necessary for computing the matrix and solving instances was, in average, 180.25 seconds, ranging between 35.06 and 1681.58 seconds.

4.1 Grandfather rights *vs.* free allocation

Figure 1 reports the results achieved by GFR and FA. The grey horizontal lines represent the median of the solution cost of GFR. Figure 1(a) shows the total cost computed over all airlines: the total cost implied by FA is on average 7.08% lower than that implied by GFR. The difference in favor of FA is statistically significant. Figure 1(b) distinguishes the cost born by incumbent airlines, which in GFR hold grandfather rights, and by new ones. The cost increase suffered by the former group when comparing GFR and FA is much lower than the cost reduction enjoyed by the latter. On the one hand, new airlines are better off in FA in 98 instances over 100; the average improvement is 93.55%, and in the two unfavorable case the cost increase is 0.82% and 5.52%, respectively. The difference is statistically significant in favor of FA. On the other hand, the costs for incumbent airlines in average increase of 2.36%, with a maximum of 11.37%. The difference is statistically significant in favor of GFR. In 28 instances even incumbent airlines would gain from the removal of grandfather rights. This situation occurs, as they want to introduce flights for which they do not have grandfather rights.

4.2 Grandfather rights *vs.* free allocation with compensation

The results of the the three compensation models described in Section 3 are introduced here. In particular we present the value of the disutility of the two groups of airlines. We compare these values with the values obtained with GFR (Figure 2), that is used as the reference model for the current situation. The grey horizontal lines



(a) Contribution to infeasibility (b) Equal flights (c) Equal airlines

Figure 2: Total shift cost of the grandfather rights model and the free allocation one with compensation.

Table 1: Percentage cost decrease with the free allocation model with and without compensation with respect to GFR. A star indicates if the difference is statistically significant at the 95% confidence level, according to the Wilcoxon rank-sum test.

	FA	FA+CI	FA+EF	FA+EA
incumbent airlines	-2.36^*	-0.48	-10.88^*	15.97^*
new airlines	93.55^*	60.47^*	1122.30^*	-19.69^*

represent the median of the solution cost of GFR. When the free allocation with the contribution to infeasibility compensation (FA+CI) is implemented (Figure 2(a)), new airlines have a significant advantage with respect to GFR. Incumbent airlines, instead, are almost indifferent. If the equal flights compensation model (FA+EF) is considered, new airlines obtain a significant relative cost decrease. Incumbent airlines, instead, suffer from a significant cost increase. When the equal airlines compensation model (FA+EA) is used (Figure 2(c)), new airlines are strongly penalized, while incumbent ones enjoy a cost decrease. The percentage cost decrease in the different scenarios with respect to GFR are summarized in Table 1.

These results suggest that FA+CI is the only model that can be accepted by both groups of airlines in case the grandfather rights were removed. It provides a slot allocation and a redistribution of costs which increase the utility of the new airlines and do not statistically penalize the incumbent ones.

5 Conclusions

In this paper we propose a mechanism for solving the airport slot allocation problem. The mechanism considers the interdependence of the slots at different airports, and it maximizes the efficiency of the system by allocating slots to the airlines that value them the most. Through an experimental analysis we quantitatively evaluated the cost imposed by the enforcement of grandfather rights, which constitute one of the main principles of the current slot allocation mechanism.

Furthermore, we introduced a monetary compensation mechanism for augmenting fairness. We tested three methods for implementing such a compensation, measuring their contribution in redistributing among airlines the surplus deriving from the elimination of grandfather rights. In conclusion, through combining a free slot allocation and a compensation mechanism, social utility increases, and even airlines that have grandfather rights are often positively affected by their elimination.

Future works will be devoted to the analysis of what is commonly known as secondary slot market, i.e., slot exchange among airlines after their primary allocation.

Acknowledgments

Lorenzo Castelli acknowledges the support from the Italian Ministry of Education, University and Research (MIUR) under the project "Enhancing the European Air Transportation System" of the PRIN 2008 programme.

References

Bertsimas, D., Lulli, G. & Odoni, A. (2008), The air traffic flow management problem: an integer optimization approach, *in* 'Algorithmic Game Theory', Vol. 5035 of *Lecture Notes in Computer Science*, Springer Berlin / Heidelberg, Berlin, Germany, pp. 34–46.

Bertsimas, D., Lulli, G. & Odoni, A. (2009), 'An integer optimization approach to large-scale air traffic flow management', *Operations Research* . In press.

Bertsimas, D. & Patterson, S. S. (1998), 'The air traffic flow management problem with enroute capacities', *Operations Research* **46**(3), 406–422.

Bertsimas, D. & Patterson, S. S. (2000), 'The traffic flow management rerouting problem in air traffic control: a dynamic network flow approach', *Transportation Science* **34**(3), 239–255.

Council of the European Community (1993), 'Regulation 95/1993'.

Council of the European Community (2004), 'Regulation 793/2004'.

DotEcon Ltd (2001), 'Auctioning airport slots'.

DotEcon Ltd (2006), 'Alternative allocation mechanisms for slots created by new airport capacity'.

Eurocontrol Experimental Centre (2009), 'European medium-term atm network capacity plan assessment 2010-2013'.

Fukui, H. (2010), 'An empirical analysis of slot trading in the Unites States', *Transportation Research Part B* **44**, 330–357.

International Air Transport Association (2010), 'Worldwide scheduling giudelines, 19th edition'.

Kleit, A. & Kobayashi, B. (1996), 'Market failure or market efficiency? Evidence on airport slot usage', *Research in Transportation Economics* **4**(1), 1–32.

Lulli, G. & Odoni, A. (2007), 'The european air traffic flow management problem', *Transportation Science* **41**(4), 431–443.

Madas, M. & Zografos, K. (2006), 'Airport slot allocation: From instruments to strategies', *Journal of Air Transport Management* **12**, 53–62.

Maldoom, D. (2003), 'Autioning capacity at airports', *Utilities Polocy* **11**, 47–51.

NERA Economic Consulting (2004), 'Study to assess the effects of different slot allocation schemes'.

Rassenti, S., Smith, V. & Bulfin, R. (1982), 'A combinatorial auction mechanism for airport time slot allocation', *Bell Journal of Economics* **13**(2), 402–417.

Sentance, A. (2003), 'Airport slot auctions: desirable or feasible?', *Utilities Polocy* **11**, 53–57.

SESAR Consortium (2007), *Milestone Deliverable D3: ATM Target Concept.*

SESAR Consortium (2008), *Milestone Deliverable D1: Air Transport Framework The Current Situation.*

Sherali, H. D. & Hill, J. M. (2009), 'Reverse time-restricted shortest paths: Application to air traffic management', *Transportation Research Part C: Emerging Technologies* **17**(6), 631–641.

Soomer, M. & Franks, G. (2008), 'Scheduling aircraft landings using airlines' preferences', *Journal of Air Transport Management* **190**, 277–291.

Starkie, D. (1998), 'Allocating airport slots: a role for the market?', *Journal of Air Transport Management* **4**, 111–116.

Verhoef, E. (2010), 'Congestion pricing, slot sales and slot trading in aviation', *Transportation Research Part B* **44**, 320–329.