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Modulation of en-route charges to redistribute traffic in the European airspace

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***Abstract*—Peak-load pricing (PLP), a two-tariffs charging scheme commonly used in public transport and utilities, is tested on the European Air Traffic Management (ATM) system as a means for reducing capacity-demand imbalances. In particular, a centralised approach to PLP (CPLP) where a Central Planner (CP) sets en-route charges on the network is presented. CPLP consists of two phases: in the first, congested airspace sectors and their peak and off-peak hours are identified; in the second, CP assesses and sets en-route charges in order to reduce overall shift on the network. Such charges should guarantee that Air Navigation Service Providers (ANSPs) are able to recover their operational costs while inducing the Airspace Users (AUs) to route their flights in a way that respects airspace capacity. The interaction between CP and AUs is modelled as a Stackelberg game and formulated by means of bilevel linear programming. Two heuristic approaches, based on Coordinate-wise Descent and Genetic Algorithms are implemented to solve the CPLP model on a data set obtained from historical data for an entire day of traffic on European airspace. Results show that significant improvements in traffic distribution in terms of shift and sector load can be achieved through this simple en-route charges modulation scheme.**

Keywords: peak-load pricing, ANS charges, modulation, heuristics, strategic traffic redistribution.

I. Introduction

European Air Navigation Service Providers (ANSPs) finance their operations through air navigation service (ANS) charges, according to EC Regulation 391/2013 [1]. 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 [2]. 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 could the charges 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, the weight of aircraft used, and the unit rate set by States (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 the recurring capacity-demand imbalances.

In this context, the Peak-Load Pricing policy for route charges modulation is introduced here. PLP is widely used for efficient capacity management in scheduled transport (public transport, railways, see for example [3]) and utilities. Basic assumptions are that peaks in demand happen periodically, in both time and location (and are therefore predictable), and that demand is to some degree elastic with respect to time and/or location of service consumption (and therefore is sensitive to its price). Under these assumptions PLP assigns a higher rate for times and/or locations where a peak demand is expected, and a lower rate for off-peak areas and times. The aim is to deviate part of the peak demand to a cheaper, non-congested option.

Modulation of ANS charges was initially investigated by [4], who envisaged the change of the unit rate to mitigate airspace congestion: higher rate in congested sectors, and lower in non-congested ones, where the total collected charges correspond to the costs incurred by ANSPs. However, the proposed concept was not elaborated in detail. A similar approach was described in [5]. The introduction of a fixed rate in peak periods is one of the four en-route modulation charging options analysed in [6], recently prepared for the European Commission. The study recommends that future work should investigate the impact of a fixed supplement to the current charging formula. Numerical examples to compare the various options are, however, very limited (e.g. only three routes), and more emphasis is given to other issues like implementation and policy recommendations.

In [7] an alternative pricing for ANS charges is introduced, by giving airlines economic incentives to modify their behaviour, so that the resulting routing choices are optimal from both social and individual points of view. The reconciliation between system (social) and user optima is also addressed by [8] who describe an anticipatory, time-dependent modulation of ANS charges to bring the traffic demand more in line with available network capacities. The charges are modulated so as to minimise the total cost to airspace users (AUs), by introducing a toll for the use of a premium resource (overloaded sector), and providing economically reasonable alternatives for users in excess. The collected tolls can subsidise the use of alternative, under-utilised sectors. The results of a medium-scale case study indicate that this mechanism may yield a fairly equitable assignment.

Adequate modelling of en-route charges modulation needs to address the impact on AUs. That is to say, the impact on the route choice that the modulation would bring along, even in a non-congested setting. In this context, [9] propose a bilevel programming pricing model for the maximisation of ANSP revenues through en-route charge modulation. Results from a small-scale real-world test case suggest that the unit rate can be an effective instrument for modification of the route choices, thus being a starting point for development of a pricing model with modulated en-route charges, with the aim to alleviate imbalances.

Building upon this suggestion, we propose a centralised approach to PLP (which we will refer to as CPLP) where a Central Planner (CP) is setting (modulating) en-route charges on the network. Since an exact solution of the CPLP has proven to be computationally intractable for a large set of flights [10], we develop two heuristic approaches able to solve CPLP in a reasonable amount of time for approximately 30000 flights (a busy day in European airspace). Both heuristics consider the trade-offs between various objectives, but differ in: (a) the way these trade-offs are analysed, and (b) the search of solution space. One approach optimises a single objective using a coordinate-wise descent (CD) method [11], while the other is a multi-objective heuristic based on genetic algorithms (GA).

The remainder of this paper is organised as follows. Section II describes the principles of the CPLP model and introduces the main assumptions, whereas complete mathematical formulation (specifically linked to CD) is illustrated in Section III. A brief overview of the two heuristic approaches is given in Section IV. Section V describes the setting of the computational experiments that lead to the results presented in the Section VI. Finally, Section VII concludes the paper.

II. CPLP Model description

CPLP consists of two phases. In the first phase, congested airspace sectors and related peak and off-peak hours are identified. The analysis of daily traffic (last filed flight plans for the day in our example) is used for this: traffic demand is counted for all the sectors, taking into account all the flights and their routes, for each hour. The ratio between hourly traffic count and nominal hourly capacity gives hourly load factor. The load factor value is used as a threshold for assigning the peak or off-peak label to a specific sector for a specific hour.

In the second phase, CP sets en-route charges on the network by assigning peak and off-peak rates, and the AUs route flights, based on the set charges. The charges should guarantee the recovery of ANSPs' operating costs, and the ability of AUs to perform flights, by avoiding the imbalance between the demand and available airspace capacity. Since unit rates are currently set once per year, and it is still impractical to change them more often, we analyse the effect of PLP at the **strategic** flight planning level (months ahead) meaning that last minutes inconveniences (e.g. weather or industrial actions) are not taken into consideration. The CP modulates charges having as a goal the reduction of the amount of shift on the network. The shift is the difference between the requested and the allocated departure and/or arrival time(s). There is often a trade-off to consider between the system level (CP) and the user level (AU) objectives. In general, allowing users to minimise their individual shifts does not lead to a solution where the global network shift is also minimised. On the contrary, optimising shift at system level only, would most certainly penalise certain users more than others, which is also not ideal from an equity point of view. Since unit rates are set by the States and the AUs can only react to them by choosing alternative and cheaper routes, we model the relationship between the CP and the AUs as a Stackelberg game where a leader (CP) makes his decision first, with the complete knowledge on how the follower(s) (AUs) would react to it [10]. The Stackelberg equilibrium is formalised by means of an optimisation problem formulated as a bilevel linear programming model. Therefore, the second phase of CPLP consists of solving an optimisation problem, where the CP sets the peak and off-peak rates and the AUs make their routing choice. The main assumptions the CPLP optimisation model is based upon are listed next.

Central Planner Peak Load Pricing Assumptions

1) *Fixed demand matrix*. Fixed number of flights between any airport pair in the network: the intention of the proposed pricing mechanism is to modify its spatial/temporal pattern to bring it in line with available capacities, not to scale down the total demand.
2) *Heterogeneous demand*, in terms of different aircraft types.
3) The *infrastructure capacity constraints* are known in advance, in terms of airspace sectorisation and maximum number of aircraft that can enter sectors per given period of time (i.e. capacity). Since the mechanism is applied strategically, only nominal sector and airport capacities are considered, without variations introduced by regulations (which are caused by weather and other less predictable reasons, tactically).
4) *Finite set of possible (reasonable) 4D routes* for each Origin/Destination/Aircraft triple: users can select a route from a set of pre-determined routes (derived from actual traffic). Duration and profile of each route is assumed to be constant, for each aircraft type (i.e., speed profiles are assumed constnt for each route/aircraft pair).
5) *Users are rational decision makers*. All AUs are assumed to choose the least-cost 4D route available. Flight cost components are attached to each route. AUs' routing decisions are therefore sensitive to modulations of en-route charges.
6) *Revenue neutrality* is established as a desired principle,

meaning ANSPs' revenues are to be kept as close as possible to their operating costs: the adjustment of charges should not generate additional revenue (on top of the cost of ANS provision), nor deficit.

7) *Distance-proportional air navigation charges with sector-period based rates*. The pricing rule applied for air navigation charges is similar to the one currently in use but instead of a unique unit rate per country, two-level rates, namely *peak* and *off-peak*, differentiated by sector and period (i.e., one hour), are defined. A peak/off-peak rate pair is unique for each ANSP and therefore valid for all considered time periods and sectors in an ANSP.
8) *Peak times and locations are known in advance*. The expected load on a sector, during a specific time is estimated by analysing initially submitted flight plans (in our case these are the last filed flight plans from EUROCONTROL's Demand Data Repository).

III. CPLP MATHEMATICAL FORMULATION

This section introduces the mathematical formulation of the CPLP model.

A. Notation

- F set of all flights, indexed by f
- N set of all ANSPs, indexed by n
- B set of all aircraft types, indexed by b
- b_f aircraft type b used to operate flight f
- W_{b_f} weight factor of aircraft type b used by flight f
- A set of all airports, indexed by a
- R set of all routes, indexed by r
- R_f set of all routes that can be flown by flight f
- S set of all sectors, indexed by s
- S_n set of all sectors controlled by ANSP n
- S_r set of all sectors crossed by route r
- H interval of time periods (hours), indexed by h
- M interval of possible time instants (minutes), indexed by m
- MGS maximum ground shift (in minutes) allowed for a flight, i.e., the maximum difference between requested and allocated departure time
- M_f interval of possible departure time instants for flight f (i.e., $m \in [dt_f - MGS, dt_f + MGS]$)
- T_h set of minutes m belonging to time period (hour) h
- $Q_s^{(h)}$ capacity of sector s during time period (hour) h
- $Q_{a,dep}^{(h)}$ departure capacity of airport a during time period (hour) h
- $Q_{a,arr}^{(h)}$ arrival capacity of airport a during time period (hour) h
- $Q_{a,gl}^{(h)}$ total (departures + arrivals) capacity of airport a during time period (hour) h
- $D_{s,r}$ route/sector distance matrix; entry is equal to one hundredth of the great-circle distance distance flown in sector s if route r intersects sector s; 0 otherwise
- $e_{s,r}$ estimated entry time since departure of route r in element (sector or airport) s
- dt_f requested departure time for flight f
- at_f requested arrival time for flight f
- $adep_f$ departure airport for flight f
- $ades_f$ arrival airport for flight f
- ca_b strategic cost of one minute of airborne operations for aircraft type b
- cg_b strategic cost of one minute of ground shift for aircraft type b
- cam_b strategic cost of one minute of airborne maintenance for aircraft type b
- cgm_b strategic cost of one minute of ground maintenance for aircraft type b
- cf_b strategic cost of one minute of fleet utilisation for aircraft type b
- cc_b strategic cost of one minute of crew utilisation for aircraft type b
- afb_b average fuel burn (Kg/min) for aircraft type b
- fc fuel cost (€/Kg)
- U_n actual en-route unit rate for ANSP n

Based on this notation, we may define the following quantities:

$$ca_b = cam_b + cf_b + cc_b + fc \cdot afb_b \qquad \forall b \in B$$

$$cg_b = cgm_b + cf_b + cc_b \qquad \forall b \in B$$

$$at_f = dt_f + \min_{r \in R_f} e_{ades_f,r} \qquad \forall f \in F$$

$$GS_{f,r}^{(m)} = \max\{0, m - dt_f\} + \max\{0, at_f - (m + e_{ades_f,r})\} \qquad \forall f \in F, r \in R_f, m \in M_f \tag{1}$$

The total shift for flight f using route r and departing at time m is the sum of minutes of earlier departure plus the number of minutes of late arrival.

$$OC_{f,r}^{(m)} = cg_b \cdot \left(GS_{f,r}^{(m)} - (e_{ades_f,r} - \min_{r' \in R_f} e_{ades_f,r'}) \right) + ca_b \cdot e_{ades_f,r} \qquad \forall f \in F, r \in R_f, m \in M_f \tag{2}$$

The airline operational costs for flight f using route r and departing at time m is given by the ground shift cost coefficient times the ground shift (e.g. later departure), plus the airborne cost coefficient, times the route duration.

B. Decision Variables

$$x_{f,r}^{(m)} = \begin{cases} 1 & \text{if flight } f \text{ departs at minute } m \text{ using route } r \\ 0 & \text{otherwise} \end{cases} \qquad \forall f \in F, r \in R_f, m \in M$$

$$P_s^{(h)} = \begin{cases} U_n + \delta_{n,pk} & \text{if } h \text{ is peak time for sector } s \\ U_n + \delta_{n,ok} & \text{otherwise} \end{cases} \qquad n | s \in S_n, \forall s \in S, h \in H$$

$\delta_{n,pk}$ unit rate variation for peak hours for ANSP n
$\delta_{n,ok}$ unit rate variation for off peak hours for ANSP n
$\alpha_s^{(h)}$ capacity violation for sector s during hour h, expressed as a number of flights in excess of sector capacity
$\alpha_{a,dep}^{(h)}$ departure capacity violation for airport a during hour h
$\alpha_{a,arr}^{(h)}$ arrival capacity violation for airport a during hour h
$\alpha_{a,gl}^{(h)}$ total capacity violation for airport a during hour h
ϵ_n revenue neutrality violation for ANSP n

C. Further definitions

$$RC_{f,r}^{(m)} = \sum_{s \in S_r, h \in H | (m+e_{s,r}) \in T_h} P_s^{(h)} \cdot D_{s,r} \cdot W_{b_f} \quad (3)$$
$$\forall f \in F, r \in R_f, m \in M_f$$

The en-route charges (RC) for flight f using route r and departing at time m are calculated per sector crossed. For each sector, the airline is charged an amount equal to the product of the rate (peak or off-peak), the great-circle distance between the entry and exit points in the sector (divided by 100 km), and the aircraft weight factor.

$$WCV = \sum_{s \in S, h \in H} \frac{\alpha_s^{(h)}}{Q_s^{(h)}} + \sum_{a \in A, h \in H} \left(\frac{\alpha_{a,dep}^{(h)}}{Q_{a,dep}^{(h)}} + \frac{\alpha_{a,arr}^{(h)}}{Q_{a,arr}^{(h)}} + \frac{\alpha_{a,gl}^{(h)}}{Q_{a,gl}^{(h)}} \right) \quad (4)$$

The total amount of capacity breaches (WCV) both for sectors and airports is the sum of the ratios of capacity violations over the capacity for each sector and airport, for every time period. The three different capacities of airports (number of departures, number of arrivals, and total number of departures and arrivals) are counted separately.

D. The complete CPLP model formulation

$$\min_x \sum_{f \in F, r \in R_f, m \in M_f} x_{f,r}^{(m)} \cdot GS_{f,r}^{(m)} + K_1 \cdot WCV + K_2 \cdot \sum_{n \in N} |\epsilon_n| \quad (5)$$

We aim to minimise three quantities: the total amount of shifts assigned to flights (Eq. 1), the amount of capacity constraint violations (Eq. 4), and the amount by which the revenue neutrality constraint is violated for each ANSP (Eq. 6). We introduce two weighting factors (K_1 and K_2) to control the relative importance of each term.

$$s.t. \sum_{\substack{f \in F, \\ r \in R, h \in H, \\ m \in M_f | m \in T_h, \\ s \in (S_n \cap S_r)}} P_s^{(h)} \cdot D_{s,r} \cdot W_{b_f} \cdot x_{f,r}^{(m)} - \sum_{\substack{f \in F, r \in R_f, \\ m \in M_f, s \in (S_n \cap S_r)}} U_n \cdot D_{s,r} \cdot W_{b_f} \cdot x_{f,r}^{(m)} = \epsilon_n \quad \forall n \in N \quad (6)$$

The revenue neutrality violation for each ANSP is calculated as the difference between the collected charges using the modulated rates and the amount that would have been levied using only the unit rates with the same routes.

$$\sum_{\substack{o \in R_f, \\ i \in M_f}} \left(RC_{f,o}^{(i)} + OC_{f,o}^{(i)} \right) \cdot x_{f,o}^{(i)} \le RC_{f,r}^{(m)} + OC_{f,r}^{(m)} \quad (7)$$
$$\forall f \in F, r \in R_f, m \in M_f$$

The objective of the AU, representing the follower's problem in the bilevel model, is to perform flights at minimum total cost (en-route charges (Eq. 3) plus operational costs (Eq. 2)). Therefore, if a route is chosen ($x_{f,o}^{(i)} = 1$), its total cost must not be larger than the total cost of any other potential route for the flight.

$$\sum_{\substack{f \in F, r \in R_f, h \in H, \\ m \in M_f | m \in T_h,}} x_{f,r}^{(m)} - Q_s^{(h)} \le \alpha_s^{(h)} \quad \forall s \in S, \forall h \in H \quad (8)$$

$$\sum_{\substack{f \in F | adep_f = a, \\ r \in R_f, h \in H, \\ m \in M_f | m \in T_h,}} x_{f,r}^{(m)} - Q_{a,dep}^{(h)} \le \alpha_{a,dep}^{(h)} \quad \forall a \in A, \forall h \in H \quad (9)$$

$$\sum_{\substack{f \in F | ades_f = a, \\ r \in R_f, h \in H, \\ m \in M_f | (m + e_{a,r}) \in T_h; e_{a,r} \neq 0}} x_{f,r}^{(m)} - Q_{a,arr}^{(h)} \le \alpha_{a,arr}^{(h)} \quad (10)$$
$$\forall a \in A, \forall h \in H$$

$$\sum_{\substack{f \in F | adep_f = a \vee ades_f = a, \\ r \in R_f, h \in H, \\ m \in M_f | (m + e_{a,r}) \in T_h,}} x_{f,r}^{(m)} - Q_{a,gl}^{(h)} \le \alpha_{a,gl}^{(h)} \quad (11)$$
$$\forall a \in A, \forall h \in H$$

The capacity violations for a sector (Eq. 8) or an airport (Eqs. 9 to 11) are equal to number of aircraft entering that sector or using the airport (take-off or landing) in a given time period minus its nominal capacity if a violation occurs. If the capacity is respected, then the associated variable is equal to zero.

$$\sum_{r \in R_f, m \in M_f} x_{f,r}^{(m)} = 1 \quad \forall f \in F \quad (12)$$

$$x_{f,r}^{(m)} \in \{0, 1\} \quad \forall f \in F, r \in R_f, m \in M_f \quad (13)$$

Each flight must select exactly one route.

$$\alpha_s^{(h)} \ge 0 \quad \forall s \in S, \forall h \in H \quad (14)$$
$$\alpha_{a,dep}^{(h)}, \alpha_{a,arr}^{(h)}, \alpha_{a,gl}^{(h)} \ge 0 \quad \forall a \in A, \forall h \in H \quad (15)$$
$$|\delta_{n,ok}| \le 50 \quad \forall n \in N \quad (16)$$
$$P_s^{(h)} \ge 0 \quad \forall n \in N \quad (17)$$

The off-peak rate variations are capped between -50 and +50 euros. The resulting peak and off-peak rates cannot be negative.

IV. Heuristic approaches

The identification of the exact optimal solution of the CPLP model (Eqs. 5 to 17) is not computationally viable when all the flights in a day are taken into consideration (see Section V). For this reason, we introduce two significantly different heuristic approaches that offer a fair compromise between the goodness of the solution and the time required to attain it.

A. Coordinate-wise Descent (CD) solving approach

Instead of attempting to find the optimal solution over the entire set of possible values of decision variables, it can be much faster to look for optimal solutions over a restricted subset of the allowed values, called a neighbourhood. For the CPLP model presented in Section III, a very efficient neighbourhood can be found by fixing the value of all rate variables $\delta_{n,pk}$ and $\delta_{n,ok}$ except a single one (δ^*). In this way, the choice of route variables $x_{f,r}^{(m)}$ will only be allowed to change at specific values of δ^*, which can be found in polynomial time (these are the values of δ^* for which two routes have equal cost). Since the first two sets of terms of the objective function (Eq. 5), i.e., $x \cdot GS$ and WCV, only depend on the route variables $x_{f,r}^{(m)}$, then their values will also only change at those specific values of δ^*. Only the last revenue neutrality terms in the objective function will vary between those values of δ^*, but these terms can be written as: $X + |Y + Z \times \delta^*|$, which is straightforward to minimise in a given interval. Therefore, finding the optimal value of δ^* can be done in polynomial time by finding all the values at which route choices change, and computing the optimal value of the objective in each interval defined by those values. This task can be done in $O(|R| \log |R| + |R|^2 + |R||S|)$ time. Since this method optimises one rate variable at a time, it is a Coordinate-wise Descent heuristic.[11]. The algorithm used to minimise the objective is thus to iterate over all peak/off-peak variables, and for each one minimise the objective over the associated neighbourhood. This is done until no further improvement is found over all possible neighbourhoods. This method leads to very fast improvements over the baseline scenario, although it can also remain stuck in local minima, especially for larger values of the K_2 parameter (see Fig. 3).

B. Genetic Algorithm (GA) solving approach

GAs are very popular stochastic optimisation methods inspired by the evolutionist theory on the origin of species and natural selection. Starting from a population of randomly generated individuals, the search iteratively evolves to make every subsequent population better than the previous one(s) (see, e.g.,[12] for a general introduction). GAs are particularly suitable for solving multi-objective problems and to find reasonably good trade-off solutions (i.e., Pareto solutions). In particular, a customised multi-objective GA, MOGASI [13], is used to solve the CPLP, taking into consideration two objectives simultaneously:

- Minimisation of the total shift for all flights ($GS_{f,r}^{(m)}$).
- Minimisation of the maximum revenue neutrality violation $|\epsilon_n|$ (Eq. 6).

Furthermore, to drive the search through the solution space towards feasible regions, i.e., fulfilling all constraints (6) - (17), we set (a) the average capacity violation ACV (defined as WCV divided by number of capacity violations) to be lower than 20%, and (b) that the revenue neutrality violation (Eq. 6) cannot exceed 20%, for each ANSP. MOGASI is able to identify a multitude of feasible optimal solutions that at the same time guarantee the excellent ANSP revenue neutrality levels without inducing unnecessary flight shifts due to unfavourable route choices to which flight operators might otherwise be forced to.

V. Description of the experiments

Computational experiments are performed on two scenarios: baseline and solution. Both scenarios share the same input data and **apply the CPLP model** to **strategically** distribute traffic while respecting the capacity constraints. The difference between the two scenarios lies in the route charging system applied: baseline scenario applies unit rates (no modulation), while solution scenario applies modulation by assigning peak and off-peak rates. Historical data was not considered suitable for comparison since, being highly tactical, it is heavily affected by regulations that are not known in the strategic phase. Further details on input data used in the experiments and the indicators used to assess results obtained from baseline and solution scenarios are given in the following.

A. Input data

The CPLP model is tested on a day of real air traffic data over European airspace network. Different data items are needed to run our model and are listed below:

1) Flights. The air traffic data is taken from 12 September 2014, the fourth busiest day of 2014, selected as not unduly disrupted by unusual events. All IFR flights that depart from or arrive in European airspace are taken into account (29539 flights).
2) Airspace configuration. The airspace sectorisation and related nominal capacities used correspond to the configuration in use on 12 September.
3) Route choices. Route is a combination of route (set of crossed sectors) and departure time. Available routes per Origin-Destination-Aircraft triple are determined through a clustering process on historical flight data from the two weeks preceding 12 September. Only routes differing significantly from one another in terms of geographical distance (specifically, more than 40 kilometres in the points where the distance between the two routes is maximal, measured in 3-dimensional space) are taken in consideration, reducing the number of viable routes per Origin-Destination-aircraft triple from the tens, to an average of 3.7 routes per triple.

Allowed departure times range between 30 minutes before and 30 minutes after the time originally scheduled for each flight.
4) Unit rates. Used values are those applied during September 2014.
5) Fuel cost. Based on 2010 costs reported by Cook and Tanner [14], the cost of fuel has been updated to January 2014 levels (0.67 Euros/kg) using Fuel Price Analysis reported by IATA [15].
6) Flight costs and aircraft types. A detailed estimation of operational costs for crew, fuel, aircraft and fleet maintenance for twelve of the most commonly used aircraft in Europe can be found in [14]; in order to estimate operational strategic costs for each flight, all aircraft used in the traffic data are grouped into twelve clusters using these twelve as cluster centroids and square root of the maximum take-off weight (MTOW) as clustering criterion.
7) Sector load factors. For each active sector, in each hour, the load factor (number of aircraft entries over sector nominal capacity) is calculated from the last filed flight plans for 12 September. If the load factor is greater than (or equal to) 0.5, the sector is considered to be in the peak hour, off-peak otherwise.
8) Airline types. For each passenger flight, the aircraft operator is classified as either a full-service, low-cost, charter or regional airline, and appropriate cost base is applied.

B. Assessment indicators

CPLP redistributes the traffic both in time (shifts in departure and/or arrival times) and space (alternative routes) to avoid congestion. Even though the bottlenecks are avoided, the resulting traffic pattern impacts other, as important phenomena. Therefore, a comprehensive assessment takes into account other indicators and looks into the resulting trade-offs. Table I lists the indicators assessed in these experiments.

TABLE I
ASSESSMENT INDICATORS

Assessment indicator	Description
Horizontal en-route flight efficiency	Difference between the en-route distance between the origin and destination of assigned route, and the great circle distance between the origin and destination, divided by the great circle distance between the origin and destination.
Route charges per flight	The sum of en-route charges applied on each flight.
Flight operational cost	The cost for operating flights is estimated considering the planned routes and strategic shifts.

VI. RESULTS

The implementation of the CPLP mechanism, using both GA and CD approaches, show that significant improvements can be achieved with respect to the baseline solution, i.e., the one computed using actual Unit Rates. For instance, Figure

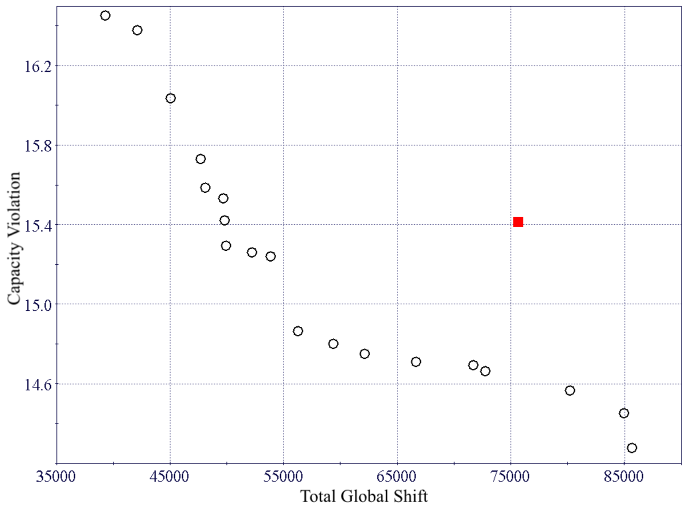

Fig. 1. Pareto front for ACV and TGS with respect to the baseline solution

1 shows that the baseline solution (the red filled square) is worse off both in terms of ACV and Total Global Shift (TGS - sum of total Shift over all flights) compared to several solutions that form a Pareto frontier. A set of four Pareto solutions was further analysed using GA heuristic. The Parallel Coordinates chart (Fig. 2) depicts multi-variate data sets and solutions in predefined ranges of some quantities. The quantities are represented by vertical lines, whereas each solution is represented by a coloured polyline. Fig. 2 shows five Pareto solutions that, besides TGS and ACV, also take into consideration:

- RNV - Maximum Revenue Neutrality Violation
- nCB - Number of Capacity Breaches, i.e., number of flights violating the capacities
- nCV - Number of Capacity Violations, i.e., number of (sector/airport,hour) pairs that had their nominal capacity level not respected.

The red line represents the baseline solution. It exhibits the highest total shift (TGS) while the revenue neutrality is perfectly matched for each ANSP[1]. An opposite behaviour is shown by the dark and light blue lines (GA2 and GA3, respectively) that, in spite of the low TGS, have a high number of capacity and revenue neutrality violations. The solution represented by the yellow line (GA1) is similar to the baseline, even though the number of capacity violations with respect to all other solutions is significantly lower. The green line (GA4) represents a highly desirable solution as it significantly improves TGS and keeps the revenue neutrality violation at around the 10% with respect to the baseline solution.

Similar evaluations can be achieved using the CD method that, however, can only handle a single objective function. Since the objective function of CPLP mechanism (Eq. 5) requires the minimisation of three distinct components , it is necessary to select two parameters (K_1 and K_2) to control

[1]This result directly follows from the way the revenue neutrality constraint is enforced (see Eq. 6).

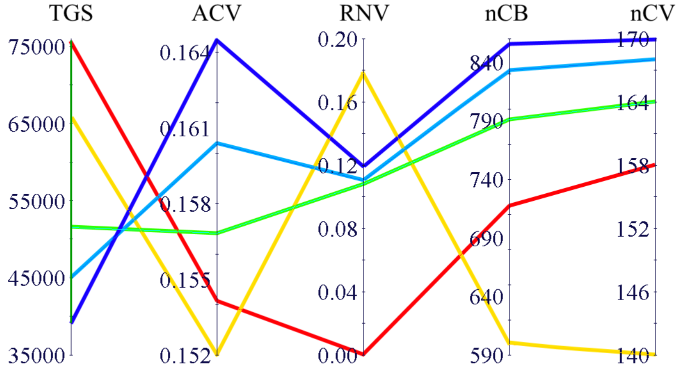

Fig. 2. Selected Pareto solutions for the five main output variables

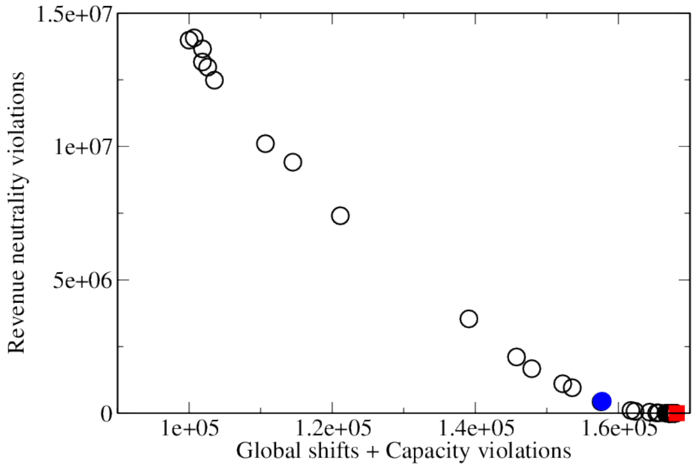

Fig. 3. Comparisons of weighted sum of global shifts and capacity violations and revenue neutrality violations using the CD method

the relative weight of the second and third component. Fig. 3 shows the relationship between the weighted total shifts and capacity violations metrics and the revenue neutrality violations metric (with $K_1 = 3600$), for various values of the K_2 parameter (the red square represents the base solution). Favouring one metric over the others significantly worsens the disfavoured ones. Furthermore, the CD method has some difficulties leaving the initial solution (all $\delta = 0$) if the K_2 is large. We thus chose the value $K_2 = 0.01$ (represented by the filled blue circle) which allows the CD method to leave the initial solution, without breaking the revenue neutrality condition outrageously.

Additional benefits of applying CPLP (either using CD or GA) can be seen in Table II on various metrics: the total shift for all flights (TGS), weighted capacity violations (WCV), total number of flights above capacity limits (nCB), and sum of relative revenue neutrality violations per ANSP ($\sum$ rel ϵ). The CD method is using the weighting parameters $K_1 = 3600$ and $K_2 = 0.01$. In this case, it can be seen that the CPLP mechanism is able to achieve a significant reduction in capacity violations (of the order of 10%), at the cost of large revenue neutrality constraint violations. These results are

TABLE II
NUMERICAL VALUES OF VARIOUS METRICS FOR SOLUTIONS OBTAINED THROUGH THE CD AND GA METHODS

Metric	Base	CD	GA1	GA2	GA3	GA4
TGS	75531	72326	65984	39286	45020	51578
WCV	25.73	23.72	21.27	27.97	26.94	25.72
nCB	706	642	599	856	833	791
$\sum$ rel ϵ	0	1.48	1.17	1.12	1.11	1.10

TABLE III
AVERAGE VALUES (PER FLIGHT) OF ASSESSMENT INDICATORS ACROSS CD AND GA SOLUTIONS

Scenario	Horizontal efficiency	En-route charges (€)	Operational costs (€)
Baseline	11.71%	901.63	6660.91
CD	11.75%	904.24	6660.68
GA1	11.68%	937.59	6659.25
GA2	11.65%	630.32	6651.88
GA3	11.67%	727.90	6652.57
GA4	11.69%	765.65	6654.77

linked to having only two rate variables (peak and off-peak) per ANSP.[2] However, the computational power required to run the heuristicis very low, since it took less than 8 minutes of CPU time to converge to the final solution in every case tested here. GA solutions (GA1 to GA4) always outperform CD in terms of TGS and revenue neutrality violations, even though GA2 to GA4 experience a limited increase in the sector load. GA1 dominates CD in all metrics. However, the computational time for a complete GA run may go up to 30 hours on a standard laptop.

The analysis of the trade-offs between the assessment indicators proposed in Section V-B is described in Table III across baseline, CD, and GA1 to GA4 solutions (values are averages, per flight). As can be seen the horizontal efficiency, and flight operational costs do not change significantly across solutions. However, the en-route charges vary. The combination of the results in Fig. 2, Tab. II and Tab. III shows that 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.

The last remark is linked to the peak and off-peak rates that make these favourable traffic redistributions possible. Fig. 4 show that the rates can significantly vary across different ANSPs: in some cases the historical unit rate (red circle) is below the off-peak and peak rates for GA1 but not for GA4, in other cases the opposite occurs, with all other alternatives being possible. This means that there is a large room, within the limits imposed by the European ATM regulations, for charges' modulation that lead to reduced congestion without worsening flight efficiency and flight operational costs.

[2]Increasing the number of rate variables per country can lead to much better results, at the cost of a more complicated rate scheme. Using one variable for each pair of sector and period ($P_s^{(h)} = U_n + \delta_s^{(h)}$) gives the following results with $K_1 = 3600$ and $K_2 = 0.01$: global shifts = 47'500, capacity violations amount = 7.54, and no revenue neutrality constraint breaches.

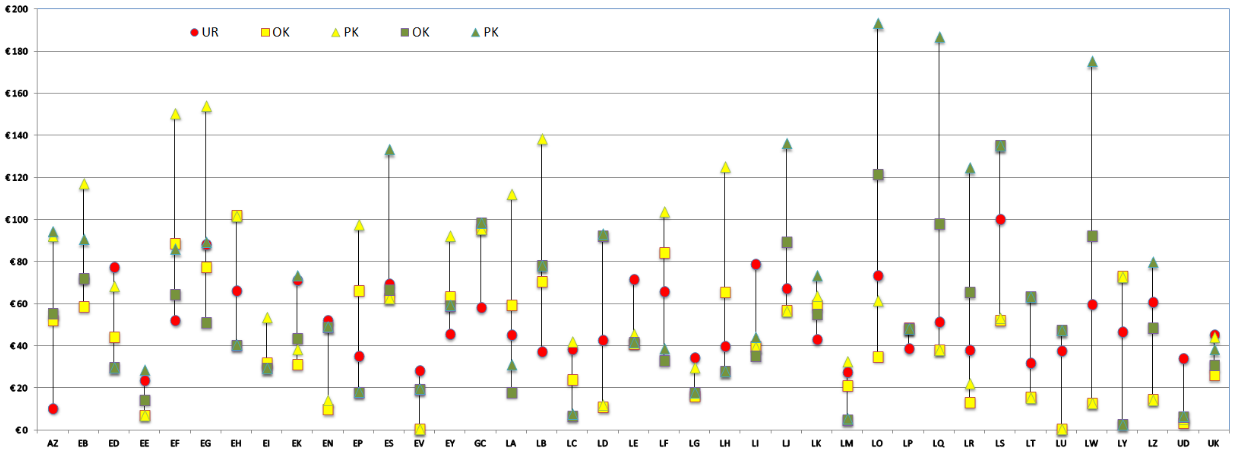

Fig. 4. Peak and off-peak rates for the GA1 (yellow) and GA4 (green) solution. The red circle is unit rate value as of September 2014.

VII. Conclusions

The work presented here demonstrates that modulation of en-route charges indeed redistributes the traffic. Applied heuristics obtain a range of possible solutions. A more detailed analysis of the results and related impacts on different indicators, not only the ones presented in this paper, is needed to have a better way to assess the solutions and the associated trade-offs. As the space is limited, we present only a vary narrow analysis of the results here. The future work will look into different aspects of CPLP application (which is to be presented in the final SATURN project deliverable due by the end of this year): (a) Detailed analysis on the distribution of costs across different types of AUs, to check if equity issues might arise; (b) Detailed analysis on the revenue distribution and the airspace utilisation across ANSPs, in order to understand how the cost-efficiency of ANSPs is impacted; (c) Update the cost values used to calculate airline operational costs to the 2014 values; (d) Vary the fuel costs to better understand how much the fuel costs impact the routing decisions, with or without modulation, and (e) Application of PLP in a decentralised manner, thus having ANSPs set the modulations, instead of the CP.

VIII. Acknowledgment

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