E.02.33-SATURN-D6.5 Final Report (Dissemination)

Document information	
Project Title	SATURN
Project Number	E.02.33
Project Manager	Università degli Studi di Trieste
Deliverable Name	Final Report (Dissemination)
Deliverable ID	D6.5
Edition	01.00.00
Template Version	03.00.00
Task contributors	
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Abstract

This document is the SATURN's Final Project Report. It gives an overview of the main mechanisms designed and implemented during the course of the project and presents the key findings. The purpose is to clearly demonstrate the success of SATURN's novel approaches to reduce demand-capacity imbalances and save airspace users operational costs. This study shows that pricing is a viable option to redistribute traffic in the European air network and quantifies the trade-offs between system's, ANSPs' and airspace users' requirements.

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Rational for rejection
N/A

Document History

Edition	Date	Status	Author	Justification
00.01.00	11/12/2015	Draft	[redacted]	Submission for possible presentation at SESAR 1 Final Event, Amsterdam, The Netherlands, 14-16 June 2016.
01.00.00	20/12/2015	Release	[redacted]	New document for review by EUROCONTROL

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Executive summary

The objective of the SATURN (Strategic Allocation of Traffic Using Redistribution in the Network) project is to make novel and credible use of market-based demand-management mechanisms to redistribute air traffic in the European airspace. This reduces congestion and saves the airspace users operational costs.

The project is motivated by frequent demand and capacity imbalances in the European airspace network, which are forecast to continue in the near future. The present and foreseen ways of dealing with such imbalances mainly concern strategic and tactical capacity-side interventions, such as re-sectorisation and opening of more sectors to deal with excess demand. These are followed by tactical demand management measures, if needed. As a result, not only do substantial costs arise, but airspace users are also typically left with no choice but to comply with imposed air traffic flow management measures.

The project shows how economic signals could be given to airspace users and air navigation service providers (ANSPs) to improve capacity-demand balancing, airspace design and usage, and what the benefits would be of a centralised planner compared with those of decentralised maximisation of self-interests (by the ANSPs and/or airspace users).

Type of novel pricing model	Main phase applied	Key benefits demonstrated
Peak-load pricing	Strategic	• Pricing is a viable option to redistribute traffic in the European air network since appropriate modulations of en-route charges achieve the reduction of sector load without increasing the horizontal efficiency and AUs' operational costs and respecting requested departure times
Rewarding predictability	Pre-tactical	• More balanced traffic distribution (utilisation of available capacities) possible at no extra cost • Efficiency of air traffic assignment/management can be improved without deteriorating equity • Balance between flexibility for airspace users and predictability for providers
Tradable Flight Permits System	Strategic	• Use of permits provides balanced traffic distribution, which ensures minimum cost routes and respects capacity constraints

1 Introduction

1.1 Purpose of the document

Under the SATURN project, different strategic pricing mechanisms are studied, aiming to redistribute air traffic in Europe when the expected demand exceeds the nominal capacities of sectors and/or airports.

This document gives an overview of the main mechanisms designed and implemented during the course of the project and presents the key findings. The purpose is to clearly demonstrate the success of SATURN's novel approaches to quantify the trade-offs between the system's, ANSPs' and airspace users' requirements in terms of, inter alia, capacity management and airspace users' route choices.

All mechanisms are tested on the entire European airspace for one of the busiest days of 2014 that is not unduly disrupted by unusual events. Additional tests were performed on a regional scale instance, exhibiting extremely challenging en-route demand/capacity imbalances. Computational runs rely on instances generated using the SATURN bespoke database that manipulates the Demand Data Repository (DDR2) data. Computations use algorithms specifically designed for this purpose during the course of the project.

This document is a draft version of the SATURN's Final Project Report.

1.2 Intended readership

This report is intended for those with an interest in strategic and pre-tactical planning in Air Traffic Management (ATM). In particular, this report is focused on the application of pure-pricing and hybrid mechanisms that may eventually reduce congestion on the day of operations. This document is intended for readers with good knowledge of air transport and ATM.

1.3 Inputs from other projects

N/A

1.4 Acronyms and Terminology

Term	Definition
ACC	Area control centres
AHM	Ad-hoc modulation
ANS	Air navigation services
ANSP	Air navigation service provider
ATFM	Air traffic flow management
ATM	Air traffic management
BMC	Baseline minimum cost
BMD	Baseline minimum distance
AU	Airspace user
CD	Coordinate-wise descent

Term	Definition
CEM	Central exchange market
CFMP	Centralised full modulation pricing
CMC	CEM minimum cost
CMD	CEM minimum distance
CP	Central planner
CPLP	Centralised peak-load pricing
DDR2	Demand data repository (second phase)
DPLP	Decentralised peak-load pricing
EC	European Commission
ECAC	European Civil Aviation Conference
GA	Genetic algorithm
IFR	Instrument flight rules
MTOW	Maximum Take-Off Weight
NEST	NEtwork Strategic Tool
PLP	Peak-load pricing
RP	Rewarding predictability
RP-D	Rewarding predictability - Deterministic
RP-S	Rewarding predictability - Stochastic
SAIPE	Strategic ATFM for initial permit endowment
SATURN	Strategic allocation of traffic under redistribution in the network
SES	Single European Sky
SMC	SAIPE minimum cost
SMD	SAIPE minimum distance
TFPS	Tradable flight permit system
TV	Traffic volume

2 Mechanisms' overview

2.1 Introduction

European air navigation service providers (ANSPs) finance their operations by charging airspace users air navigation service (ANS) charges, according to EC Regulation 391/2013 European Commission, 2013). ANS charges are composed of en-route and terminal charges, for the en-route and terminal portions of the flight, respectively. They play a pivotal role in the economics of the European ATM industry as they represent 76% and 14% of all ANSPs' revenues, respectively (PRU, 2015). ANS charges are a non-negligible operational cost (sometimes higher than 10%) for airlines, especially when fuel costs are low. For these reasons, understanding how much airlines' route choices depend on ANS charges, en-route charges in particular, and to what extent the charges could then be used as an effective tool to balance demand and capacity is of great importance. Currently, the en-route charges depend on the distance flown in the airspace of a state, on the weight of the aircraft and on a unit rate set by each state (annually). Article 16 of EC Regulation 391/2013 states: "Member States [...] may [...] reduce the overall costs of air navigation services and increase their efficiency, in particular by modulating charges according to the level of congestion of the network in a specific area or on a specific route at specific times. [...] The modulation of charges shall not result in any overall change in revenue for the air navigation service provider [...]". This feature gives Member States and hence, ANSPs, the opportunity to use pricing as an instrument to reduce recurring congestion problems.

With this in mind, SATURN explores pure pricing and hybrid mechanisms, aimed at redistributing air traffic in Europe when the expected demand exceeds the nominal capacities of sectors and/or airports. Two main pure pricing mechanisms are studied:

- "peak-load pricing"- employs a variation of charges with regard to time and location of consumption
- "rewarding predictability" - adds another dimension, with time of purchase serving as a further basis for price variation.

Hybrid pricing ("tradable flight permits system") uses time-place specific permits, which are distributed to airlines in the first phase of the mechanism, thus assigning routes and departure times to flights. In the second phase, airlines are allowed to exchange permits through a centralised market mechanism, to allow for finding a more convenient routing.

Since unit rates are currently set once per year, and it is still impractical to change the rates more often, SATURN analyses the effect of pricing mainly at the strategic flight planning level (months ahead) meaning that last minutes inconveniences (e.g. weather or industrial actions) are not taken into consideration. Figure 1 shows the relationship between the mechanisms (and their variations), and the time frame of their applicability.

All of the mentioned mechanisms share these key assumptions[1]:

1. *Fixed demand matrix*. Fixed number of flights between any airport pair in the network. The intention of the mechanisms investigated is not to scale down the total demand but to modify its spatial and temporal distribution to bring it in line with available capacities.
2. *Heterogeneous demand*, in terms of different aircraft types with cost profiles for operations differentiated on an airline category basis.
3. *Infrastructure capacity constraints* are known in advance, in terms of pre-defined airspace sectorisations and maximum numbers of aircraft that can enter each sector per given period of time (that is, capacity). Since we are assuming the mechanisms will be applied strategically, or pre-tactically, nominal sector and airport (for peak-load pricing and tradable permits) capacities are considered, without variations introduced by regulations (which are applied tactically, due to weather and other conditions that are not predictable significantly in advance).

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[1] Assumptions 3 and 4 are slightly modified in a specific case study of the rewarding predictability mechanism.

4. *Finite set of possible 4D trajectories* for each origin-destination-aircraft triplet: users can select a route from a set of pre-determined routes. Duration and profile of each route is assumed to be constant for each aircraft type (i.e., speed profiles are constant for each route/aircraft pair).

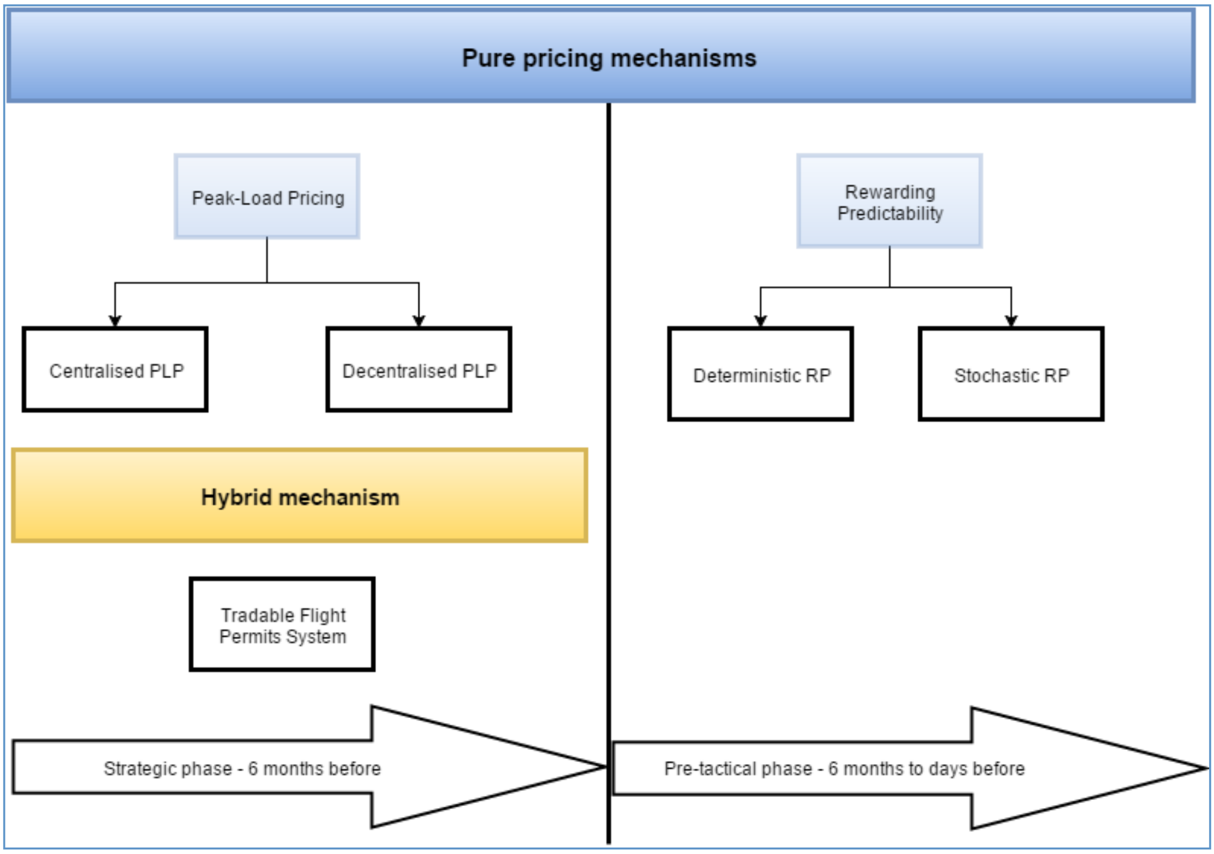

Figure 1. SATURN mechanisms and the time-line of their application.

2.2 Peak-load pricing

Peak-load pricing (PLP) is aimed at efficient capacity management commonly used in transport and utilities. It is a simplified form of congestion pricing with the fundamental assumptions that peaks in demand are occurring periodically, in both time and location (and are therefore predictable) and that demand has some degree of elasticity towards time and/or location of service consumption (and therefore is sensitive to its price). Under these assumptions, PLP assigns a higher rate where and when a peak in demand is expected, and a lower rate for off-peak areas and/or times. By doing so, it is expected that part of the peak demand will redistribute to cheaper options. Therefore it is essential that peak and off-peak rates are set so that the pricing policy is effective with regard to business sustainability, and efficient capacity management; the former can be achieved by imposing the constraint that total revenues are not lower than total marginal costs; the latter can be obtained by setting peak rates greater than the willingness of the users to pay, who will therefore prefer the cheaper off-peak option. Here, the PLP policy is implemented through an optimisation. In order to apply it, two steps are needed: traffic demand analysis and optimal traffic redistribution:

- For traffic demand analysis, congested airspace sectors and related peak and off-peak hours are identified. The identification is done by analysing past traffic and route choice data (despite a long-term trend of traffic growth, air traffic typically shows seasonal periodicity throughout the year). Traffic demand is counted for all the sectors, taking into account all the flights and their routes, for a chosen time horizon (one hour). The ratio between the hourly traffic count and the nominal hourly capacity gives an hourly load factor. The load factor is used as a threshold for assigning the peak or off-peak designation to a specific sector for a specific hour.

- *For* optimal traffic redistribution, peak and off-peak rates are set in the network, and AUs route each flight taking these into account. The en-route charges with peak and off-peak rates should guarantee the recovery of ANSPs' operational costs, and the ability of AUs to perform flights, while preventing the imbalance between the demand and the available airspace capacity.

The PLP takes as input the airspace capacity, demand, and costs of flights and provision of service; through the optimisation sets the peak and off-peak rates which result in traffic distribution (routes and times assigned to flights) that respects that airspace capacity and revenue neutrality.

The responsibility for modulating en-route charges can be allocated at the central (system) or local level, resulting in two variations of the PLP mechanism, centralised and decentralised, each described in more detail in the subsequent sections.

In addition to Assumptions 1-4 (see Section 2.1), PLP shares these specific assumptions:

1. *Users are rational decision makers.* All AUs are assumed to choose the minimum-cost 4D trajectory available.
2. *Revenue neutrality* is established as a desired principle, reflecting the fact that ANSPs' revenues are to be kept as close as possible to their operational costs: the adjustment of charges is not to generate any additional revenue (on top of the cost of ANS provision), nor should it result in revenue deficit.
3. *Distance-proportional air navigation charges with sector-period-based rates.* The pricing rule applied for air navigation charges is similar to the one currently used, but instead of a unique unit rate per country, a peak/off-peak rate pair is established for each ANSP, for all its sectors.
4. *Peak times and locations are known in advance.* Peak and off-peak configurations are assigned by analysing past traffic distributions. The expected load on a sector, during a specific time is estimated by analysing submitted flight plans (in our case these are the last-filed flight plans from EUROCONTROL's Demand Data Repository), and used as a threshold for assigning peak or off-peak status.

Details on the mathematical formulations of the PLP mechanisms are available in Castelli et al. (2015).

2.2.1 Centralised PLP

PLP assigns a higher rate where and when a peak in demand is expected, and a lower rate for off-peak areas and/or times. By doing so, it is expected that part of the peak demand will redistribute to cheaper options. SATURN first focuses on a centralised approach to PLP (CPLP) where a central planner (CP) is responsible for setting en-route charges on the network and airspace users (AUs) assess the routing of each flight. Set en-route charges should guarantee that ANSPs are able to recover their operational costs, and that AUs perform their flights avoiding imbalances between demand and available airspace capacity. Like in the current charging system, in CPLP AUs react to en-route charges (which are imposed by CP instead of ANSPs) by choosing alternative and cheaper routes. The relationship between the CP and the AUs is modelled as a Stackelberg game where a leader (CP) makes his decision first, with complete knowledge on how the follower(s) (AUs) would react to it. The equilibrium is obtained by means of an optimisation problem, formulated as bilevel linear programming, where the CP sets, for each ANSP, one peak and one off-peak en-route charge and the AUs make their routing choice (Castelli et al., 2013).

Since an exact solution of the CPLP has proven to be computationally intractable for a large set of flights, we develop two heuristic approaches able to solve CPLP in a reasonable amount of time for approximately 30000 flights, usually seen on busy days in European airspace. Both heuristics consider the trade-offs between the network's total shift and capacity load, and the ANSP's revenues, but differ in: (a) the way the trade-offs are analysed, and (b) the search of the solution space. One approach optimises a single objective using a coordinate-wise descent (CD) method[2] (Friedman et al. 2007), while the other is a multi objective heuristic based on genetic algorithms (GA).

As part of the SATURN project, we also have defined other variants of the CPLP mechanism to serve as point of comparison, such as to be better able to assess the CPLP advantages and disadvantages. One variant increases the number of different rate variables, and one variant use a decentralised decision process.

2.2.1.1 Centralised Full Modulation Pricing

In the CPLP mechanism, there are only up to two rates per ANSP: one for sectors that are at their peak time and one for sectors that are not at their peak time. This heavily restricts the optimisation procedure that may not have enough flexibility to encourage airspace users to use the airspace as efficiently as they could.

Instead of having only those two rates per ANSP, we can define a mechanism where there is a different rate for every possible pair of sector and time period. This is the Centralised Full Modulation Pricing (CFMP) mechanism.

2.2.1.2 Decentralised PLP

Under a decentralised PLP (DPLP) policy, each ANSP is in charge of setting rates in the network it controls and has little or no influence on the actions of neighbouring ANSPs. AUs respond to the pricing policies of the ANSPs by choosing a routing option that minimises their operating and navigation costs, as under the centralised PLP policy. The CP is either not present or has a limited role (e.g., acting as a regulator in disputes between ANSPs). The only actors taken into consideration for the decentralised PLP mechanism are ANSPs and AUs.

It is assumed that ANSPs share no knowledge of each other’s actions, and therefore act independently. However, since they set peak and off-peak rates influenced by both operating costs and users’ route choices while having no direct influence in setting other ANSPs’ pricing strategies, such a configuration represents, in fact, a competition with no direct information sharing. When, on the other hand, information on pricing strategies is shared and overall network efficiency is a priority for all ANSPs, we have a collaborative behaviour that basically coincides with the centralised perspective (i.e., CPLP).

As with CPLP, the main objective of DPLP is to reduce the load on the network by redistributing traffic in a balanced way, and to reduce the amount of shift in the network. In this case, however, the network is divided into sub-regions (national airspaces), each controlled by an ANSP. Hence, traffic redistribution and shift minimisation are performed on a local basis, each ANSP optimising its own national airspace.

The DPLP mechanism is as follow:

- The list of ANSPs is ordered according to the order by which they will decide on their rates. This ordering is arbitrary, and can be done alphabetically, randomly, by size, or by any other criterion.
- Each ANSP modifies its unit rate variation variables according to its own objective function, while considering the other ANSPs variables as being constant.
- The process is repeated a few times (5) for the rates to stabilise. It should be noted that there is no guarantee that the final state will be at equilibrium, so a maximum number of iterations is required.

As for CPLP, heuristic approaches based on CD and GA are designed and implemented.

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[2] This method does not attempt to find the optimal value of all decision variables at once, but determines the optimal value of a single decision variable only. The heuristic then loops over all variables, updating each of them to their optimal value (for fixed values of the other variables) until a fixed point is reached.

2.3 Rewarding predictability

The idea behind the rewarding predictability (RP) mechanism is to give airspace users incentives to reduce uncertainties imposed on ANSPs/ CP by filing their flight intentions earlier and adhering to them as much as possible. Apart from employing the peak-load pricing rationale, such a charging system rewards earlier filing of flight intentions, since such user behaviour improves predictability for ANSPs/CP and might thus improve the performance of the network as a whole (EUROCONTROL, 2014). The RP mechanism employs the concept of intertemporal pricing for the first time in ATM applications. Intertemporal pricing uses time of service purchase as an additional basis for price variation (on top of the already employed time of use and location of use). Predictability in this context relates primarily to a reduction of uncertainty concerning the amount of resources (staff etc.) needed by ANSPs to manage the traffic at a targeted level of service.

The RP mechanism exploits the fact that a given airspace network segment (e.g. a “cluster” – grouping of several sectors) can handle different levels of traffic, depending on the level of its fragmentation. General maximum capabilities of each network segment are known to the CP, in terms of handling a certain level of traffic, at a certain level of utilisation of internal resources. Early filing of flight plans (‘purchasing of routes‘ by airspace users) could therefore provide a valuable indication as to which level of fragmentation of such clusters is likely to be used on the day of operations. Different levels of cluster fragmentation naturally come at different levels of capacity provision cost. Helios (2006) suggests an average EUR 3-4 million annual Area Control Centre (ACC) cost per sector for European ANSPs. This implies that being able to handle the planned traffic with fewer sectors might translate into significant cost savings, in the order of magnitude of millions of euros per annum.

In addition to Assumptions 1-4, we proceed by introducing and discussing the environment and assumptions for the proposed approach.

1. Unit (incremental) costs of capacity provision are known in advance for each network segment.
2. CP is a mediator, as the only actor that supposedly fully comprehends the network effects of individual stakeholders’ actions. Airspace users thus communicate with the CP only, and the CP communicates with ANSPs. The CP posts prices for trajectories, based on incremental costs of capacity provision. ANSPs provide capacity, and are reimbursed for the cost of capacity provided/traffic controlled.
3. A menu of routes for a given OD pair and a given date and take-off period is a dynamic category, that is, it may change over time, both in terms of offered routes and their prices, reflecting the known capacity constraints. Once the capacity of some network segment is fully consumed by previous route purchases, all routes that pass through that network segment are withdrawn from the menus. The initial menu of routes contains the broadest set of offered routes, that is, no generation of new routes is allowed compared to the initial menu, so as the time of departure approaches, the choices can only be reduced.
4. The price of a given 4D route at any given moment (the information as seen by airspace users) is calculated as the sum of prices attached to all network segments (sector-periods) constituting that route. Therefore, at any particular moment any user wishing to file a 4D trajectory between airports A and B will be offered a menu of 4D routes available at that moment, along with prices attached to each available route. In other words, time of purchase affects both availability of options and prices thereof.
5. Initially posted route prices are calculated based on constituting sector-periods’ entry charges, which are in turn based on their anticipated ’scarcity levels‘. More specifically, initially posted route prices are based on expected (or historical) capacity utilisations (filed demand/capacity ratio) of sector-periods constituting those routes.
6. Presently, for the sake of simplicity, we apply a no-refund policy, meaning that once a user makes their choice of 4D trajectory, they have no-refund available. If the AU decides not to use the purchased product, they go back to the beginning of the process and purchase a new route from the new availabilities and prices.

7. The pricing scheme is revenue neutral at the network level, within a decided period (e.g. day, week, month, quarter, year – ultimately a policy decision). No extra revenue (vs. aggregate cost of capacity provision) is to be generated by the proposed mechanism.

The route charge is calculated as the sum of charges attached to sector-periods that constitute that route option. The sector-period charge is calculated as a product of the base rate (qualitatively similar to the unit rate in the present European setting) and of three multipliers: $M1$, $M2$ and $M3$, as follows:

$$\text{Sector-period charge} = \text{Base rate} \times M1 \times M2 \times M3$$

The M1, ANSP-period load multiplier is a linearly increasing function of the number of flights that already purchased a capacity increment (through the route they purchased) in the considered national airspace (controlled by the ANSP) in the considered time period, e.g. 30 minutes. Therefore, as the system successively fills up, the $M1$ value increases, between the pre-defined values (lower and upper bound, which reflect minimum and maximum airspace fragmentation).

The M2, sector-period load multiplier is the function of the cumulated number of flights in the given sector-period, resulting from already completed route purchases. M2 increases in a stepwise manner as the number of contracted (purchased) sector-period entries increases.

The M3, sector utilisation multiplier is associated with individual sectors and reflects their expected (or historical) utilisation levels. The historically more requested (utilised) sectors will therefore be more expensive than those less requested, *ceteris paribus*.

2.3.1 Algorithm description

The proposed approach (extensively described in Jovanović et al. (2015b)) assumes the fully deterministic least-cost route-choice rule is applied (RP-D). It works sequentially, which necessitates an assumption on the order of users' (flights') appearance in the system, i.e. of route purchase. We use randomly generated ordering of flights in each mechanism run. In a more advanced version we incorporate a more realistic representation of the route choice process into the RP mechanism, informed and facilitated by the findings of Delgado (2015). The analysis of Delgado (*ibid.*) suggests that, on average, five out of six flights opt for the shortest route available. Furthermore, one out of 16 flights was found to select longer routes and save on ANS charges. Finally, a similar proportion of flights was found to exercise *seemingly* irrational route choice behaviour, choosing longer and at the same time more expensive (higher ANS charges) routes. Being fully aware that reasons other than the few observed ones - route length and ANS charges – might be driving such behaviour, we believe that the employed statistical approach better simulates the real process than the deterministic least-cost rule. Operationally, we use stochastic simulation (Monte Carlo) to replicate the aggregate high-level statistics observed in Delgado (2015)[3]. The standard Monte-Carlo approach was applied: in each run, each individual user (flight) is assigned one type of route-choice behaviour, facilitated by pre-defined ranges of random numbers.

2.4 Tradable Flight Permit System

To complement pure pricing, SATURN has developed an additional pricing mechanism that also encompasses non-monetary features (hybrid pricing). The goal of this mechanism, called 'Tradable Flight Permit System' (TFPS), is to alleviate airspace capacity-demand imbalances at the strategic phase. TFPS is an adaptation to strategic ATM of the Tradable Mobility Permit approach used in roadway transportation by Fan and Jiang (2013). TFPS consists of two distinct steps: a permit distribution (or initial permit endowment) and a permit exchange market. Permit distribution can be seen as a non-monetary traffic assignment problem, resulting in initial flight plans that respect strategic (declared) airspace capacities by re-distributing traffic in excess through the shifting of departure/arrival times and/or assignment of a different route. The assigned permit sets can then be traded (for money) in the exchange market, offering additional flexibility and the possibility of further flight cost reductions for airlines. The exchange market is the natural continuation of permit distribution.

Time-place specific permits are used in TFPS. A permit entitles its owner to plan the entry in a sector, departure from or arrival at an airport, within a given time period. An initial flight plan is composed of a

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[3] The project team is currently elaborating these findings with a factor analysis of airline route choices.

set of permits for each airspace network element to be used (airports and sectors). Each airspace element has a permit quota attached to it, for each time period under consideration. The permit quota corresponds to the declared capacity of the sector or airport during the given time period, following the European definition of capacity (capacity is the number of entries into a volume of airspace during a time period). Permit distribution determines the initial flight plans and therefore the traffic distribution over the network. The initial permit endowment is performed through an integer linear programming model, which we call Strategic ATFM for Initial Permit Endowment (SAIPE), and which considers two alternative objective functions:

1. Flight cost minimisation: the sum of the operational costs of all flights is minimised. Since actual costs to operate the same aircraft type differ across airlines, the use of the airlines' actual operational costs would favour airlines with higher costs. For a fair distribution of permits, we consider the average operational costs of the aircraft type planned to operate each flight. Hence, all flights performed by the same aircraft type share the same cost parameters.
2. Shift minimisation: the sum of the differences between the assigned and requested times (shifts), both at departure and arrival, of all flights is minimised.

The fair initial endowment of permits considers the industry-wide average, not the actual costs for an airline to operate its flights. Different airlines typically have different costs to operate the same aircraft type, due to factors such as crew and passenger costs, which can be very different from airline to airline, as detailed in the study on European airline delay costs by Cook and Tanner (2011). As a result, the initial endowment solution minimises the average operational costs, which therefore may still be improved. Such improvements should be left to the airlines, allowing them to trade endowed permits. Furthermore, in case schedule shift minimisation is the objective of the initial endowment, flight operational costs are not considered at all. Airlines may economically benefit from trading permits in this case as well. Permit exchanges are achieved by implementing a market mechanism as a centralised optimisation model, named central exchange market (CEM), which performs exchanges based on data provided by the airlines. The data provides the information on the airlines' willingness to pay for a more convenient route, or their willingness to be paid to switch to a less convenient route. No other information is necessary.

It is important to highlight that permits are used to produce initial flight plans in the strategic phase. Note that tactical revisions of initial flight plans may be needed, as in current practice, should the declared capacity be reduced on the day of operations, e.g., due to bad weather, but these are not modelled here.

3 Experimental design

This section describes the experimental design employed. First, the input data are defined. Second, the scenarios under which the models are run are presented. These scenarios describe different conditions: usually the current and variously modelled situations Lastly, the assessment indicators and the assessment framework are introduced.

3.1 Input data

All models are applied on a day of real air traffic data involving the entire European airspace, and on a regional instance for RP. Data required to run the models include: flights, airspace configuration and capacities of resources (sectors and airports), route choices, aircraft types and their flight costs[4], and airline types. The data on air traffic and air network structures are taken from EUROCONTROL's DDR2 and shaped to the needs of SATURN. Cost data are taken from various sources as detailed below. The input data are the same for all SATURN mechanisms and models.

3.1.1 Flights

The air traffic data are taken from 12 September 2014, the fourth busiest day of 2014, selected as not unduly disrupted by unusual events. All IFR scheduled passenger flights that depart from or arrive in European airspace are taken into account (29539 flights after excluding military, overflights, helicopters, flights departing and arriving at the same airport and all flights with departure or arrival set to "ZZZZ" or "AFIL"). The data is sourced from DDR2 M1 (last-filed flight plans).

3.1.2 Airspace configuration and capacities of resources

The configuration of the airspace network changes throughout the day, depending mainly (but not only) on the planned traffic flows. Therefore, it is important to represent the changes in airspace configuration, represented as opening and closing times of sectors. In some portions of the airspace, configurations may change many times throughout the day, where some configurations may be active for a very short time. These short openings are due to tactical airspace management that is not subject of our strategic mechanism. However, as the configurations do change over the day, we apply the dynamic sectorisation in place on 12 September 2014.

Airspace configuration data give information not only on the openings and closures of sectors, but also on capacities needed at each point in time. DDR data contains information on declared sector capacities, which is given through the so-called traffic volume (TV) capacity.

Airports constitute another set of resources for which capacity data are needed.[5] The airport capacity data are also sourced from DDR. However, some of the airport capacity figures were corrected as on closer inspection the declared capacity figures were much lower than the actual number of operations handled, across a period of time. Capacity figures needing corrections were at the following airports: London Gatwick (EGKK); Nice Cote D'Azur (LFMN); Dusseldorf (EDDL); Istanbul Ataturk (LTBA); and Bergamo Orio al Serio (LIME).

3.1.3 Route choices

A route is given as a combination of route (set of crossed sectors) and departure time. Between each origin-destination pair, for each aircraft type used, a set of 3D routes is defined. The routes per origin-destination-aircraft triplet are determined through a clustering process on historical flight data from the two weeks preceding 12 September 2014. Only routes differing significantly from one another in terms of geographical distance (specifically, more than 20 Km) in the points where the distance between the two routes is maximal, measured in 3-dimensional space) are taken into consideration. This reduces the number of viable routes per origin-destination-aircraft type triplet from the tens available in the data to an average of 3.4 routes per triplet.

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[4] The unit rate values (for en-route navigation charges) used are those applied in September 2014.

[5] PLP and TFPS models take airport capacity into account, while RP is focused on the airspace capacity only.

3.1.4 Aircraft types and their flight costs

The main airline operating costs comprise: fuel, crew, fleet (i.e. depreciation, rentals and leases) and maintenance costs. Reference values for the most commonly used aircraft in Europe covering ‘low’, ‘base’ and ‘high’ cost scenarios by phase of flight have previously been reported in Cook and Tanner (2011). These reference values have been updated and extended (Cook and Tanner, 2015):

- All costs have been updated from 2010 to 2014 Euro values;
- The costs for 15 aircraft are now included, extended from the original 12 aircraft types (B733, B734, B735, B738, B752, A319, A320, A321, AT43, AT72, B744 and B763) with the inclusion of DH8D, E190 and A332;
- Allocated seats per aircraft type per cost scenario have been updated using recent typical seating ranges; this has an effect on the modelled crew costs, with some aircraft now having ±1 flight attendant if the cabin crew-to-seat threshold has been crossed;
- The method of estimating fleet costs has been enhanced for the 2014 cost calculations;
- Although the cost of carbon emissions (to airlines) has been considered, this has been disregarded due to its minor impact on fuel costs;
- For the original 12 aircraft, on average, the en-route strategic costs (including fuel costs) for the base cost scenario have increased by 11% between 2010 and 2014.

The good fits obtained between the square root of the maximum take-off weight and the modelled costs of delay are useful for estimating cost data for aircraft not included explicitly in the model. All aircraft used for passenger services have been grouped into clusters using the 15 modelled aircraft types as cluster centroids (see Table 1), with √MTOW used as the clustering criterion. Furthermore, an additional aircraft cluster (‘other’) is added, for all the aircraft with MTOW<10t, which constitute a fair proportion of flights on the chosen day (about 7%). The decision was made to keep these aircraft and associated flights in the sample, to avoid adjustments of airspace sectorisation, as the removal of these flights would leave us with a low traffic load for the given sectorisation.

Table 1. Clustering results (example)

Reference Aircraft (ICAO designator)	Reference MTOW (source: NEST)	Other aircraft in the same cluster: ICAO designator
A319	68.98	B737
A320	74.48	MD83; MD88; MD90
A321	86.47	B722; TU22
A332	229.51	B773; B788; MD11; A333; A342; A343
AT43	16.83	AT44 ; AT45; B25; DH8A; IL28
AT72	22.15	AT75 ; E135 ; E145; AN26
B733	61.6	B736 ; MD87 ; AN12
B734	65.63	A318 ; MD81
B735	56.55	DC92 ; B732
B738	76.47	B721 ; B739
B744	392.09	B773 ; A346 ; B741; A388; A345
B752	111.17	B720 ; B753; B701
B763	181.81	B764; B787; A310
DH8D	29.11	E170; GLF3
E190	49.07	T134; RJ85;

3.1.5 Airline types

Airline types. Airlines are subdivided into four types: full-service, low-cost, charter, and regional. Based on this subdivision, flights can be grouped into three different flight operational cost profiles, as shown in Table 2.

Table 2. Cost scenarios assigned to flights

Cost scenario	Flight categorisation	Proportion of flights
Low	All low-cost carrier flights	30%
High	Full-service flights into hub airports Regional flights into hub airports	20%
Base	All other flights	50%

The high cost scenario has been used for full-service and regional flights *into* hub airports (i.e. inbound flights only). 14 ECAC hub airports were selected using ACI EUROPE's Group 1 definition – airports with over 25 million passengers in 2014 (ACI EUROPE, 2015).

3.2 Scenarios

Usually, comparisons are made between the *baseline* ('do nothing') and *solution* scenarios. In the current system, very little is done in the strategic phase, and most importantly, final routing decisions are not taken then. Historical traffic data we have access to is composed of last-filed flight plans that are tactical (a few hours before the flight). Thus, this data takes into account the regulations that are not known in the strategic phase. This fact makes the last-filed flight plans unsuitable for a baseline. In order to address this issue, suitable strategic baseline scenarios need to be created. In the PLP model, the baseline is obtained by fixing all of the charges at their respective historical unit rates, and assigning each flight to their lowest cost trajectory (considering both operational costs and route charges from the unit rates). In the RP mechanism, the baseline is obtained by setting all multiplier values (M1-M2-M3) to 1, meaning that no modulation of base rates is in place, i.e. that static pricing per sector entry is employed throughout the day. TFPS model has two baselines: minimum duration or minimum cost. In minimum cost, the least cost route is assigned to all flights, and in the minimum duration, the route of minimum duration is assigned to all flights.

Computational experiments are then performed on baseline and solution scenarios. Both baseline and solution scenarios share the same input data.

3.2.1 Assessment indicators

SATURN mechanisms redistribute the traffic both in time (shifts in departure and/or arrival times) and space (alternative routes) to balance demand and capacity. Even though bottlenecks are avoided, the resulting traffic pattern impacts other important phenomena. Therefore, a comprehensive assessment takes into account other indicators and looks into the resulting trade-offs. The indicators are calculated for each scenario (and scenario variant) to enable a comparison of impacts across different scenarios. The following indicators are taken into account:

1. *Horizontal en-route flight efficiency*. The horizontal en-route efficiency that we use is the difference between the origin-destination en-route distance of assigned routes (L), and the great circle distance (G) between the origin and destination, expressed as a percentage of the great circle distance ((L-G)/G, %).
2. *Sector capacity utilisation*. This indicator shows for each open sector the capacity utilisation, measured as the number of sector entries over the declared capacity (for each hour).
3. *Charges per flight*. This indicator measures the charges imposed on the flights, used to cover the costs of ANS provision. In the current setting, it is the sum of route charges. For the SATURN mechanisms it is sum of charges per flight, where the costs include route charges, modulation of charges, or incentives, as applied by the model/mechanism applied.
4. *Distribution of charges across airline types/airlines*. The aim of this indicator is to assess the equity that the different mechanisms produce. In practice, it is the aggregation of *charges per flight* across airline types (or airlines).
5. *Flight operation costs*. Based on the cost data found in Cook and Tanner (2015), the cost of operation of flights is calculated considering the assigned routes and strategic ground shifts.
6. *Departure shift*. Absolute difference between the originally-requested and assigned departure time.
7. *Arrival shift*. Absolute difference between the arrival time obtained by departing at the requested time using the shortest route and the assigned arrival time.

4 Results

This section presents the main results of the three mechanisms (CPLP and RP for pure pricing, and TFSP for hybrid pricing) introduced in Section 2.

4.1 Centralised Peak-Load Pricing

The implementation of the CPLP mechanism with both the GA and the CD approaches shows significant improvements with respect to the baseline solution computed using the historical unit rates (i.e., September 2014). The idea behind this mechanism is in fact to apply peak and off-peak rates to achieve an efficient air traffic re-distribution, in terms of low capacity violations, reduced flight shifts, and ANSP revenue neutrality violations kept below a pre-defined threshold.

The GA generates about 100,000 solutions, out of which approximately 30,000 are feasible, i.e., we have approximately 30,000 combinations of peak and off-peak rates that ensure the respect of all constraints. We consider the following indicators:

- Total Shift for all flights: the sum of the difference, in absolute value, between the actual and the scheduled departure time.
- Maximum Revenue Neutrality Violation: the absolute value of the highest difference between the collected charges using the modulated rates and the amount that would have been levied using the September 2014 unit rates in the baseline scenario.
- Violated Capacity: number of (sector/airport, hour) pairs that violate their nominal capacity level.
- Cumulative Capacity Violation: the sum over all (sector/airport, hour) pairs of the number of flights that violate the nominal capacity divided by the nominal capacity of the (sector/airport, hour) pair
- Avg. Capacity Violation: Cumulative Capacity Violation/Violated Capacity

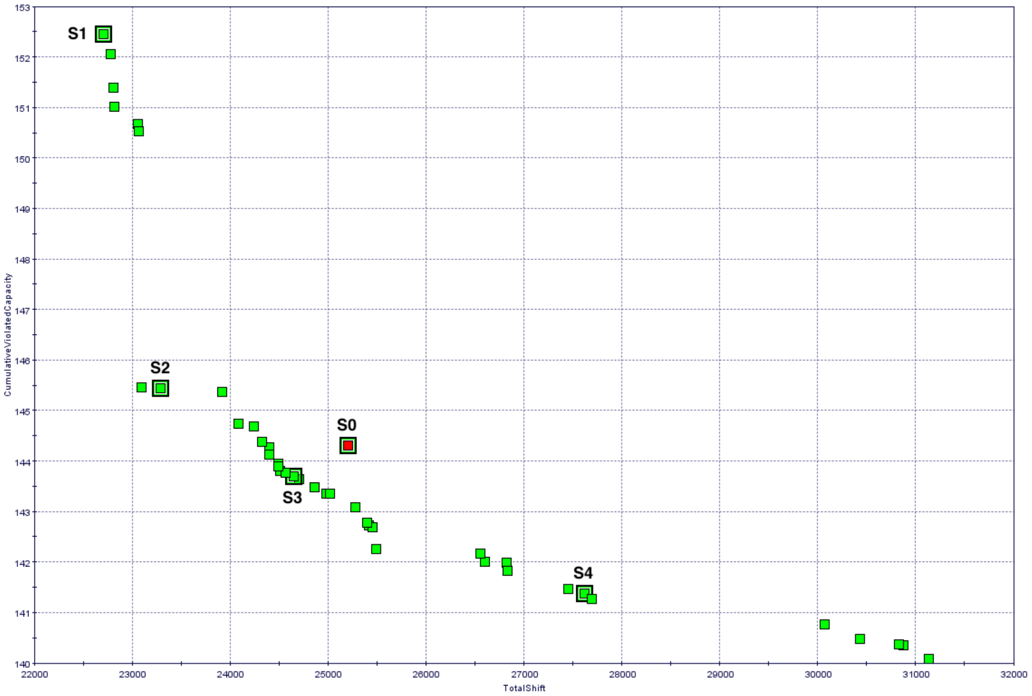

Figure 2. CPLP – Pareto front for Cumulative Capacity Violation vs. Total shift

Among all these feasible solutions, the scatter chart in Figure 2 displays a collection of selected Pareto solutions (green squares) in terms of Capacity Violations (ordinate) vs Total shift (abscissa). Both objectives are to be minimized. The red square represents the baseline solution computed with the historical unit rates. It clearly appears that the GA approach, being it a case of multi-objective optimisation, identified a number of equally good alternatives for both objectives, which entirely dominate the baseline solution. Furthermore, the plot shows a negative correlation between the objectives: shifting flights can significantly reduce capacity violations, and this can be an economically viable option by the application of peak and off-peak rates.

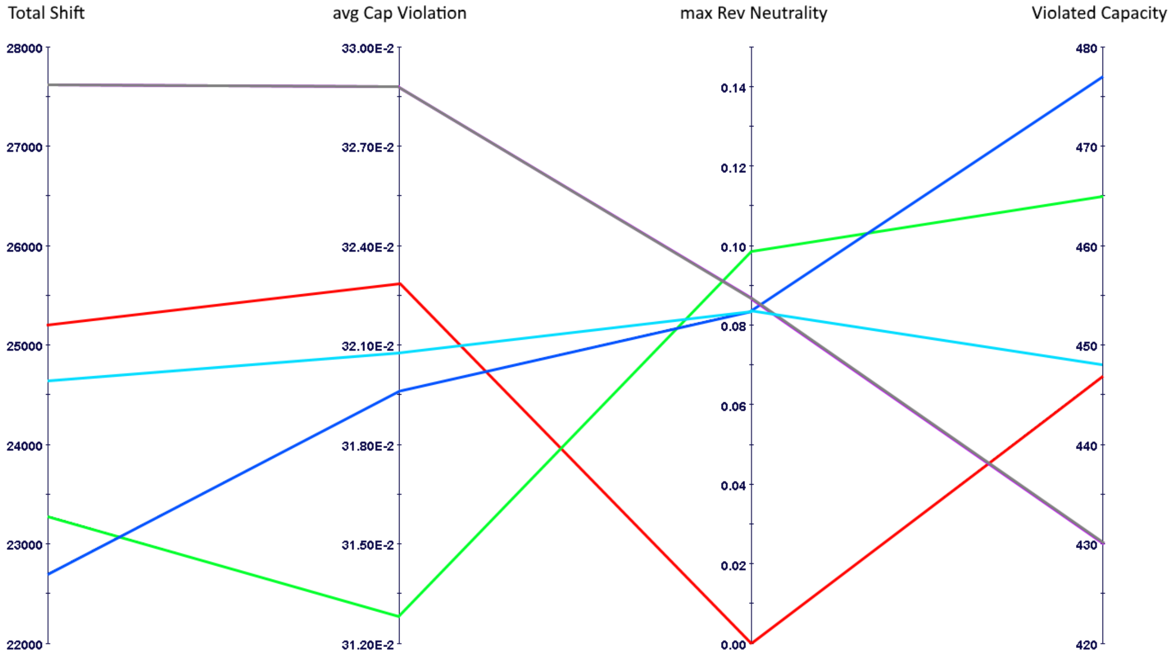

Figure 3. Trade-offs among four Pareto-solutions and the baseline solution

The Parallel Coordinates chart is a practical tool for visualizing and analysing high-dimensional and multi-variate data in predefined adjustable value ranges, spotting patterns in the objectives' behaviour and correlations between them, and filtering out "bad" data. Dimensions (objectives) are represented by equally spaced parallel vertical lines, whereas each solution is represented by a coloured polyline connecting vertices on the vertical axes.

Figure 3 shows four Pareto solutions. None of them have optimal values in all objectives. Instead, they all represent equally valid trade-offs between opposing requirements, achieved by simply re-distributing air traffic in different ways. The red line represents the baseline solution. It exhibits a medium Total Shift while the revenue neutrality is perfectly matched for each ANSP (by definition). However, this is not an optimal solution since we are striving to balance up all optimisation objectives, and keep the number of violations (i.e. capacity indicators and revenue neutrality) as low as possible and in any case below the pre-defined thresholds. The solution represented by the light blue line (S3) can be considered as the best compromise from several aspects. First, the revenue neutrality violation is no worse than the other solutions (except the baseline, of course). Second, both total shift and capacity violations indicators are better than or nearly equal to the baseline solution.

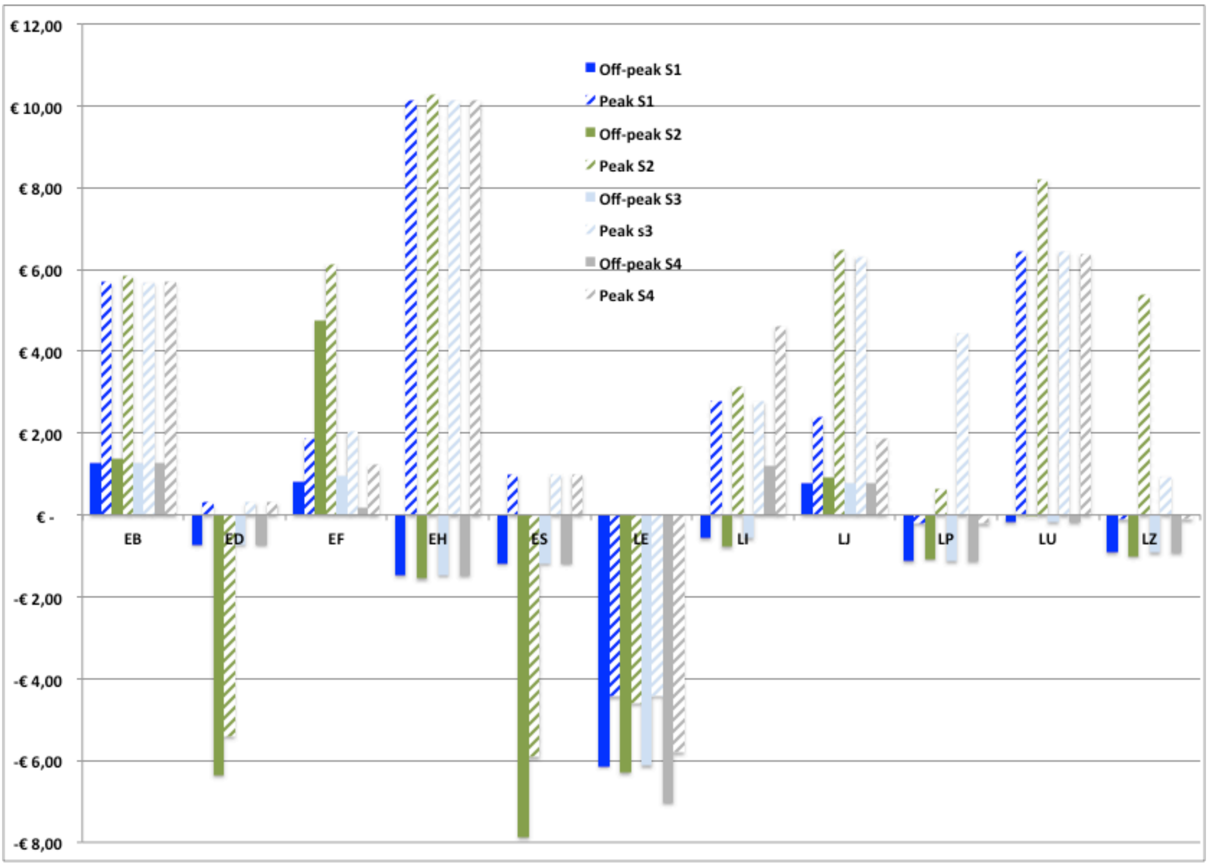

Figure 4. Peak and off-peak rates for selected ANSPs

An additional remark is linked to the peak and off-peak rates that make these favourable traffic redistributions possible. Figure 4 shows peak and off-peak rates for the four selected solutions only in the case at least one of which deviates more than 4 Euros from the September 2014 unit rate. For some states (such as Belgium and Luxemburg (EB), Finland (EF), and Slovenia (LJ)) both peak and off-peak rates appear to be higher than historical rates in all solutions. In other cases, such as for Spain (LE), the opposite occurs, with all other intermediate alternatives being possible, as for The Netherlands (EH) where off –peak rates are always lower than and peak rates always higher than the historical rate. This means that there is a large room, within the limits imposed by the European ATM regulations, for charges' modulation that leads to reduced congestion without worsening flight efficiency and flight operational costs.

Table 3 compares the different solutions in terms of the number of flights that fly different routes. For instance, in S4 there are 541 flights that use a different route from S0, 1236 flights that fly a different route from S1, etc. Similarly, Table 4 compares the different solutions in terms of the number of flights that have different shifts. Figure 5 displays an example of the spatial traffic redistribution for the Rome Fiumicino (LIRF) – Helsinki (EFHK) flight: the red route is the baseline solution (unit rates as in September 2014) whereas the light blue line represents the route chosen under solution S3.

Table 3. Number of flights that use different routes between two solutions

	S0	S1	S2	S3	S4
S0	0	858	550	258	541
S1		0	525	642	1236
S2			0	320	936
S3				0	644
S4					0

Table 4. Number of flights that have different total shifts between two solutions

	S0	S1	S2	S3	S4
S0	0	1000	685	308	643
S1		0	629	744	1420
S2			0	412	1114
S3				0	740
S4					0

These figures show that it is possible to improve the baseline solution through a very limited spatial and/or temporal redistribution of traffic. Solutions that experience larger differences, as S1 vs S4, are indeed on the opposite sides of the Pareto frontier.

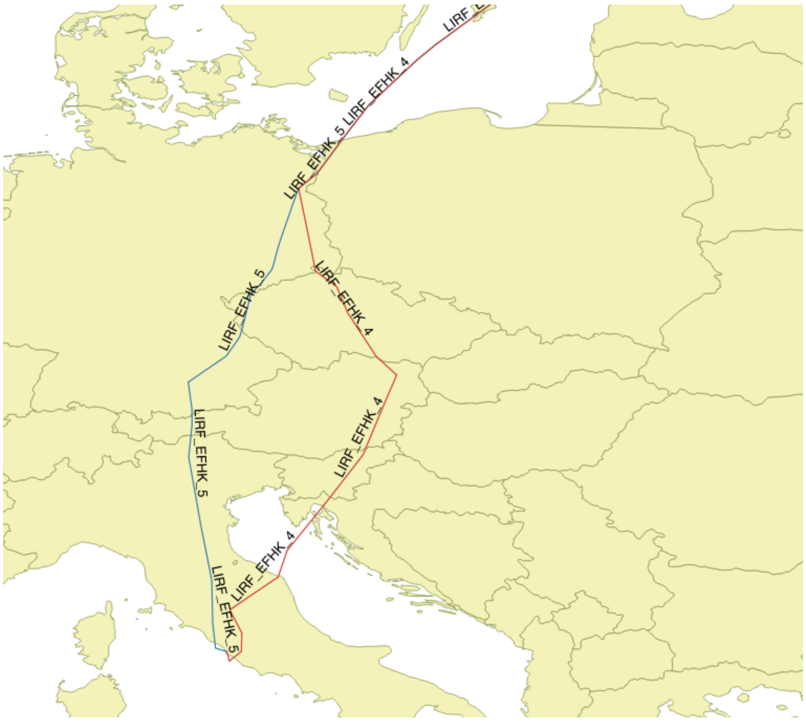

Figure 5. Example of the effect of charges modulation on LIRF-EFHK

4.1.1 Peak-Load Pricing variants

Table 5 shows the impact that the additional degrees of freedom have on the ability of the pricing mechanism to redistribute the traffic. In the case of the CFMP mechanism, the capacity violations have been mostly eliminated (only 28% of them remains from the base scenario) and the revenue neutrality principle is fully satisfied. Hence the baseline solution is completely dominated, a situation not available for any of the selected solutions shown in Figures 2 and 3. However, these powerful results are only possible due to the flexibility added by the 12279 different rate variables of the mechanism.

Table 5. Baseline and CFMP numerical results

Metric	Baseline (S0)	CFMP
Number of distinct rates	78	12279
Total Global Shifts	25201	24421
Number of Capacity Violations	447	123
Maximum Revenue Neutrality Violation (%)	0	0

Finally, Table 6 presents the results for the numerical tests of the DPLP mechanism on the 12SEP14 data, using various methods for deciding the order in which the different ANSPs select their own rates: in alphabetical order, in a fixed randomly-chosen order, or in randomly-chosen order which is reselected at every iteration of the mechanism. Each of these tests was done using 5 iterations of the mechanism.

In comparison with the CPLP selected solutions in Figures 2 and 3, DPLP produces solutions that

a) have a slightly lower total shift than S0 and S1, but a higher shift than S2, S3 and S4;

b) largely exceed the number of capacity violations of all CPLP solutions;

c) largely exceed the revenue neutrality violation of all CPLP solutions.

This means that if it was to be implemented in a decentralised fashion, a Peak-Load Pricing scheme would be somewhat worse than if the scheme was to be implemented in a centralised fashion.

Table 6. DPLP numerical results

Metric	**Baseline (S0)**	**DPLP (alpha)**	**DPLP (fixed random)**	**DPLP (non-fixed random)**
Total Global Shifts	25201	24762	24663	24732
Number of Capacity Violations	447	513	519	519
Maximum Revenue Neutrality Violation (%)	0	1.41	0.38	1.41

4.1.2 Non-deterministic effect

All the numerical results in this section for the different mechanisms based on CPLP (CPLP itself, CFMP, and DPLP) have been done assuming that the behaviour of the AUs is perfectly predictable. This would clearly impossible be impossible for a real-world implementation of the mechanisms. What follows is an analysis of the robustness of those results in the scenario where the peak and off-peak rate are chosen assuming perfect predictions, but the predictions miss the mark.

Table 7. CPLP non-deterministic fuel price, lower price than predicted

Fuel price:	**50%**		**75%**	
Metric	$\delta(100\%)$	$\delta(50\%)$	$\delta(100\%)$	$\delta(75\%)$
Total Global Shifts	28’623	28’379	26’174	25’992
Number of Capacity Violations	692	640	690	674
Efficiency (%)	50.64		74.89	

Table 8. CPLP non-deterministic fuel price, higher price than predicted

Fuel price:	**150%**		**125%**	
Metric	$\delta(100\%)$	$\delta(150\%)$	$\delta(100\%)$	$\delta(125\%)$
Total Global Shifts	21’286	21’076	22’474	22’239
Number of Capacity Violations	726	679	710	687
Efficiency (%)	55.71		71.75	

Table 7 and Table 8 present the effect of using peak and off-peak rates obtained from running the CD algorithm using the strategic costs ($\delta(100\%)$), but where the AUs choose their trajectories according to strategic costs that are adjusted to take into account modified fuel prices. 4 scenarios are presented, each with a different fuel price: 50%, 75%, 125%, and 150% of the fuel price as defined in the ‘base’ cost scenario (see Section 3.1.4). These results are compared to what would have happened if the peak and off-peak rates had been chosen using the modified fuel prices.

The efficiency of the mechanism is defined as the ratio of the objective function improvement with the wrong fuel prices and the objective function improvement with the correct fuel prices. It measures the cost that a wrong prediction of fuel prices has on the benefit of the CPLP mechanism. As can be seen in the tables, the efficiency is down by about 50% if the fuel costs prediction is wrong by 50%, and the efficiency is down by about 25% if the fuel costs prediction is wrong by 25%. This shows how important an accurate prediction of the fuel costs is to reap the benefits of the CPLP mechanism.

4.2 Rewarding predictability

4.2.1 12SEP14 experiment

Table 5 summarises key results of application of a selection of different scenarios of RP mechanism in 12SEP14 experiment (29,149 flights; 22,837 active half-hourly sector-periods). Five simulation runs were performed per each RP scenario shown. Since very small variation was recorded in displacement cost and revenue collected, we calculated but did not show values of standard deviation in Table 9, to save space.

The values of displacement cost in different RP scenarios are shown relative to the “Base Case” solution, wherein all multipliers are set to 1, meaning that static sector-entry-charges apply throughout the day.

“Heavily delayed flight” label means that there was no available route for the considered flight at the moment of its show-up. Since only delays of 10, 20 and 30 minutes were possible by mechanism design, we assumed the cost of 50 minutes of delay for each such (“heavily delayed”) flight when calculating total displacement cost.

Table 9. Summary results of RP mechanism, 12SEP14 experiment

			Distribution of delayed flights: median (min, max)						
Pricing scenario (RP-D mechanism unless otherwise stated)*	**M1 bounds**	**M2 coefficients**	**Heavily delayed flights**	**30' delayed flights**	**20' delayed flights**	**10' delayed flights**	**Extra displacement cost vs. Base Case, mean (M EUR)**	**Charges revenue vs. Base Case, mean (M EUR)**	**Share of highly loaded sector-periods, mean (%)**
1. Base Case: M1=1; M2=1; M3=1	1.0-1.0	1-1-1	853 (848, 881)	443 (430, 475)	511 (484, 534)	822 (807, 856)	0.00	0.00	6.2
2. “Default” (Warsaw ACC)	0.8-1.2	0.98-1.17-1.52	767 (744, 775)	485 (445, 500)	560 (539, 575)	966 (933, 986)	-0.16	0.29	5.7
3. M1=1; M2 default	1.0-1.0	0.98-1.17-1.52	734 (713, 736)	506 (487, 513)	613 (603, 637)	1059 (1011, 1070)	-0.08	1.71	5.6
4. M1 default; M2 stretched	0.8-1.2	0.8-1.3-2.0	674 (662, 695)	691 (666, 724)	752 (740, 824)	1288 (1233, 1357)	-0.08	0.51	5.1
5. M1 default; M2 extra stretched	0.8-1.2	0.7-1.4-2.8	613 (593, 620)	1000 (992, 1072)	1085 (1050, 1099)	1549 (1499, 1571)	0.12	1.72	4.6
6. M1 stretched; M2 default	0.7-1.3	0.98-1.17-1.52	757 (736, 776)	477 (447, 508)	556 (534, 582)	937 (914, 961)	-0.11	-0.40	5.8

* M3 default values assumed unless otherwise stated.

The results suggest that pricing policies can notably decrease the share of ‘highly loaded’ sector-periods (that is, those with utilisation of declared capacity >90%, see last column), and yield a more balanced traffic distribution across the network. However, tested pricing assumptions at the same time only yield a fairly modest variation in total displacement cost, especially given the size of the traffic sample. Those roughly differ from the Base Case value at most by ±150,000 EUR (or about ±5 EUR per flight, on average), with best performer in this respect being Scenario 2, with “default” multiplier values, calibrated on small Warsaw ACC example, described in Jovanović et al. (2015a).

More notable is variation in numbers of flights affected by different durations of at-gate delay. For instance, number of ‘heavily delayed’ flights can be reduced by more than 200 (e.g. Scenario 5 vs. Base Case scenario). Yet, trade-offs involved between the four categories of affected flights are quite obvious from Table 5, resulting in fairly mild net cost differentials between scenarios, on aggregate.

The route charges revenues are far more sensitive to variations in pricing assumptions, with both M1 and M2 being influential in this respect. We typically observe revenue surpluses for the range of tested scenarios, compared to the Base Case, except in Scenario 6, which assumes the 30% discount for early route purchasers (i.e. lower M1 bound set to 0.7).

As for M2 multiplier, which is, by design, a function of sector-period utilisation, stretching its range typically results in reduction of the number of “heavily delayed” flights and highly loaded sector-periods, but this necessarily comes at the expense of strong increase the incidence of flights delayed up to 30 minutes. The net effect of stretching the M2 range on total displacement costs is at first positive, yielding best results when last remaining sector capacity increments are charged about 55% higher than the first ones. Stretching M2 further yields mild negative net effect on displacement costs, on top of further increasing the revenue surplus.

Finally, Figure 6 enables a more focused insight into tradeoffs involved between different RP scenarios. It shows how each of the selected scenarios performs against the best obtained individual indicator value across all tested RP scenarios, except with charges revenue, where we used Base Case revenue as a benchmark. These indicators are thus expressed as % of best/target value (“benchmark”). The log10 scale is used to provide an easier insight, meaning that the benchmark of 100% corresponds to value “2” on the chart (the smallest heptagon). In other words, the closer an indicator’s value is to 2, the better the performance of the considered pricing scenario in that respect. Only values ≥2 are thus possible, except for revenue indicator, wherein revenue deficit corresponds to values less than 2. Figure 6 clearly illustrates the trade-offs between different performance indicators involved. As such, it is considered a useful summary of mechanism results for policy makers.

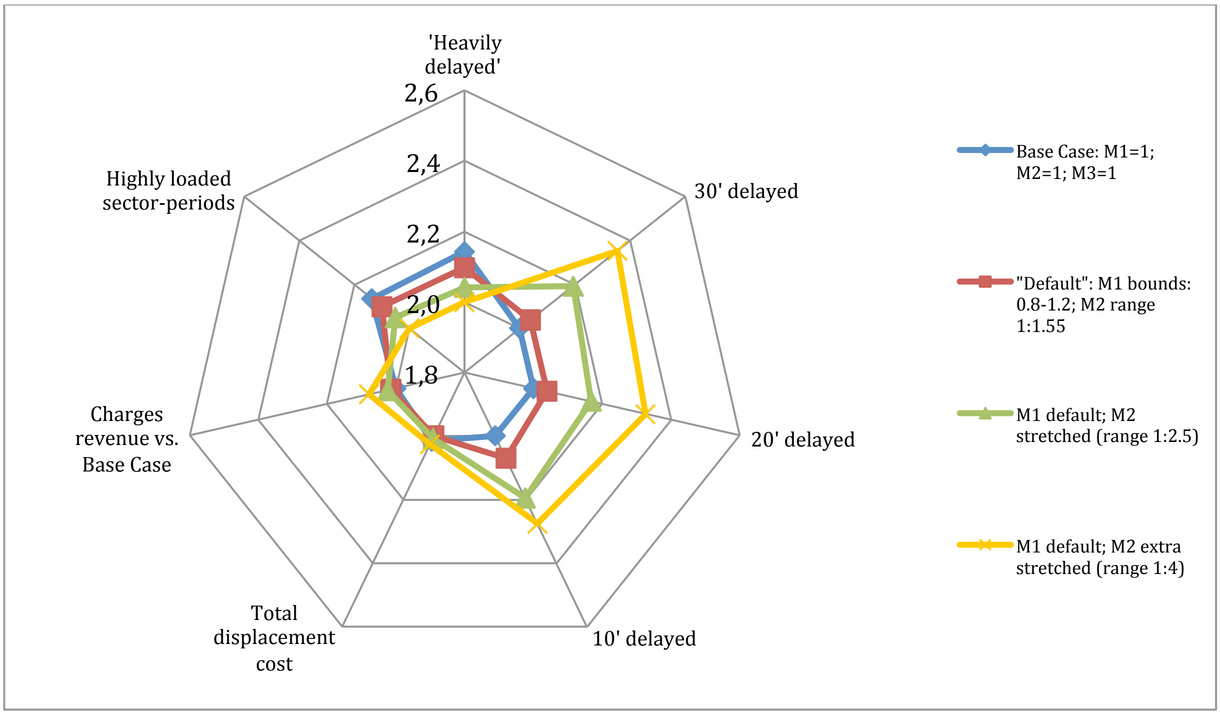

Figure 6. Comparative performance of selected RP pricing scenarios, against benchmark value per indicator; 12SEP14 example

Note: log10 scale employed, i.e. benchmark=2⇔100%.

4.2.2 Regional instance, 01AUG14

On top of all-day Europe-wide instance, 12SEP14, an additional – regional test instance was also employed, exhibiting more pronounced en-route demand/capacity imbalances, and a higher share of longer flight delays as a consequence thereof. To that end, the very challenging traffic/capacity imbalance recorded on 01AUG14 in the part of the European airspace was identified as an appropriate case. More specifically, the core period between 10:00 and 15:00 hours was selected, encompassing 11 en-route regulations and approximately 1,100 regulated flights. The core airspace under consideration covers Poland, Germany, MUAC area, France and Spain.

The final modelling scope comprised 7,697 flights and the airspace of 566 sectors. Table 10 summarises key results of application of different scenarios of RP mechanism in 01AUG14 experiment.

Table 10. Summary results of RP mechanism, regional instance.

			Distribution of delayed flights: median (min, max)					
Pricing scenario (RP-D mechanism unless otherwise stated)*	**M1 bounds**	**M2 coefficients**	**'Heavily delayed' flights**	**30' delayed flights**	**15' delayed flights**	**Extra displacement cost vs. AHM value, mean (M EUR)**	**Charges revenue vs. target, mean (M EUR)**	**Share of highly loaded sector-periods, mean (%)**
S1. Ad-hoc modulation (AHM) mechanism - system optimum	n/a	n/a	0	9	37	0.00	0**	10.0
S2. Base Case: M1=1; M2=1; M3=1	1.0-1.0	1-1-1	49 (33,57)	78 (61,89)	60 (52,80)	0.31	-0.65	7.2
S3. Static scarcity pricing: M1=1; M2=1	1.0-1.0	1-1-1	41 (31,50)	79 (72,87)	64 (55,74)	0.32	-0.31	7.1
S4. 'Default' values***	0.8-1.2	0.98-1.17-1.52	31 (25,38)	86 (78,99)	61 (48,74)	0.29	-0.32	6.3
S5. M1=1; M2 default	1.0-1.0	0.98-1.17-1.52	25 (19,36)	104 (93, 118)	61 (49,74)	0.32	0.30	6.2
S6. M1 default; M2 stretched	0.8-1.2	0.8-1.3-2.0	21 (16,34)	134 (118,153)	79 (68,99)	0.30	-0.16	5.8
S7. M1 default; M2 extra stretched	0.8-1.2	0.7-1.4-2.8	12 (7, 19)	212 (200, 247)	139 (117,160)	0.39	0.45	4.6
S8. M1 stretched; M2 extra stretched	0.7-1.2	0.7-1.4-2.8	15 (11,28)	199 (184,231)	130 (118,145)	0.36	0.02	4.9
S9. M1 stretched; M2 ultra stretched	0.7-1.2	0.6-1.8-5.4	7 (5, 14)	379 (349,425)	331 (297,364)	0.69	2.21	3.0
S10. Stochastic RP – 'Default'	0.8-1.2	0.8-1.3-2.0	81 (70,100)	122 (101,143)	125 (112,147)	0.52	0.12	8.2

* M3 default values unless otherwise stated.
** AHM mechanism is revenue neutral by design.
*** As calibrated on Warsaw ACC example, described in Jovanović et al. (2015a)

Besides RP mechanism results, Table 10 shows the "system-optimum" solution, as calculated by the Ad-hoc modulations (AHM) mechanism, employing network-centric two-level optimisation, described in Jovanović et al. (2014). We use the AHM results as a reference, acting as an upper bound of what could be achieved for the given set of flights, routes and capacities, in terms of minimising total displacement cost. Therefore, the values of displacement cost in different RP scenarios are shown relative to solution obtained by AHM.

Twenty simulation runs were performed per each RP scenario shown. The results suggest that deterministic RP pricing scenarios yield higher total displacement cost (efficiency deterioration) of at least 0.30 million EUR, compared to the AHM mechanism (corresponding to difference of nearly 40 EUR per flight, on average). This cost difference stems from greater number of "heavily delayed flights" and flights delayed 15 and 30 minutes in RP mechanism, compared to AHM.

Turning our attention to comparison of results between different RP scenarios, we observe a fairly small variation in total displacement cost for most of the scenarios considered, ranging between 0.29 and 0.36 million EUR vs. AHM value. Other indicators considered: heavily delayed flights, number of flights affected by delays, as well as collected revenue, show greater sensitivity with respect to different pricing assumptions. For instance, number of heavily delayed flights can be strongly reduced by stretching the M2 range, but this comes (at an extreme) at a price of substantial increase of flights delayed by 15' and 30', with a net effect of increasing the total displacement cost, as well as generating the considerable (undesired) revenue surplus.

On the other hand, the M1 multiplier itself exerts fairly mild impact on aggregate distribution of affected flights, as well as on total displacement cost. However, it considerably impacts the collected charges revenues, which can be used to counterbalance the effect of M2 multiplier in this respect.

The application of stochastic RP mechanism (RP-S) yields route allocation which is, on average, about 0.2M EUR more expensive than those arising from deterministic mechanism's application. Overall, the RP-S mechanism is far less sensitive on pricing assumptions in all aspects except for the revenue collected.

Finally, the results (see last column in Table 10) also suggest that pricing mechanisms can yield more balanced distribution of traffic across available airspace capacities. In particular, number of 'highly loaded' sector-periods (wherein utilisation of capacity is >90%) can be substantially reduced. For instance, in the Base Case scenario 7.2% of sector-periods have utilisation greater than 90%. This share can be reduced more than twofold, to 3%, in Scenario 9, which assumes extreme M2 coefficients range.

Figure 7 enables a more focused insight into tradeoffs involved between different RP scenarios. As with Figure 6, it shows how each of the selected scenarios performs against the best obtained individual indicator value across all tested RP scenarios, except with charges revenue, where we used target revenue as a benchmark. As before, the closer an indicator's value is to 2, the better the performance of the considered pricing scenario in that respect. Figure 7 suggests that, whereas distribution of traffic (and of displacement effects) can be considerably influenced by various pricing scenarios tested, the associated net gains, in terms of reduction of total displacement cost compared to Base Case solution, seem fairly mild. On a more general level, taking into account the results of both European and regional experiment, it seems that more can be expected from demand-side pricing policies in terms of balancing the distributional effects than in terms of yielding significant cost savings to airspace users on aggregate (as a whole).

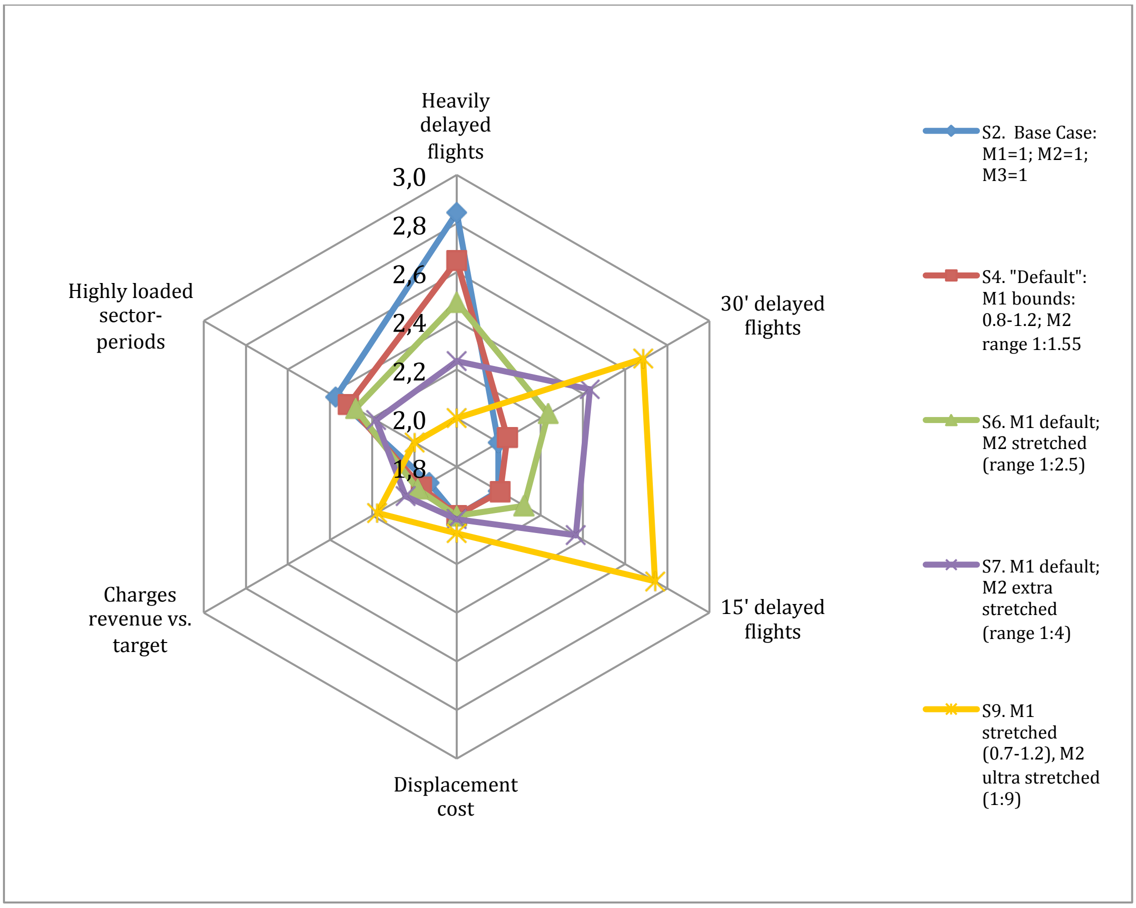

Figure 7. Comparative performance of selected RP-D pricing scenarios, against benchmark value per indicator; regional instance, 01AUG14

Note: $\log_{10}$ scale employed, i.e. best performance benchmark=2⇔100%.

4.3 Tradable Flight Permit System

Two *baseline* scenarios are determined first: minimum distance (BMD) and minimum cost (BMC). These two scenarios assign minimum distance and minimum cost routes to each flight, respectively, without considering capacity limitations. Then, two *solution* scenarios are run, performing the initial endowment with the SAIPE model, using base flight operational costs to guarantee a fair initial distribution of permits: MC SAIPE (SMC) using the minimum cost objective function, and MS SAIPE (SMS) using the minimum shift objective function. *Solution* scenarios provide initial flight plans that respect nominal capacity constraints. The exchange market is then performed with the CEM model on each of the two SAIPE *solution* scenarios, which are referred to as CEM MC (CMC) and CEM MS (CMS), respectively. In the exchange market, different flight cost profiles are assigned to flights, based on the airline type and the flight type, as described in section 3.1.

Analysis of shifts. BMD has no shift by definition, and similarly, BMC has no departure shift by definition. The initial endowment, performed with the SAIPE model, must respect available capacity, which is ignored by these two baseline scenarios. Table 11 shows the values of departure and arrival shifts per shifted flight, the number of shifted flights in each scenario, and the departure and arrival shifts per flight (average over all flights). As can be seen, SMS results in the minimum shifts and the minimum number of shifted flights, as the objective function is to minimise the shift. SMC and CMC have very similar results. Keep in mind that the shift values are obtained with respect to the routes of minimum duration, therefore even in CMC there are 2,090 shifted flights. CMS represents the application of the exchange market on the SMS results. Here, we can see that the number of shifted flights increases, as well as the values of the departure and arrival shifts, as the AUs opt for longer, but cheaper routes.

Table 11. Departure and arrival shifts, number of shifted flights

	Dep shift per shifted flight (min/shifted flight)	Arr shift per shifted flight (min/shifted flight)	Number of shifted flights	Dep shift per flight (min/flight)	Arr shift per flight (min/flight)
BMC	0.00	2.74	378	0.00	0.04
SMS	5.34	5.34	1133	0.39	0.42
SMC	6.62	5.90	2098	0.19	0.19
CMC	6.67	5.98	2090	0.39	0.43
CMS	6.87	6.33	1930	0.38	0.41

Figure 8 below shows the distribution of the number of flights shifted by a specific number of minutes, for both departure and arrival shifts. It can be seen that, in the SMS scenario, the number of shifted flights for each specific amount of minutes is the lowest, while the CMC scenario provides the upper bound. SMC and CMC scenarios have almost identical shift results.

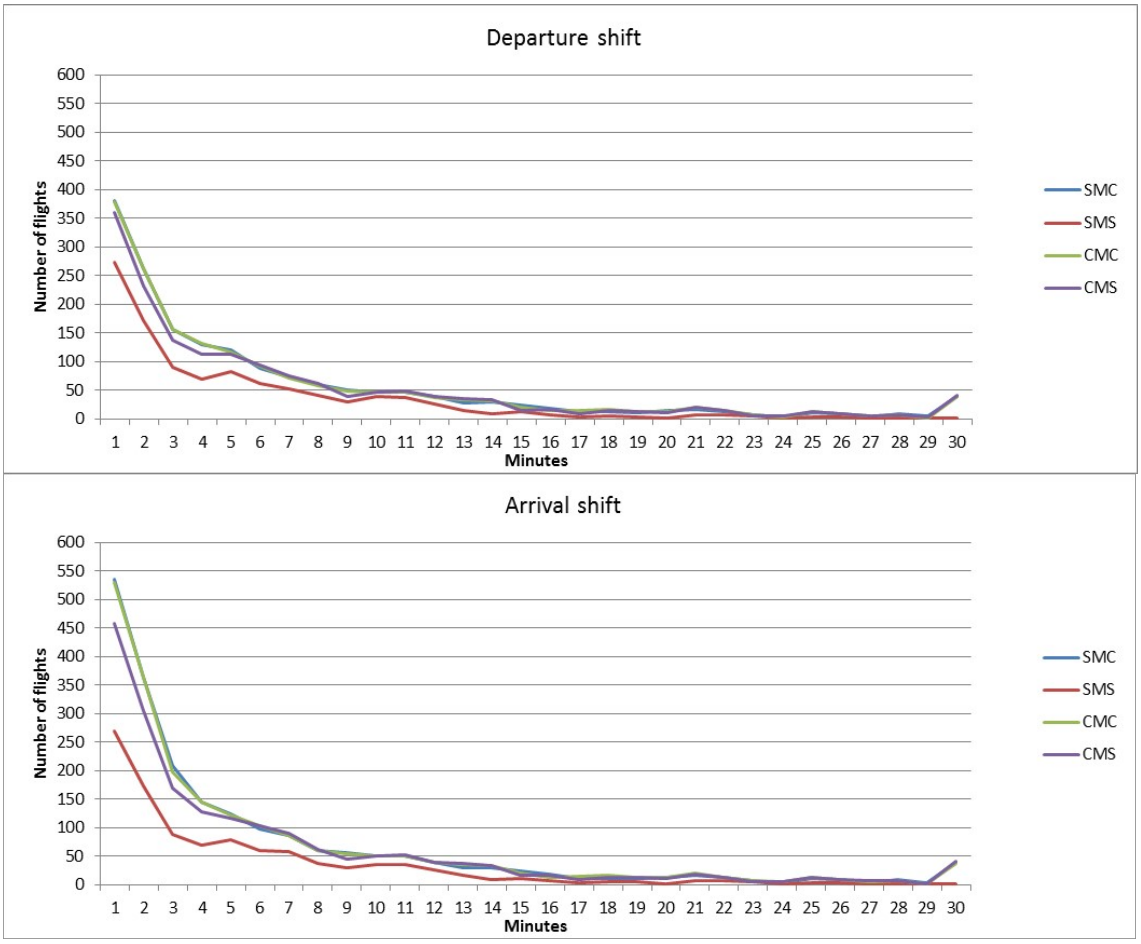

Figure 8. Number of shifted flights, for each value of shift, across different scenarios.

Analysis of flight operational costs. Table 12 shows the average operational costs across all scenarios. We notice that scenarios that do not optimise route charges costs (BMD, and SMS) report a higher total cost. Exchange market scenarios (CMC and CMS) result in the highest total cost, which is due to the use of the "actual" AUs' costs for their flights, as in SMS and SMC the industry-wide average costs are used. As can be seen from various components of the total flight costs, route charges are the main source of total cost variation between BMC, BMD, SMC and SMS scenarios.

Table 12. Average flight operations costs (per flight).

	Airborne Costs	Fuel	Ground Costs	Route charges	Total costs
BMC	€ 3311.51	€ 4782.45	€ -	€ 717.20	€ 8811.15
BMD	€ 3310.57	€ 4781.24	€ -	€ 745.71	€ 8837.53
SMC	€ 3311.49	€ 4782.41	€ 4.35	€ 719.39	€ 8817.63
SMS	€ 3311.22	€ 4782.04	€ 2.62	€ 742.00	€ 8837.87
CMC	€ 3480.46	€ 4797.28	€ 3.78	€ 719.39	€ 9000.91
CMS	€ 3480.38	€ 4797.24	€ 3.79	€ 720.01	€ 9001.42

Figure 9 shows the average route charges in each of the six scenarios. Scenarios are grouped by the flight plan assignment criterion used: the first three (BMC, SMC, and CMC) assign flight plans based on minimum cost route selection, while the last three (BMD, SMS, CMS) assign flight plans based on route minimum duration (BMD) or minimum shift (SMS, CMS). It can be seen that the average route charges in the first three are significantly lower with respect to the BMD and SMS scenarios (for about 25€). Route charges for the CMS scenario are very similar to those of SMC and CMC. This demonstrates that by participating in the exchange market after the SMS flight distribution, the AUs opt for cheaper routes. Of course, this implies an increase of the shift, as is shown in **Analysis of shifts**. BMD has no shift by definition, and similarly, BMC has no departure shift by definition. The initial endowment, performed with the SAIPE model, must respect available capacity, which is ignored by these two baseline scenarios. Table 11 shows the values of departure and arrival shifts per shifted flight, the number of shifted flights in each scenario, and the departure and arrival shifts per flight (average over all flights). As can be seen, SMS results in the minimum shifts and the minimum number of shifted flights, as the objective function is to minimise the shift. SMC and CMC have very similar results. Keep in mind that the shift values are obtained with respect to the routes of minimum duration, therefore even in CMC there are 2,090 shifted flights. CMS represents the application of the exchange market on the SMS results. Here, we can see that the number of shifted flights increases, as well as the values of the departure and arrival shifts, as the AUs opt for longer, but cheaper routes.

Table 11.

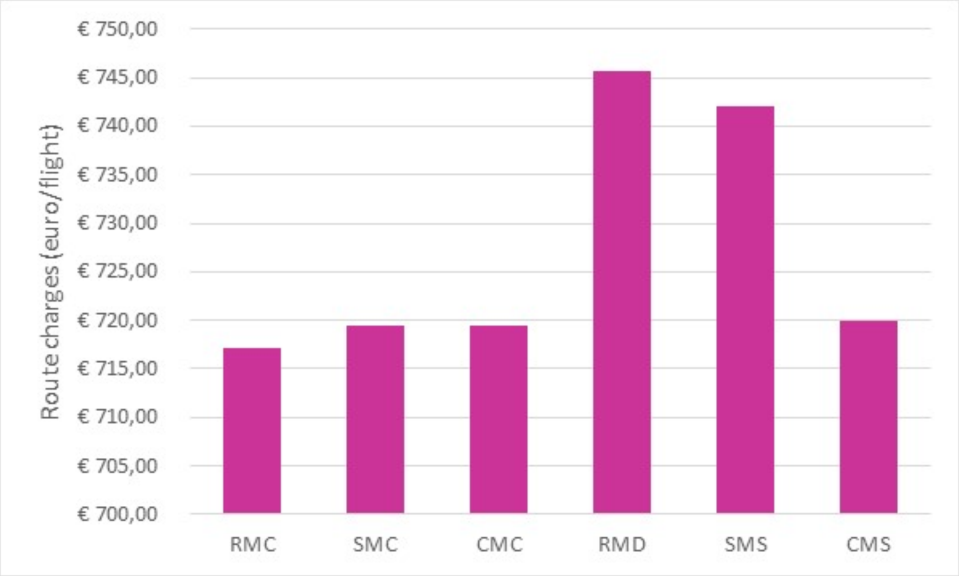

Figure 9. Average route charges across scenarios.

Exchange market analysis. The initial endowment solutions – SMS and SMC – use the industry-wide average operational costs, which may still be improved. Such improvements are left to the airlines, allowing them to trade endowed permits in the exchange market, making their trading decisions based on their actual costs, not industry-wide averages. The AUs need to provide the information on their willingness to pay for a more convenient route, or their willingness to be paid to switch to a less convenient route. Table 13 shows the number of exchanges in the exchange market after the SMC (CMC) and SMS (CMS) scenarios. As can be seen, after the SMC, only 255 flights exchange routes, which is less than 1% of all flights. On the other hand, after the SMS, about 10% of flights participate in the exchange market, pointing out that shift minimisation leaves ample room to AUs for finding better solutions in the market.

Table 13. Number of flights exchanging permits in the exchange market.

	Number of exchanges
CMC	255
CMS	3125

Sector capacity utilisation. The goal of the TFPS mechanism is to alleviate airspace capacity-demand imbalances at the strategic phase. With that in mind, let us turn to the sector capacity utilization. Figure 10 shows the change in capacity utilisation between the baseline (BMC) and the solution (SMC) scenarios. It can be seen that in the majority of cases the sector utilisation is between 0-25%. Both scenarios give very similar results for low and medium sector capacity utilization (0-

75%). As in the BMC scenario the capacity constraints are not respected, we can see that However, it is interesting to note that in almost 5% of the cases the capacity is seriously breached. Using our model to redistribute flights, in the SMC case, we can see that most of the excess demand is moved from the overloaded sectors to the sectors with capacity utilization of 75-100%.

Furthermore, Figure 11 depicts the change in sector capacity utilisation over a region in Europe, between 14:00-15:00, for RMC (left) and SMC (right). The numbers within the contours of sectors represent the capacity utilisation during the hour (14:00-15:00). Looking at both colour shade of the sectors and the capacity numbers, it can be noticed that with SMC there are no sectors with capacity utilisation over 100%. Additionally, one can notice that traffic is shifted from overloaded sectors to the ones that have spare capacity.

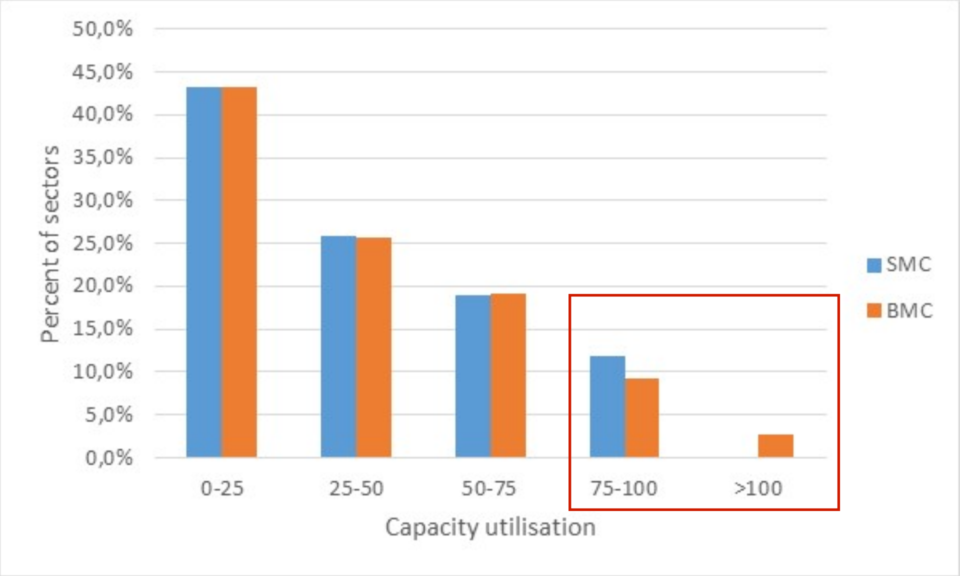

Figure 10. Change in capacity utilisation between the SMC and BMC scenarios.

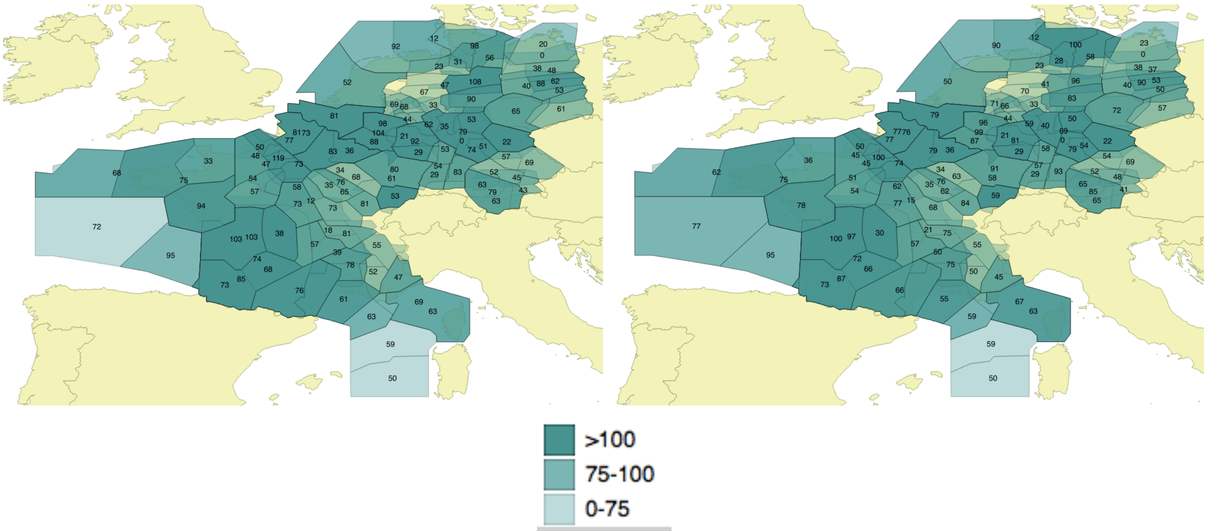

Figure 11. Change in capacity utilisation between the BMC (left) and SMC (right), over a region of Europe between 14:00 and 15:00.

Comprehensive analysis. In order to compare the four solution scenarios, we use a radar chart, where the values of various indicators are presented in log10 scale, to provide an easier insight. Figure 12 depicts how different *solution* scenarios perform across these indicators: number of flights shifted up to 10, 20 or 30 minutes in departure, number of flights shifted up to 10, 20 or 30 minutes in arrival, total average flight cost, average route charges.

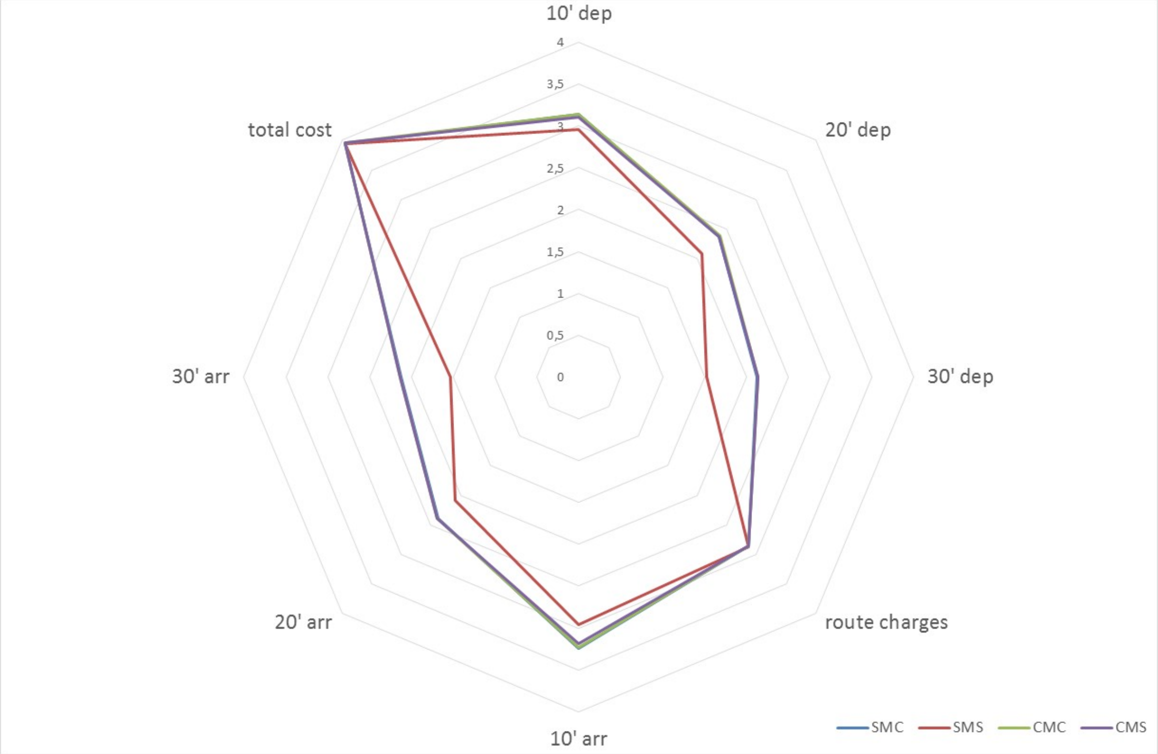

Figure 12. Comparison between SMC, SMS, CMC, and CMS, across different indicators.

As it can be seen from Figure 11, SMC, CMC and CMS scenarios give overall very similar results. The exchange market starting from either of the two initial endowments (SMC or SMS) tends to converge to a similar common solution. For MC SAIPE only a small number of flights participate in the exchange market, indicating that the initial endowment based on base flight operational costs is close to the optimal solution that considers actual flight operational costs. If the goal of the system is the minimisation of flight operational costs alone, it can be argued that the gains offered by the exchange market are limited, and thus the complication of implementation of a market mechanism would outweigh the potential gains (for a rather small percentage of users). Exchange market results from either initial endowment are very similar to those of the MC SAIPE, pointing to the fact that very good results in terms of cost savings to airlines, acceptable level of shift, ANSP revenues, and capacity utilisation can be achieved by using just this initial endowment (keep in mind that the average airline costs are used here).

Sensitivity analysis. In order to evaluate the behaviour of the initial endowment and exchange market models under different conditions that may arise due to uncertainty, we studied the models under different fuel cost and actual flight operational cost values. First, three fuel cost profiles (low, base, high) were considered in the initial endowment of flights. Initial endowment results obtained using low and high fuel cost profiles reported the same behaviour of the results that use base fuel cost, reported above. Then, for each of the initial endowment results, we ran the exchange market model 10 times, each with different random cost profiles assigned to airlines. These random cost profiles allow the assessment of the results quality over different actual flight operational costs distributions, which is not taken into account in the initial endowment of permits. The results of the exchange market resulted to be similar throughout the different executions. Figure 12 shows the variability of the exchange market gains across the 10 different runs for each of the six studied cases. These results are important as they show that the TFPS mechanism can perform well in real life conditions, with uncertainty affecting various cost sources.

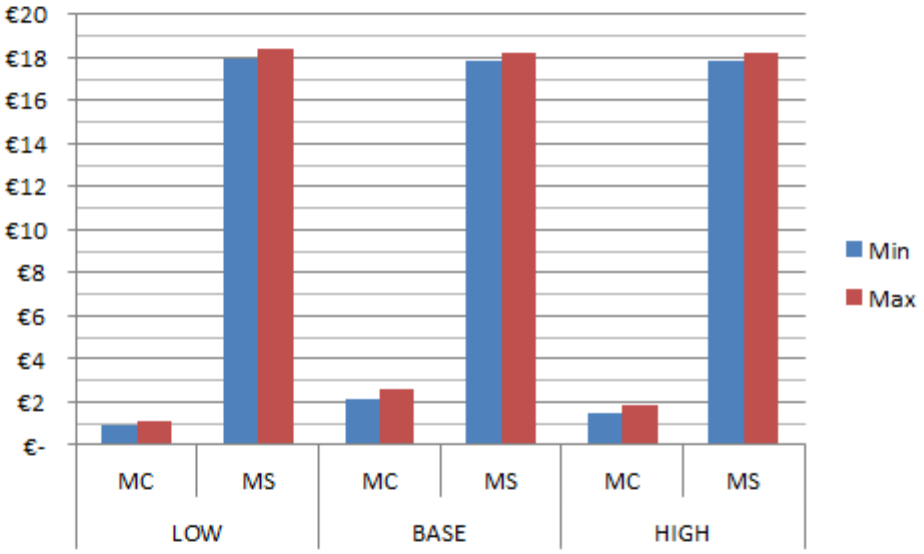

Figure 13. Comparison between SMC, SMS, CMC, and CMS, across different indicators.

4.4 Comparative analysis using performance indicators

Here we present the assessment of a selection of SATURN's models:

1. CD approach: CPLP solved using CD heuristic, baseline (base) and solution (CPLP) scenario,
2. GA approach: CPLP solved using GA approach, baseline (base) and solution (CPLP) scenario,
3. TFPS mechanism: the initial endowment for Baseline minimum cost (BMC) and SAIPE minimum cost (SMC),

Note that baseline models in both CD and GA approaches already respect the sector capacities.

We also show some figures for the flights actually flown on September 12th, for illustration purposes.

First, the number of shifted flights is shown. A flight is shifted if in the solution scenario its departure and/or arrival times are different from the ones in the baseline scenario, or if it uses a different route from the one in the baseline scenario. The CPLP solved by GA approach shifts the lowest number of flights, only 405 (about 1% of all flights). On the other hand, SMC shifts the most flights with respect to its baseline scenario (BMC), 6954 flights, which is about 24%.

Next, let us turn to departure shift. As can be seen, the values of departure shift per flight (average over all flights) are less than one minute in all the cases. Further, the average departure shifts, per shifted flight, are lower than 5 minutes, indicating that high values of shift are assigned to a very small number of shifted flights. The same conclusions can be drawn for the arrival shifts.

The route charges depend on the length of the route, unit rate (and thus ANSP) applied, and the aircraft weight. When we look at how the route charges change, we can see that in both CPLP approaches the route charges decrease in the solution scenario, on average on the order of 30€ per flight. This might be considered enough of an incentive for the airlines to offset the increase of departure and/or arrival shifts of these flights. In case of the TFPS, the solution scenario (SMC) route charges are higher than the ones in the BMC. This is to be expected as in the BMC the cheapest route is assigned to each flight, and the sector capacities are not respected. In order to respect the capacity constraints, the flights need to be re-distributed (to avoid overloaded sectors). However, that implies the longer and/or more expensive routes need to be assigned, which is the cause behind the higher route charges in SMC scenario.

Another important point to assess is the horizontal efficiency of the flights, expressed as the difference between the origin-destination en-route distance of assigned routes (L), and the great circle distance (G) between the origin and destination, expressed as a percentage of the great circle distance ((L-G)/G, %). As can be seen from Table 14, horizontal efficiency does not change much across different scenarios, indicating that the proposed solutions, while resolving capacity-demand imbalances do not worsen the flight efficiency.

Table 14. Assessment indicator values for a selection of models.

	CD approach		GA approach		TFPS		
	Base	**CPLP**	**Base**	**CPLP**	**BMC**	**SMC**	**Actual**
Number of shifted flights		1764		405		6954	
Departure shift (per flight)	0,47	0,61	0,47	0,48	0,00	0,39	
Arrival shift (per flight)	0,83	0,71	0,83	0,80	0,04	0,42	
Departure shift (per shifted flight)	1,60	3,82	2,17	2,35	0,00	1,64	
Arrival shift (per shifted flight)	4,58	2,44	4,99	2,61	0,05	1,68	
Route charges	€ 1.020,19	€ 989,91	€ 1.020,19	€ 985,60	€ 717,20	€ 719,39	€ 1.112,38
Route charges for shifted flights	€ 1.516,01	€ 1.464,93	€ 1.710,52	€ 1.647,48	€ 751,60	€ 760,82	
Total costs	€ 7.901,86	€ 7.872,29	€ 7.901,86	€ 7.867,23	€ 8.811,15	€ 8.817,63	€ 7.990,32
Horizontal efficiency	11,69%	11,71%	11,69%	11,68%	6,56%	6,57%	12,92%
Horizontal efficiency per shifted	9,67%	10,11%	8,80%	8,50%	6,38%	6,40%	
Percentage of sector-periods with utilisation >90%	5,03%	5,00%	5,04%	5,12%	5,10% *(2,6%)*	5,30%	9,14%

Lastly, all the models shift flights, in time and/or in space, in order to respect the capacity constraints. As it can be seen from the last row of Table 14, all models end up having about 5% of sector-periods that have utilisation higher than 90%. In the case of BMC, 2,6% of those sector-periods are overloaded (> 100%). While these figures are very similar across all baselines and solutions, it is interesting to compare them to the percentage of heavily loaded and overloaded sectors on 12SEP14, which is 9%, almost twice the values obtained by SATURN models.

5 Conclusion and future work

This study shows that pricing is a viable option to redistribute traffic in the European air network. In particular, the modulation of en-route charges, as advocated by EC Regulation 391/2013, may produce changes in the airspace users' operational costs that may incentivise airlines to reroute some flights, or to request different departure times, to avoid expensive areas or to take advantage of reduced charges.

The SATURN project has analysed the effects of three main mechanisms, peak-load pricing (PLP) and reward predictability (RP), and Tradable Flight Permit System (TFPS), on one full day of European air traffic, 12 September 2014, including additional tests on regional instances.

All mechanisms have been formulated and implemented through exact and heuristic algorithms developed during the course of the project by different consortium members. The implementation of a geographic bespoke database proved to be a decisive factor for the success of the project.

All mechanisms test the *solution* scenario (pricing is applied) against an ad-hoc *baseline* scenario, which represents how airlines would schedule and route their flights in a strategic (i.e., months ahead the day of operations) setting.

The test day was a busy day (the fourth busiest day of 2014, selected as not unduly disrupted by unusual events) but did not show a high level of congestion in the network, except for very few sector/hour spots. In other words, for most of the day in large portions of airspace the demand was below the nominal capacity. Hence, a performance indicator computed at the network level cannot capture the effect of local traffic redistribution, as the large share of traffic did not need to be moved.

Trade-offs between the total shift, satisfaction of capacity and revenue neutrality constraints naturally exist. SATURN results show that solutions quite different from the *baseline* scenario do exist, since a modulation of en-route charges enables the reduction of sector load and total shift without increasing the horizontal efficiency and the AUs' operational costs.

While the SATURN project gives strategic insight in terms of network management, charging mechanisms and incentives, and ANSP regulation, the consortium is fully aware of the need of further work to draw robust conclusions and inform EC policy on Single European Sky (SES), including Functional Airspace Blocks, and economic regulation (Table 9).

Table 15. SATURN's future considerations

Future consideration	**Mechanism type to which applies**	**Major benefit accrued to state of the art**
Consideration of *flexible* capacity provision	PLP, RP, TFSP	Extends the scope of the model and could also be linked to evaluating cost-efficiency, quality of service and other SES Performance Scheme target impacts (including related changes to planned capital expenditure by ANSPs); could also include extending the integrity of the ANSP cost functions to include fixed and variable components
Alignment with 4D trajectory provision	RP, TFSP	Purchasers of tactical trajectories are likely to seek compensation if the route is not flyable due to weather, in which case a system of compensatory credits might be incorporated into a wider European model, deploying disturbance models already used by the SATURN team
Enhanced pricing flexibility	PLP	More rates applied than simpler peak and off-peak, thus enabling the research team to explore enhanced pricing solutions
Using AU's originally-filed flight	PLP, RP, TFSP	Using originally-filed flight plan data

plans		available from EUROCONTROL's Integrated Initial Flight Plan Processing System (IFPS) would further improve the modelling of the true AU strategic demand and correspondingly reduce the dependency on the observed tactical situation
Extending AU route choices	PLP, RP, TFSP	Better modelling of AU route options and choice determinants (through interviews and factor analysis) would allow better representation of demand options
Including estimates of AU elasticities	PLP, RP, TFSP	Such elasticities could reflect AU responsiveness strategically and tactically to route extension / delay costs c.f. total route charges
Including an estimate of AU's tactical delay costs	PLP, RP, TFSP	Improves the extent of the full benefits accrued through improved demand management; could also be explored in terms of user equity
Incorporating AU's *network* impacts into Key Performance Indicators deployed	PLP, RP, TFSP	Would allow a more comprehensive assessment of impacts such as the 'arrival shift', through network effects dependent on passenger and crew connectivities, turnaround buffers and airport slot availabilities

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