Tradable Mobility Permits for the Strategic Allocation of Air Traffic

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***Abstract*—Current strategic decisions involving air traffic flows are limited to the allocation of airport slots. In this work, a first strategic market-based mechanism for the allocation of en route resources, i.e., sector capacity, is proposed. Identifying en route capacity shortages at this phase can lead to strategic actions to reduce flight delays on the day of operations. Tradable mobility permits previously developed for roadway transportation are analyzed and adapted to the air transport case. A trading mechanism for the strategic alleviation of air traffic congestion that uses time-place specific permits is proposed, providing alternative implementations. We call this new approach Tradable Flight Permit System (TFPS). An example of its use is illustrated, showing how it can lead to cost reductions for the airlines competing for a single sector access permit. We also highlight the improvements it can provide compared to current practice and a variety of alternative methods.**

Keywords: strategic traffic allocation, tradable mobility permits, trading, congestion, strategic air traffic flow, SATURN

I. Introduction

Air traffic congestion on the day of operations causes high delay expenses for airlines and aircraft operators. While it can also be a relevant issue at busy airports, airspace congestion in Europe is critical. In 2012, eight Area Control Centers (ACCs) in Europe recorded an average en route Air Traffic Flow Management (ATFM) delay of over one minute per flight for more than 30 days [1]. The average cost of ATFM delay was estimated by the University of Westminster [2] to be 83€ per minute, including direct costs, the network effect, and the estimated costs for airlines to retain passenger loyalty.

Currently, at the strategic phase, i.e., months before the operation of flights, only time slots needed to operate flights at airports are assigned. This assignment follows the guidelines of the International Air Transport Association (IATA) [3] and of the European Regulation 95/1993. An airport slot is a permit allowing the use of the complete set of resources needed to operate a flight at a specific airport at a given time. An extensive analysis of the existing slot allocation procedures and of related issues on the long, medium, and short-term was presented by Ball *et al.* [4], who focused on the US case. Many authors studied the use of market-based mechanisms in airport slot allocation, see Rassenti *et al.* [5], Starkie [6], and Fukui [7], among others. Congestion pricing mechanisms at airports have also been evaluated as an alternative to auctioning, see Daniel [8, 9] and Verhoef [10]. To a minor extent, mathematical optimization has also been used to allocate airport slots under a central regulator perspective. The single-airport case was studied by Zografos *et al.* [11], while Castelli *et al.* [12] and Pellegrini *et al.* [13, 14] studied the simultaneous allocation at multiple airports. Corolli [15] also studied the multi-airport case with stochastic weather. At the strategic phase, mechanisms that modulate air navigation charges to alleviate air traffic congestion in Europe are also studied, see Raffarin [16] and Jovanović *et al.* [17].

Currently, en route capacity is verified only in the tactical phase, on the day of operation of flights or the day before, resulting in ATFM regulations whose goal is to balance capacity and demand. An ATFM regulation usually assigns delays to flights, both en route and on the ground. The ATFM problem has been widely addressed using operations research, both with deterministic models (see Odoni [18], Bertsimas and Stock Patterson [19], Lulli and Odoni [20], and Bertsimas *et al.* [21]) and stochastic models (see Alonso et al. [22], Mukherjee and Hansen [23], Andreatta *et al.* [24], and Agustin *et al.* [25]).

In this paper, we develop a first market-based mechanism to alleviate airspace congestion at the strategic level – after airport time slot allocation and before the day of operations – in the European ATM context. This novel approach is being developed within the Strategic Allocation of Traffic Using Redistribution in the Network (SATURN – www.saturn-sesar.eu) project. The aim of the new mechanism is to minimize the cost of delay for airlines by taking appropriate strategic actions. Market-based mechanisms have the advantage of favoring the assignment of resources to users who value them the most. Currently, the only widely used market-based mechanism in aviation is the EU Emissions Trading Scheme (ETS) [26], which is aimed at mitigating the climate impacts of aviation. The strategic approach presented in this paper is based on Tradable Mobility Permits (TMPs), which are widely studied in other transportation fields. For a review on TMPs in the field of roadway transportation, the interested reader may refer to Fan and Jiang [27].

This paper unfolds as follows. In Section II, the phases of definition of TMPs are discussed. In Section III, the implementation of TMPs for strategic flight planning is illustrated. An example of the proposed mechanism is discussed in Section IV, where its performance is compared with some alternative methods. Finally, in Section V the conclusions are drawn and the future directions of our research are delineated.

II. Definition of Tradable Mobility Permits

According to Fan and Jiang [27], there are five phases in the definition of TMPs. The first phase is the most important as it is the *delineation* of the permits, where the meaning and validity of permits are defined. All other features of TMPs depend on the delineation of the permits. Second, the total quota of available permits needs to be defined and distributed among eligible users. This phase is called *initial endowment* of the permits. Since permits are tradable, an *exchange market* needs to be defined next, followed by the definition of the permit *consumption* mechanism. Finally, a set of *enforcements* for the valid use of permits is needed. In the following text, the five phases of definition of a TMP system are illustrated. Approaches studied in the field of roadway mobility are also discussed.

A. Delineation

Delineation is a crucial phase for the definition of TMPs, as the meaning and validity of a permit unit are defined. Five main types of permits can be identified in the field of roadway mobility, each discussed below.

First, *day permits* specify the number of days over a time horizon of valid vehicle use in a specific part of a network for an eligible user. In roadway mobility, this may correspond to the allowance to use a car for a specific number of days a week. Day permits usually have permanent validity. Their application to large cities was discussed by Goddard [28]. The effectiveness of these permits is limited, as users are able to reschedule activities on allowed travel days, and have an incentive to buy more vehicles to avoid limitations.

Using *Vehicle Miles Traveled (VMT)* it is possible to set a limit on the total miles traveled on the whole system. A VMT credit allows the owner to travel for a pre-specified length (e.g., one mile) on the controlled system. This type of permits was discussed by Verhoef *et al.* [29]. Permits are periodically endowed, e.g., every month, and may have limited or permanent validity.

Verhoef *et al.* [29] also discussed *fuel permits.* This system requires permits to buy fuel, managing congestion through the control of fuel usage. Similarly to VMT, fuel permits are endowed at regular intervals, and their validity is either limited in time or perpetual. Due to their nature, fuel permits are effective for emission control, but have limited impact on congestion control, as the use of low fuel consumption vehicles can allow users to increase their traveled distance.

To overcome the limitations of the VMT and fuel permit systems, *credit allowances* can be used. A system using credits is more difficult to define than previous systems, as a credit unit does not necessarily correspond to a physical good. This allows a credit system to be more flexible, as different quantities of credits may be required to travel in different places at different times. This approach is more efficient in terms of congestion control than VMT as users have an incentive to choose cheaper routes, where congestion is usually limited. Several implementations have been proposed in roadway mobility. Verhoef *et al.* [29] described a general system based on smart cards installed in vehicles. Although the use of credits instead of money makes the system more socially acceptable, Kockelman and Kalmanje [30] proposed a system that uses real money but is revenue neutral, redistributing system revenues at regular intervals. The credit allowance approach is similar to congestion pricing, using credits instead of real money to allocate the resources that require different quantity of credits depending on the place and time of requested use. Assuming perfect information, the price associated with each resource can guarantee that capacity will not be exceeded. This, however, is not a realistic assumption in practice, see Akamatsu [31] for a discussion on this issue.

Finally, we describe *time-place specific permits.* One permit unit allows the owner to use a specific piece of the network (place) at a specific time. The great advantage of this method is its ability to guarantee that capacity will not be exceeded, as it corresponds to the quota of permits that can be assigned to the users. Among the first to discuss time-place specific permits for roadway mobility were Akahane and Kuwahara [32], who developed a trip reservation system inspired from train seat reservation, and Wong [33], who based his work on airline seat booking and applied it to highway access. More recently, Buitelaar *et al.* [34] faced congestion through the privatization of roads, as they identify privatization of the right to use the road as a prerequisite for a competitive market. Prices are defined road-by-road in a market competition, assigning time-place limited resources. Finally, Akamatsu [31] discussed a permit system for network bottlenecks, called Tradable Bottleneck Permits, suggesting either a market selling or a free distribution scheme for the distribution of the permits. In general, the application of time-place specific permits to roadway mobility can be impractical as it requires car drivers to schedule their activities in advance.

B. Initial endowment

Depending on the delineation of the permits, different quantities may be assigned to eligible users. First, the **total quota** of permits needs to be defined. For day permits, VMT, and fuel permits, the meaning of the total quota is quite straightforward. For time-place specific permits, the number of permits available for the same time-place couple, i.e., a specific resource, corresponds to the time-based capacity of the resource. Credit allowances are more difficult to endow, since one credit unit does not directly correspond to a specific physical good. Their total quota may either be arbitrary or based on the prices set to get access to system resources, defining a sufficient number of credits to acquire access to them.

The second step in the initial endowment is the **distribution** of permits among eligible users. Equity is an issue of great concern at this stage, since some criteria may favor certain categories of users. In roadway mobility, permits are typically equally distributed among eligible users. However, workers who need to travel long distances to get to work may be discriminated against. Some approaches take this factor explicitly into account. Other approaches suggest a distribution of permits proportional to the tax contribution of a single user, which clearly favors users with a high income. Issues in air transportation, however, differ greatly from issues in roadway mobility. Eligible users in roadway mobility are people, who are largely homogeneous. Airlines, on the other hand, are very heterogeneous, as they may be small or large, may operate local or international flights, etc. These factors raise significantly different equity issues.

C. Exchange market

Depending on the tradability of endowed permits, an exchange market may have to be defined. The definition of the market involves both transactional and infrastructural issues. Transactional, because the more transactions are needed to obtain a resource, the more complicated is the access to it. Spending a lot of time on transactions can be expensive for users, and therefore not desirable. Infrastructural, because users need a specific place where they can easily and safely buy and sell permits. Exchanges may or may not involve real money.

D. Consumption

Similarly to the initial endowment, the consumption of day permits, VMT, and fuel permits is straightforward. Credits, on the other hand, are consumed at differentiated rates depending on the time and place of travel, requiring more accurate devices to be installed on vehicles (e.g., a GPS system). Consumption of time-place specific permits takes place when a vehicle enters (or is inside) a place at a given time.

E. Enforcements

Some enforcements are necessary both for the exchange market and permit consumption. Enforcements on permit exchanges can be embedded in the definition of the infrastructure of the exchange market. Enforcements on permit consumption are related to the way permits are consumed in practice. Devices installed on vehicles are typically used to consume permits. Additional external devices aimed at checking the valid use of permits may also be used, and specific actions against invalid permit use may have to be defined.

III. TRADABLE FLIGHT PERMIT SYSTEM

In this section, we propose an adaptation of TMPs to the strategic management of air traffic, named Tradable Flight Permit System (TFPS). Each of the five TMP definition steps is discussed, focusing on their application to strategic air traffic management and discussing different feasible implementations.

A. Delineation

The goal of the TFPS mechanism is to prevent demand-capacity imbalances that may arise on the day of operation – which result in costly delays – through appropriate strategic actions. Not all of the permit types fit this goal. Day permits would place a time limit on the use of aircraft, whereas VMT and fuel permits are inefficient in alleviating congestion. Furthermore, fuel permits are already used in air traffic in Europe under the EU ETS [26]. Credit allowances would correspond to an additional congestion charging mechanism along the EUROCONTROL route charge system, which would make their use difficult to be accepted. Time-place specific permits best fit the needs of air traffic congestion management. The total quota of a single time-place resource, in fact, corresponds to the capacity of the resource during the specified time interval (further referred to as "capacity"). To enforce capacity constraints it is therefore sufficient to assign a limited number of permits for each sector and time period. Also, their validity in time is clear, since they are defined for use in a specific time period. For these reasons, we use time-place specific permits in the TFPS mechanism. For the sake of simplicity, from now on we refer to time-place specific permits as "permits".

B. Initial endowment

The initial endowment takes place at the strategic phase, after airport time slot allocation, and defines both the total quota and the distribution of permits. The total quota of permits is easy to define, as the number of permits for a specific time-place resource corresponds to its capacity. Resources are (place, time period) pairs, where the place may be either an air sector or an airport. Notice that, at coordinated airports, we consider airport slots as fixed, therefore permits are already assigned at such airports. Air sector capacity in Europe is defined as the number of flights that can enter a sector per time period. Air sector permits therefore allow a flight to enter an air sector at a specific time period. A permit is required to enter any sector, in order to guarantee that capacity is respected throughout the network.

The initial distribution of the permits is more problematic. Who should receive the access to air sectors and how? We propose three alternative solutions:

1. *Optimized endowment*. Permits to enter air sectors at specific times are assigned at no cost through the use of a deterministic optimization model that minimizes the system delay. Since optimization models from literature usually enforce equity among flights rather than airlines, the fair assignment of permits may be questioned.
2. *First-Come, First-Served (FCFS).* Permits are assigned at no cost to airlines on a FCFS basis. That is, permits are assigned by the regulator whenever a request for an available permit is received. This approach rewards the airlines that first submit requests for permits, and is insensitive to the value that a permit has for different airlines.
3. *Auctioning*. Auctions allow the assignment of resources to users who most value them. An auctioning system would optimally allocate permits for which demand exceeds capacity. On the other hand, auctions raise equity concerns since resources are typically assigned to users – in this case, airlines – who can afford to pay for them the most.

C. Exchange market

Implementing permits alone with no market mechanism would not be much different from existing mechanisms. For this reason, a possibility of exchange of permits after their endowment – still at the strategic phase – is a crucial point of the TFPS mechanism. In particular, we identify three exchange options that may take place:

1. *Permit for money*. Any airline may buy or sell a permit in exchange for an agreed amount of money.
2. *Permit for permit*. Any two airlines may exchange a permit for another.
3. *Permit and money for permit*. Any airline may buy or sell a permit in exchange for another permit and additional money.

At least one of these exchange options should be implemented in the system, to let airlines minimize their flight operation costs after the initial permit endowment. Without the implementation of at least one market exchange option, airlines would not be able to switch to more convenient flight plans, based on their estimated operation costs. Airlines should also be able to receive unassigned permits at no cost, to be able to switch to different flight plans.

D. Consumption

We identify two alternative ways for permit consumption. Both consumption methods take place on the day of operations. The first is to consume permits using radar data, i.e., a permit is consumed when a flight enters an air sector at a given time. This approach consumes permits in the operational phase. The second alternative, which provides more ATC flexibility, is to consume permits when the flight plan is submitted on the day of operation. This approach, which consumes permits at the tactical phase, is easier to implement in practice, as it is easier to monitor. In case of imposition of a discrepancy between the first filed flight plan and the actual flight, actions to partially pay an airline back for the disservice should also be evaluated.

E. Enforcements

A unique system should be developed for the initial endowment, exchange market, and consumption of permits. Having a single centralized system is of great importance to guarantee simple and valid permit exchanges. Simple, because airlines who want to buy permits from other airlines may submit public offers in this system, and airlines who own the requested permits may decide to sell them at the proposed price. Valid, because exchanges performed in this system may be directly monitored and validated by the regulator. A link with the existing infrastructure that monitors flights would also be needed both for the verification and consumption of permits, at least in the phase of definition of a flight plan, as explained above. Specific rules should be defined for the day-of-operations adjustment of permits, e.g., what actions should be taken if capacity is expected to be less than the nominal. More detailed enforcements should be outlined based on the analysis of existing infrastructure, which goes beyond the scope of this paper. However, it is important to notice that the implementation of a system based on tradable permits is much easier here than in roadway mobility, as the number of airlines is much smaller than the number of car drivers and flight operations are planned, unlike car trips.

IV. PRACTICAL EXAMPLE

In this section, we present an example of application of the proposed system. First, the mechanism's characteristics are specified, and some basic assumptions are made. Then, the possible operation of the system is shown, and it is compared to some alternative methods, including current practice, to illustrate the improvements that can be achieved by using it.

A. Characteristics and assumptions

The total quota of permits is equal to the capacity of each sector for a single time period. In this example, capacity is set to one for all sectors, and 10 minute time periods are considered. Permits are endowed strategically, after airport time slot allocation, by the FCFS method. Finally, airlines are allowed to exchange permits for money, as a free market mechanism.

For the sake of simplicity, only two flights operated by different airlines and competing for the same permit are considered. The flights are referred to as "flight 1" and "flight 2", operated by "airline 1" and "airline 2", respectively. The two flights are represented in Fig. 1, where the possible routes of each flight are depicted. The planned departure time of flight 1 is 10:00, and it can be operated either through its "upper route" (sectors S1, S3, S6) or "lower route" (sectors S1, S4, S6). Similarly, flight 2 is scheduled to depart at 10:01, and can follow its "upper route" (sectors S2, S4, S7) or "lower route" (sectors S2, S5, S7).

To set up the example, additional information regarding airlines' operation costs needs to be defined. The assumptions are that flight 1 is operated with an Airbus A320-200, while flight 2 is operated with the stretched version of that aircraft, the Airbus A321-200. Four cost types are identified based on the real aircraft data reported by the study of the University of Westminster for EUROCONTROL [2]. For each aircraft, these costs are: strategic ground holding cost, strategic airborne operation cost, tactical ground delay cost, and tactical airborne delay cost. Ground operations planned at a strategic phase involve aircraft maintenance, fleet utilization, and crew costs. For the airborne portion of the flights, fuel expenses are added as well. Tactical delay presents additional costs for aircraft maintenance and the crew, including passenger-related costs, resulting in higher costs than the strategic ones. Updating the costs reported in the aforementioned study with the cost of fuel in January 2014 (0.78€/l, as reported by IATA [35]), we obtained the per-minute flight operation costs reported in Table I. The cost of reactionary delay, i.e., delay which may be

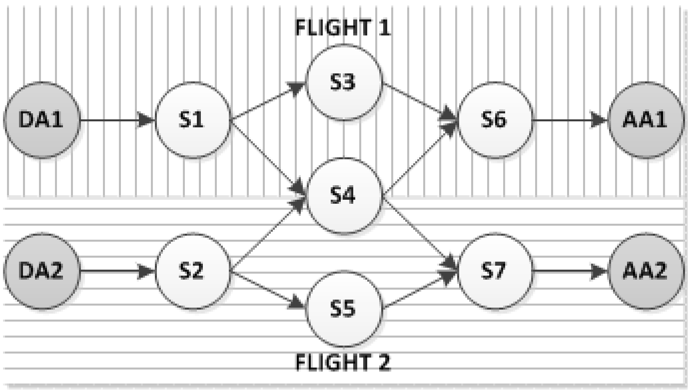

Figure 1. Example of flights competing for a single permit

TABLE I. OPERATION COSTS PER AIRCRAFT TYPE, PER MINUTE

Cost type	A320	A321
Strategic ground	17.83€	20.33€
Strategic airborne	59.15€	69.27€
Tactical ground delay	28.26€	31.32€
Tactical airborne delay	72.58€	83.86€

directly attributed to delay on another flight, is not taken into account in these figures, as it depends on the buffer time for the turnaround of a flight after its arrival. The buffer time is the amount of delay of an incoming flight that may be absorbed without causing reactionary delay to a subsequent flight. Consequently, the late arrival of a flight may or may not cause disruptions in the system depending on the buffer time of its connected flights. Different flights operated by the same aircraft may therefore have very different reactionary delay costs. We assume that the cost of reduction of the buffer time by one minute for the two flights in this analysis is 20€ per minute. Finally, since the system does not alter taxi times, the related costs are not taken into account.

Another source of cost for flights is route charges. In practice, unit rates of route charges are defined for each state. For the sake of simplicity, the unit rate of the corresponding state is assigned to each sector. EUROCONTROL route charges are calculated using three basic elements [36]: the aircraft weight factor, the distance factor, and the unit rate of charge. The unit rate of charge specifies the monetary charge for 100km of flight, considering a unitary aircraft weight factor. Based on data reported by Air Berlin [37, 38], we calculated the weight factors of the two aircraft, which are 1.21 and 1.36 for the A320 and the A321 aircraft, respectively. The unit rates defined for this example are arbitrarily defined, following realistic values. They are provided in Table II. Furthermore, the flight distance within each sector is set to 200km, corresponding to 20 minutes of flight. Sectors S3 and S5 are exceptions, as they are not on the shortest route for the two flights. The flight distance in these two sectors is 220km each, corresponding to 22 minutes of flight time. These figures are chosen for the sake of simplicity, as the goal of this section is to illustrate the functioning of the proposed system. The arbitrary choices made do not detract from the general applicability of the proposed method.

TABLE II. CHARGE UNITS PER SECTOR

Sector	Charge Unit
S1	60€
S2	50€
S3	30€
S4	60€
S5	50€
S6	40€
S7	60€

Given this information, it is possible to determine the operation costs for each airline, on each route available. Costs of operating the flights departing at the next time period, i.e., delaying the departure at 10:10, are also provided. We suppose that, due to airport time slot limitations, the two airlines do not consider moving departure times ahead of schedule, only delaying departures. The cost of all the considered alternatives is described in Table III.

B. *Description of the system operation*

The prerequisite for the system to function is the initial endowment of permits. First, the total quota of permits is defined: one permit is available for each sector at each time period. Then, permits are distributed. Permit distribution is based on the FCFS mechanism, i.e., it takes place strategically, after airport time slot allocation, as the regulator receives requests for permits. In this example, airline 1 is the first to request permits, assuming it is faster to request permits than airline 2. The reverse case is also later considered.

The cheapest option for airline 1 to operate flight 1 is to take its lower route, the cost of which is 3,936.20€ (see Table III). Since flight 1 is scheduled to depart at 10:00, airline 1 requests the assignment of permits for S1 at time period 10:00-10:10, S4 at time period 10:20-10:30, and S6 at time period 10:40-10:50. Since these permits are available, the regulator assigns them to airline 1.

After this assignment, airline 2 requests permits for its flight. Table III indicates that the cheapest option for airline 2 is to request the permits for the flight's upper route. As the departure time is planned at 10:01, the airline requests the assignment of permits for S2 at time period 10:00-10:10, S4 at time period 10:20-10:30, and S7 at time period 10:40-10:50. However, the permit to enter sector S4 at time period 10:20-10:30 is not available, as it was previously assigned to airline 1. Airline 2 must therefore evaluate the following set of options to operate flight 2:

1) Use the lower route, for a cost of 4,783.54€.
2) Use the upper route with 9 minutes of ground delay, to operate at the next time period, for a cost of 4,801.57€.
3) Make an offer to airline 1 for the permit to use S4 at time period 10:20-10:30 and use the upper route with no delay. Since the cost to use the upper route with no delay is 4,618.60€, and the cheapest alternative is the first, which costs 4,783.54€, the maximum convenient offer for the permit is the difference between the two values. We call this difference "best route value", and it is equal to 4,783.54€ - 4,618.60€ = 164.94€.

From the costs above, the second option should be avoided as it is not convenient. The cheapest option is the third, provided that airline 1 is willing to sell its permit for S4 for at most 164.94€. Should that not be the case, the first option should be chosen. To evaluate what happens, the behavior of airline 1 should be investigated. If it sold the permit for S4 to airline 2,

TABLE III. STRATEGIC ROUTE PRICES

Flight	Route	On time cost	Delayed dep. cost
1	Upper	4,029.16€	4,407.46€
1	Lower	3,936.20€	4,314.50€
2	Upper	4,618.60€	4,801.57€
2	Lower	4,783.54€	4,966.51€

its alternative options would be the following:

1) Use the upper route, for a cost of 4,029.16€.
2) Use the lower route with 10 minutes of ground delay, operating at the next time period, for a cost of 4,314.50€.

The cheapest alternative is the first, i.e., the use of the upper route. The current cost to operate flight 1 is 3,936.20€. The minimum acceptable offer is its best route value, which is the difference between the cost of alternative 1) and the current operation costs. The best route value amounts to 4,029.16€ - 3,936.20€ = 92.96€.

If an airline is selling a permit, it wishes to achieve some monetary benefit, and not simply switch to a different route at equal cost, favoring a competitor by selling it a permit it needs. Therefore, the permit selling price should also include a minimum selling margin, defining the minimum profit that an airline desires to achieve selling a permit. Similarly, a buyer also defines a minimum buying margin, to avoid buying a permit at a price that does not make it save any money. Let us denote with m_1 the margin imposed for flight 1 (airline 1 is the seller), m_2 the margin for flight 2 (airline 2 is the buyer), b_1 the best route value for flight 1, and b_2 the best route value for flight 2. Then, we can define the minimum selling price, the maximum buying price, and the exchange convenience condition, as follows:

$$p_1 = b_1 + m_1 \quad (1)$$

$$p_2 = b_2 + m_2 \quad (2)$$

$$p_1 \leq p_2 \quad (3)$$

Equation (1) defines the minimum selling price for flight 1 as the sum of its best route value and its minimum selling margin. Similarly, equation (2) defines the maximum buying price for flight 2. The exchange takes place if the exchange convenience condition (3) is met. This condition requires the minimum selling price to be less than or equal to the maximum buying price. Any value between the minimum selling price and the maximum buying price can be the price at which the exchange takes place, which we call permit exchange price. For example, consider buying and selling margins of 20€, and airline 2 making offers for the permit to use S4 that increase 1€ at a time. In this case, the selling price of the permit that airline 1 accepts is 113€, and the final costs to operate the flights – including the permit exchange price – will be:

- Flight 1: 4,029.16€ (upper route cost) – 113€ (permit exchange price) = 3,916.16€
- Flight 2: 4,618.60€ (upper route cost) + 113(permit exchange price) = 4,731.60

The costs for both flights are lower than they would have been without the application of the permit exchange, i.e., only applying the FCFS mechanism at the strategic phase. Flight 1 would have maintained the previous cost of 3,936.20€, while flight 2 would have opted for the lower route, for a cost of 4,783.54€. The total system cost would have amounted to 8,719.74€, while the cost achieved in the permit exchange case is 8,647.76€. The difference, which is 71.98€, is equal to the difference between the best route value of the seller and the best route value of the buyer.

The total system cost, i.e., the sum of the costs of flights 1 and 2, does not depend on the permit exchange price, as the money spent by an airline is received by the other. The introduction of buying and selling margins can guarantee minimum levels of cost reduction for both airlines involved. The permit exchange price can also be considered as the price that airline 2 has to pay for not submitting the request for permits before airline 1. Similarly, airline 1 achieves a monetary gain, equal to the permit exchange price, for having submitted the request for permits before airline 2.

The case in which airline 2 submits its request for permits before airline 1 can easily be analyzed. Airline 2 receives the permits to use the upper route, and airline 1 has to evaluate an offer. The best route values for the two flights are the same as in the previous case. However, condition (3) is now not satisfied, as the minimum selling price and the maximum buying price are reversed compared to the previous case. Airline 1 will therefore reserve the permits for the upper route, resulting in the same route choice as before. Airline 2 is able to save the money spent for the permit to use S4 (113€) compared to the previous case, as the exchange is now not necessary.

C. *Comparison with alternatives and current practice*

To evaluate the ability of the proposed system to reduce flight operation costs, we compare the discussed results with those of some alternative methods. First, the First-Planned, First-Served (FPFS) approach applied to the tactical level is considered. This corresponds to what is currently done in practice. To evaluate tactical decisions, the tactical cost of operation of different routes should be assessed. Flights 1 and 2 are scheduled to depart at 10:00 and 10:01, respectively, both arriving 1 hour later at destination. Any difference planned at the tactical level results in tactical delay, which increases flight operation costs. Considering the operation costs reported in Table I, the tactical route operation costs for the two flights are estimated and reported in Table IV. In this table, notice that only departing on time using the preferred routes (lower route for flight 1, upper route for flight 2) does not result in an increased cost of operation compared with strategic costs. This is due to the fact that they are the only options that allow flights to land at the scheduled time of arrival. All other options introduce some delay, resulting in additional tactical expenses.

Applying the FPFS method used in current practice, flight 1 has the precedence over flight 2, since it is scheduled to depart before flight 2. Flight 1 does not incur in any tactical delay, and keeps the costs for using the lower route at the strategic phase,

TABLE IV. TACTICAL ROUTE PRICES

Flight	Route	On time cost	Delayed dep. cost
1	Upper	4,056.02€	4,538.62€
1	Lower	3,936.20€	4,418.80€
2	Upper	4,618.60€	5,080.48€
2	Lower	4,812.72€	5,274.60€

i.e., 3,936.20€. Flight 2, on the other hand, cannot use the upper route as the unitary capacity of S4 is already reserved by flight 1 at time period 10:20-10:30. From Table IV, the cheapest alternative option it has is to use the lower route, which costs 4,812.72€. Since current practice is being evaluated, no market mechanism follows this FPFS assignment, and these allocations are final. The total system cost is 8,748.92€, which is greater than the cost of 8,647.76€ achieved with the TFPS mechanism.

Performing the FPFS assignment at the strategic level would lead to an improvement compared with tactical FPFS. Since flight 1 has the precedence with FPFS, the result would be the same as that previously illustrated for the strategic FCFS with no market mechanism and precedence to flight 1. The total system cost for this case is 8,719.74€, which is greater than the cost achieved with the TFPS mechanism, but smaller than the cost obtained applying the FPFS method at the tactical phase.

Finally, the effect of the application of the TFPS mechanism to the tactical phase is evaluated. Supposing that airline 1 acts first, it reserves the permits for the lower route of flight 1, which cost 3,936.20€. The corresponding best route value is 119.82€. Airline 2 wishes to receive the permits to operate the upper route of flight 2, but permit S4 is already assigned to airline 1. The best route value for flight 2 is 194.12€. Considering 20€ buying and selling margins, the permit to use S4 may be sold to airline 2 for 140€. Airline 2 may therefore operate its flight along the upper route, for a cost of 4,618.60€ + 140€ = 4,758.60€. Flight 1, on the other hand, will be executed on its upper route, which costs 4,056.02€ - 140€ = 3,916.02€. The total system cost is 8,674.62€, which is greater than the cost achieved by applying the TFPS mechanism at the strategic phase. Similarly to the strategic case, switching the permit request precedence to consider requests from airline 2 first does not change the system cost, but only avoids the exchange of the permit for S4. In Table V, the operation cost for both flights in all considered cases is reported, as well as the total system cost. We can see that the permit mechanism (strategic FCFS with market) provides the lowest system cost among all analyzed methods. Without the market mechanism, the total system cost resulting from the FCFS method depends on the order of permit requests. The TFPS mechanism applied to the tactical phase provides slightly worse results compared with the results of its strategic application for this example. However, since tactical costs are always higher than strategic costs, it is more convenient to apply the mechanism at the strategic level. For this example, the tactical application of the TFPS mechanism provided better results than the strategic implementation of FPFS. Finally, tactical FPFS, which reflects current practice, provided the worst results, with an increased total system cost of 101.16€.

TABLE V. COSTS COMPARISON BY SYSTEM

System	Flight 1 cost	Flight 2 cost	System cost
Strategic FCFS with market, flight 1 first	3,916.16€	4,731.60€	8,647.76€
Strategic FCFS with market, flight 2 first	4,029.16€	4,618.60€	8,647.76€
Strategic FCFS without market, flight 1 first	3,936.20€	4,783.54€	8,719.74€
Strategic FCFS without market, flight 2 first	4,029.16€	4,618.60€	8,647.76€
Strategic FPFS	3,936.20€	4,783.54€	8,719.74€
Tactical FPFS	3,936.20€	4,812.72€	8,748.92€
Tactical FCFS with market, flight 1 first	3,916.02€	4,758.60€	8,674.62€
Tactical FCFS with market, flight 2 first	4,056.02€	4,618.60€	8,674.62€

V. CONCLUSIONS

In this paper, we present a new market-based mechanism to regulate the whole route of a flight at the strategic level, with the goal of avoiding demand-capacity imbalances on the day of operation of flights. This mechanism draws upon experience from the field of roadway mobility, using time-place specific permits to enforce sector capacity constraints. We propose a simple example that shows the viability of the proposed mechanism, and demonstrate that it can provide better results compared to a variety of alternatives, including the current tactical FPFS allocation. Our approach is a first strategic attempt that uses a market-based mechanism to reserve air sector capacity after airport time slot allocation. In the example provided in Section IV, the monetary savings achieved are small. However, our goal was to show that a mechanism based on tradable permits that can reduce costs for all airlines involved is viable.

The future work will focus on the mathematical formulation and implementation of the proposed approach on a real-size air traffic system. First, the optimized initial endowment will be formalized and implemented. This endowment method may require fewer market exchanges, as the initial endowment of permits would be closer to the optimal permit distribution. Then, the market mechanism granting all users individual rationality will be formalized and implemented. The complete system will be simulated using historical European traffic data, allowing the estimation of the positive effect that this approach may have in practice on costs and delays. Furthermore, we will explicitly consider the effect of the uncertainty of capacity availability, typically due to weather uncertainty, on the assignment of permits. We will also investigate the effect that cost fluctuations over time, e.g., fuel cost variations, have on strategic decisions. In addition, the use of credits to substitute monetary exchanges will also be investigated.

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