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Peak-load pricing for the European Air Traffic Management system using modulation of en-route charges

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This paper extends the use of peak-load pricing (PLP) to the context of the European Air Traffic Management system, as EU regulation No 391/2013 allows the modulation of en-route charges to avoid network capacity-demand imbalance in a specific area or on a specific route at specific times. In particular, we propose 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 air navigation service providers (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. Hence, we model this relationship between the CP and the AUs as a Stackelberg game where a leader (CP) makes his/her decision first, with complete knowledge on how the follower(s) (AUs) would react to it. The Stackelberg equilibrium is obtained by means of an optimisation problem formulated as a bilevel mixed-integer linear programming model, where the CP sets, for each ANSP, one peak and one off-peak en-route charge and the AUs make their routing choice. Preliminary results on real data instances on a regional scale are presented.

Keywords: *airspace users, air traffic management (ATM), air transport, congestion pricing, modulation of en-route charges, peak-load pricing*

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1. Introduction

Peak-load pricing (PLP) is a pricing mechanism 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 time, at some specific locations (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, the PLP policy is to assign a higher toll where and when a peak in demand is expected, and a lower toll 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 tolls are set in a way that the pricing policy is effective with regard to business sustainability, and efficient capacity management. The former can be achieved by imposing that total revenues are not lower than total marginal costs; the latter can be obtained by setting peak tolls greater than the willingness to pay of the users in excess, which will therefore prefer the cheaper off-peak option (in Borenstein et al., 2002) this principle is exemplified for the electricity

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retail market. PLP is widely used in scheduled transport (public urban transport, railways, see for example Peter, 2003) and is, in general, transparent and predictable to users, since peak times and prices are known in advance.

This paper investigates the effectiveness of applying a PLP policy to the European Air Traffic Management (ATM) system with the aim of redistributing traffic demand in congested areas during peak hours. European Air Navigation Service Providers (ANSP) finance their operations by charging airspace users according to EC Regulation 391/2013 (see European Commission, 2013). Air navigation service (ANS) charges are composed of en-route and terminal charges, for the provision of air navigation services for the en-route and terminal segments of the flight, respectively. En-route charges, to be paid by a flight, are currently calculated as the sum of the charges generated in each individual State traversed by this flight. Such national charge is equal to the product of the distance factor[4], the weight factor of the aircraft used[5], and a national unit rate (the rate is set annually by each State). Article 16 of EC Regulation 391/2013 states that *"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 of Regulation 391/2013 provides Member States and ANSPs with an instrument to implement demand management for dealing with the recurring congestion problems.

In the current Air Traffic Management practice in Europe, two main phases in flight planning can be distinguished: strategic (up to 6 months before the flight), and tactical (several hours before the flight). Flight information that is available in the strategic phase is usually limited to origin and destination airports, the departure/arrival times, and aircraft type, as these are required for publishing seasonal schedules. In order to create the schedule, the airlines first need to obtain the airport slots for flights to/from congested airports. An airport slot constitutes a permission to use the airport infrastructure within the assigned time window. The amount of airport slots is limited to the airport's declared capacity, and the slots are assigned following the IATA's worldwide slot guidelines (IATA, 2015), before the start of each season. A significant number of European airports (170) participate in the slot allocation process as their level of congestion puts them in the coordinated (congested all the time) or schedules facilitated (congested in some periods) category. Thus, all the congested airports in Europe already have a mechanism that limits the number of flights, applied in the strategic phase. Furthermore, only two European airports fill up the airport slot quota for a significant part of the day: London Heathrow (throughout the day), and London Gatwick (morning hours); all the other airports have the slot capacity to spare (Steer Davies Gleave, 2011). On the other hand, flight route information, which affects the airspace capacity and consequently congestion, is usually filed just a few hours before the flight, in tactical phase. Flight route information is shared with the ANSPs and Network Manager, but not with other airlines. ANSPs evaluate the impact on their airspace, and if the foreseen traffic demand is greater than the available capacity, they enforce the capacity to be respected by imposing regulation(s). The flights that are planned to pass through regulated airspace are then assigned delays in order to spread the demand through time. In the current system, the regulations are the only information on the location and duration of congestion that is available to the airlines. If possible, affected airlines will re-plan the flight around the regulation(s); otherwise, the assigned delay will be accepted. Note that, one of the characteristics of sectors is nominal capacity. By

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[4] The distance factor is equal to the hundredth of the great circle distance, expressed in kilometres, between the aerodrome of departure within, or the point of entry into, the airspace of the flight information regions of the state and the aerodrome of first destination within, or the point of exit from, that airspace. The entry and exit points are the points at which the lateral limits of the airspace are crossed by the route described in the last filed flight plan. The actual distance taken into account is equal to the distance calculated on the basis described above less 20 km for each take-off and each landing in a given state.

[5] The weight factor is the square root of the quotient obtained by dividing by 50 the number of metric tons in the maximum take-off weight of the aircraft.

definition, as long as the traffic demand is lower or equal to nominal capacity, no delays should be incurred by AUs.

The possibility of modulating ANS charges by modifying the unit rate was initially investigated by Andreatta and Odoni (2001), who envisaged en-route charges adjusted to reflect the presence of airspace congestion. The authors propose a set of differential charges, higher in congested sectors and lower in less congested ones, such that the total amount of collected charges corresponds to the cumulative cost incurred by ANSPs. This work is related to the idea of modulated charges. In accordance with this rationale, Ranieri and Castelli (2008) demonstrate, on a small-scale real-world example, the trade-offs between the (ground) ATFM delay and rerouting in terms of airlines' costs. Their preliminary results suggest that the system performance (i.e., aggregate delay) can be improved by giving incentives to a relatively minor number of users to reroute from an overloaded to neighbouring sector with spare capacity. However, high unit rate values are necessary to achieve this outcome, along with some associated "unfair" effects, as judged by the authors themselves. An approach similar to peak-load pricing was proposed in Deschinkel et al. (2002); here, an assignment of price levels from a pre-determined set to airspace sector/hour pairs is formulated as a Logit model and solved through a simulated annealing algorithm.

In Raffarin (2004) an alternative pricing rule for air navigation charges is proposed, based on the idea of 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 author points out the limitations of the pricing rule in use today for air navigation charges in Europe, observing that it normally penalises larger aircraft, when in fact smaller ones are the ones more likely to cause congestion. Starting from this observation, a new pricing rule is proposed where demand and frequency of flights are re-defined as functions of customers' utility; eventually, optimal tariffs are identified by equalling marginal utility to marginal costs. Unfortunately, no conclusion on its effectiveness can be drawn due to the lack of computational tests.

An anticipatory, time-dependent modulation of air navigation charges to bring the traffic demand more in line with available network capacities is proposed by Jovanović et al. (2014). The charges are modulated so as to minimise the total cost to AUs. The paper brings a desirable feature: revenue neutrality of the pricing scheme, meaning that no additional revenue should be generated by applying the modulation. This is achieved by introducing a toll for the use of a premium resource (overloaded network segment), and providing economically reasonable alternatives for users who cannot get access to it due to capacity constraints. The collected tolls are used to subsidise the use of alternative, under-utilised network segments. The results of a medium-scale case study indicate that the use of revenue neutral tolls and subsidies on a congested airspace network may yield an equitable assignment, from both charges distribution and capacity utilisation perspectives.

Adequate modelling of route charges modulation (through modification of the unit rate) needs to address the impact on AUs - the obvious impact on the route choice stage that the modulation would bring along, even in a non-congested setting. In this context, Castelli et al. (2013) propose a bilevel programming pricing model for the maximisation of ANSP revenues through en-route charges modulation. Results from a small-scale real-world test case suggest that ANSPs' revenues depend highly on the unit rate value. Furthermore, it is demonstrated that the airlines change the routing choices. Therefore, the unit rate can be an effective instrument for modification of the route choice of flights; thus offering a starting point for the development of a pricing model with modulated en-route charges, with the aim to alleviate congestion.

Building on this conclusion, this paper proposes a centralised approach to PLP (which we will refer to as CPLP) where a central authority (or Central Planner, CP) is responsible for setting en-route charges on the network. CPLP consists of two phases. In the first phase, congested airspace sectors, related peak, and off-peak hours are identified. The identification can be 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), or by analysing forecast Origin/Destination (O/D) demand. Using the former method, traffic demand is counted for all the sectors, taking into account all the flights and their operated routes, along a chosen time horizon (for example one hour). The ratio between hourly traffic count and nominal hourly capacity gives hourly load factor. The value of load factor is used to assign the peak or off-peak label to a specific region for a specific hour.

In the second phase, CP has to modulate en-route charges on the network, and AUs need to route each flight, based on the set charges. Note that as unit rates are currently set once per year, and it is still impractical to change the rates more often, we analyse the effect of PLP at the strategic flight planning level (months ahead) meaning that last minute inconveniences (e.g. weather or industrial actions) are not taken into consideration. The charges 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. En-route charges are modulated by the CP to achieve a network level objective, such as to reduce the amount of shift on the network. The shift is the difference between the requested and the allocated departure and/or arrival time(s). Since en-route charges today are set by the States (ANSPs) 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 game, where a leader (CP) sets the prices (which we will refer to in further text as *rates*), for peak and off-peak periods for each ANSP, anticipating the reaction of the followers (AUs) that will choose the cheapest routing option available. There is therefore a hierarchical relationship between two decision levels, the leader (upper level) and the follower (lower level), where the leader has complete knowledge of the follower's strategy, while the opposite does not hold. The follower can therefore only react to the leader's action. This type of model is known as Stackelberg game (see Von Stackelberg, 1952) and its solution is referred to as Stackelberg equilibrium, as opposed for example to Nash's equilibrium where both players have complete knowledge of each other's strategy.

The remainder of this paper is organised as follows. Section 2 introduces the nomenclature, the main assumptions the CPLP is subject to, and describes the problems addressed by CP and AUs in terms of objective functions and constraints. The two problems are then merged in the final bilevel mixed-integer linear programming formulation presented in Section 3, along with the reformulation into a mixed-integer linear model. An application of the CPLP on a regional scale example is introduced in Section 4 and the results are shown in Section 5, whereas Section 6 concludes the paper.

2. Mathematical modelling

This section introduces the main assumptions and nomenclature of the CPLP model, and mathematically formalises the problem faced by the CP and the AUs.

2.1 CPLP assumptions

1. *Fixed demand matrix*. Fixed number of flights between any airport pair in the network. The intention of the proposed pricing mechanism 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 having different aircraft types.
3. *Infrastructure capacity constraints* are known in advance, in terms of pre-defined airspace sectorisation and maximum number of aircraft which can enter each sector (or airport) per given period of time (that is, capacity). Since we are assuming the mechanism will be applied strategically, only nominal sector and airport capacities are considered, without

variations introduced by regulations (which are applied tactically, due to weather and other conditions that are not predictable so far in advance).

4. *Finite set of possible 4D trajectories* for each Origin/Destination/Aircraft triple: users can select a route from a set of pre-determined routes (derived from actual traffic). The duration of each route is differentiated according to the aircraft type but constant for all aircraft of the same type. (i.e., there is only one speed profile for each route/aircraft pair).
5. *Users are rational decision makers*. All AUs are assumed to choose the least-cost 4D trajectory available. The route costs are composed of flight operations costs and route charges. AUs' routing decisions are sensitive to modulations of route charges.
6. *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.
7. *Distance-proportional air navigation charges with sector-period-based rates*. The pricing rule applied for air navigation charges is similar to the currently used one, but instead of a unique unit rate per country, a peak/off-peak rate pair is established for each ANSP and valid for all sectors in the charging zone under the responsibility of that ANSP (explained further in section 2.3).
8. *Peak times and locations are known in advance*. Peak and off-peak times and locations are assigned by analysing past traffic distribution. The expected load on a sector, during a specific time is estimated by analysing the last filed flight plans from EUROCONTROL's Demand Data Repository data.

Nomenclature

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
bf	aircraft type b used to operate flight f
Wb_f	weight factor of aircraft b used by flight f, where $Wb_f = \sqrt{\frac{MaximumTakeoffWeight}{50}}$
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	time periods (hours), indexed by h
M	time instants (minutes), indexed by m
dt_f	requested departure time for flight f
at_f	requested arrival time for flight f
dep_f	departure airport for flight f
des_f	arrival airport

MGS	maximum ground shift (in minutes) allowed for a flight
Mf	possible departure time instants for flight *f*, i.e., $m \in [dt_f - MGS, dt_f + MGS]$
Th	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*
$D_{S,r}$	distance factor in sector *s* using route *r* (km/100)
Ur_n	historic unit rate of ANSP *n* (€)
$e_{S,r}$	entry time since departure on route *r* in element (sector or airport) indexed by *s*

2.2 Central Planner (CP)

The decision process of the CP is illustrated by an optimisation problem that identifies peak and off-peak rates for every sector of the considered airspace such that a user-optimal assignment of routes to flights will minimise flight shifts. CP's decision variables are defined as:

$$P_s^{(h)} = \begin{cases} P_{p,n} if\ h\ is\ peak\ time\ for\ sector\ s \\ P_{o,n} otherwise \end{cases} \qquad \forall s \in S_n, \forall \mathrm{n} \in \mathrm{N}, h \in H \quad (1)$$

where $P_{p,n}$ and $P_{o,n}$ are the variables that represent peak and off-peak rates for ANSP n, to which sector s belongs.

AUs' decision variables are:

$$x_{f,r}^{(m)} = \begin{cases} 1\ if\ flight\ f\ departs\ at\ minute\ m\ using\ route\ r \\ 0\qquad\qquad otherwise \end{cases} \qquad \forall f \in F, r \in R_f, m \in M_f \quad (2)$$

In the strategic planning phase, the CP therefore sets peak and off-peak rates to minimise the sum of total (ground plus airborne) shift assigned to flights.

$$min \sum_{\boldsymbol{f \in F, r \in R_f, m \in M_f}} GS_{f,r}^{(m)} \cdot x_{f,r}^{(m)} \quad (3)$$

The total shift for flight *f* using route *r* and departing at time *m* is defined as the sum of minutes of later-than-requested departure plus the number of minutes of earlier-than-requested arrival.

$$GS_{f,r}^{(m)} = max\,\{0, m - dt_f\} + \max\,\{0, at_f - \left(m + e_{des_f,r}\right)\} \qquad \forall f \in F, r \in R_f, m \in M_f \quad (4)$$

The requested arrival time at_f is defined as the sum of the requested departure time and flight time along the shortest available route:

$$at_f = dt_f + min_{r \in R_f} e_{des_f,r} \qquad \forall f \in F \quad (5)$$

The CP optimises the peak and off-peak rates so that ANSPs are guaranteed to recover their operational costs for providing air navigation services to AUs. Assuming the cost for providing ANS within a sector is proportional the Great Circle Distance between entry and exit point, cost recovery is ensured by imposing the following constraint:

$$\sum_{\substack{f \in F, r \in R_f, m \in M_f, \\ h \in H |\ (m + e_{s,r}) \in T_h, \\ s \in S | (s \in S_{n)} \wedge (s \in S_{r)}}} P_s^{(h)} \cdot D_{s,r} \cdot Wb_f \cdot x_{f,r}^{(m)} \geq \sum_{\substack{f \in F, r \in R_f, m \in M_f \\ s \in S | (s \in S_{n)} \wedge (s \in S_r)}} Ur_n \cdot D_{s,r} \cdot Wb_f \cdot x_{f,r}^{(m)}\ \forall f \in \mathrm{F} \quad (6)$$

This implies that the revenues levied by each ANSP under the CPLP policy should allow recovering operational costs of providing air navigation services. ANSP costs are traffic-proportional where the unit rate Ur represents, by definition, the cost for providing one *service unit,* which is the product of distance factor and weight factor.

In addition to the objective and cost recovery constraint, it is necessary to impose further constraints for bounding route choice to available capacity for sectors (eq. 7) and airports (eq. 8-10):

$$\sum_{\substack{f\in F, r\in R_f, h\in H,\\ m\in M_f|(m+e_{s,r})\in T_h}} x_{f,r}^{(m)} \leq Q_s^{(h)} \qquad \forall s\in S, h\in H \qquad (7)$$

$$\sum_{\substack{f\in F|\ dep_f=a,\\ r\in R_f, h\in H,\\ m\in M_f|m\in T_h}} x_{f,r}^{(m)} \leq Q_{a,dep}^{(h)} \qquad \forall a\in A, h\in H \qquad (8)$$

$$\sum_{\substack{f\in F|\ des_f=a,\\ r\in R_f, h\in H,\\ m\in M_f|(m+e_{a,r})\in T_h}} x_{f,r}^{(m)} \leq Q_{a,arr}^{(h)} \qquad \forall a\in A, h\in H \qquad (9)$$

$$\sum_{\substack{f\in F|\ (dep_f=a)\vee(des_f=a),\\ r\in R_f, h\in H,\\ m\in M_f|(m+e_{a,r})\in T_h}} x_{f,r}^{(m)} \leq Q_{a,gl}^{(h)} \qquad \forall a\in A, h\in H \qquad (10)$$

Finally, it should be imposed that, for every flight, exactly one route *r* and one departure time *m* are chosen:

$$\sum_{\substack{r\in R_f,\\ m\in M_f}} x_{f,r}^{(m)} = 1 \qquad \forall f\in F \qquad (11)$$

2.3 Airspace Users (AUs)

The decision process of the AU is modelled as an optimisation problem where each AU aims at choosing the routes that minimise costs for each of its flights. We believe that this assumption is reasonable, as we are addressing the strategic flight planning phase where the possible shifting of a flight influences the buffer added to the schedule, and does not delay the flight per se. Hence, before the schedule is built and any tickets are sold to passengers, thus ignoring passenger costs.

AUs' decision variables are introduced in eq. 2. The cost of a flight typically includes route and terminal charges, aircraft fuel and maintenance costs, fleet utilisation, and staff costs (see for example Ryanair, 2014). The AU objective function therefore minimises strategic flight operations costs, which include route charges, ground shift, and airborne operations (see the additional nomenclature introduced below). We exclude terminal charges from cost calculation because we consider the demand (i.e., origin and destination airports) to be constant. Diverse cost profiles (low, base and high, see Section 4 for more details) are assigned to different types of flights, based on the airline type and the role the flight has in the airline's network (e.g. low cost, feeder flight into a hub).

Nomenclature

cam_b	cost for one minute of airborne maintenance for aircraft *b*
cgm_b	cost for one minute of ground maintenance for aircraft *b*

cf_b	cost for one minute of fleet utilisation for aircraft b
cc_b	cost for one minute of crew utilisation for aircraft b
afb_b	average fuel burn for aircraft b (kg/min)
$cr_{r,b}$	route charges for route r flown with aircraft
fc	fuel cost (€/kg)

En-route charges are calculated proportionally to the great circle distance between entry and exit point of each sector, weight factor of the used aircraft type, multiplied by the rate set at entry time (either peak or off-peak rate):

$$cr_{r,b} = \sum_{\substack{s\in S_r, h\in H,\\ m\in M_f | m\in T_h}} P_s^{(h)} \cdot D_{s,r} \cdot W_b \tag{12}$$

Ground operations costs include aircraft maintenance, fleet and crew utilisation costs. Cost of one minute of ground operations is therefore defined as:

$$cg_b = cgm_b + cf_b + cc_b \tag{13}$$

These costs are accounted for every minute of strategic ground shift assigned to a flight, that is, the amount of total shift that is not airborne:

$$gs_{f,r}^{(m)} = GS_{f,r}^{(m)} - (e_{des_f,r} - min_{r\in R_f} e_{des_f,r}) \tag{14}$$

Airborne operational costs include aircraft maintenance, fleet and crew utilisation costs plus fuel costs, given by the product of the average fuel burn (afb_b) and fuel cost (*fc*). Cost of one minute of airborne operations is defined as:

$$ca_b = cam_b + cf_b + cc_b + afb_b \cdot fc \tag{15}$$

These costs are calculated for the duration of a flight along a chosen-route, where the duration of route *r* is given by $e_{des,r}$.

Total flight operations costs, defined as the costs to operate an aircraft *b* along route *r* with *t* units of ground shift are therefore calculated as:

$$C_{r,t}^b = cg_b \cdot t + ca_b \cdot e_{des,r} + cr_{r,b} \tag{16}$$

The objective that each AU minimises is therefore the following:

$$\min \sum_{\substack{r\in R_f,\\ m\in M_f'}} C^{b_f}_{r,gs_{f,r}^{(m)}} \cdot x_{f,r}^{(m)} \qquad \forall f \in F \tag{17}$$

Further constraints for the AU problem are the uniqueness of chosen-route and departure time constraints (Eq. 11), as already illustrated for the CP problem.

3. Bilevel formulation of the CPLP

The CP problem can be combined with the AU problem into a bilevel formulation that represents a Stackelberg game between the two agents, with the CP acting as leader and the AUs as followers. In such a configuration, the CP is able to anticipate the followers' reaction (in terms of route choice) to her/his pricing strategies and can therefore choose a set of rates that will optimise her/his objective by anticipating the associated followers' optimal route choice. The formulation of the bilevel optimisation problem is:

$$min \sum_{\boldsymbol{f\in F, r\in R_f, m\in M_f}} GS_{f,r}^{(m)} \cdot x_{f,r}^{(m)} \tag{18}$$

$$s.t. \sum_{\substack{\boldsymbol{f\in F, r\in R_f, m\in M_f,}\\ \boldsymbol{h\in H|\ (m+e_{s,r})\in T_h,}\\ \boldsymbol{s\in S|(s\in S_n)\wedge(s\in S_r)}}} P_s^{(h)} \cdot D_{s,r} \cdot Wb_f \cdot x_{f,r}^{(m)} \geq \sum_{\substack{\boldsymbol{f\in F, r\in R_f, m\in M_f}\\ \boldsymbol{s\in S|(s\in S_n)\wedge(s\in S_r)}}} Ur_n \cdot D_{s,r} \cdot Wb_f \cdot x_{f,r}^{(m)} \qquad \forall n \in N \tag{19}$$

$$\min \sum_{\substack{r\in R_f,\\ m\in M_f'}} C^{b_f}_{r,gs_{f,r}^{(m)}} \cdot x_{f,r}^{(m)} \qquad \forall f \in F \tag{20}$$

$$s.t. \sum_{\substack{f\in F, r\in R_f, h\in H,\\ m\in M_f|(m+e_{s,r})\in T_h}} x_{f,r}^{(m)} \leq Q_s^{(h)} \qquad \forall s \in S, h \in H \tag{21}$$

$$\sum_{\substack{f\in F|\ dep_f=a,\\ r\in R_f, h\in H,\\ m\in M_f|m\in T_h}} x_{f,r}^{(m)} \leq Q_{a,dep}^{(h)} \qquad \forall a \in A, h \in H \tag{22}$$

$$\sum_{\substack{f\in F|\ des_f=a,\\ r\in R_f, h\in H,\\ m\in M_f|(m+e_{a,r})\in T_h}} x_{f,r}^{(m)} \leq Q_{a,arr}^{(h)} \qquad \forall a \in A, h \in H \tag{23}$$

$$\sum_{\substack{f\in F|\ (dep_f=a)\vee(des_f=a),\\ r\in R_f, h\in H,\\ m\in M_f|(m+e_{a,r})\in T_h}} x_{f,r}^{(m)} \leq Q_{a,gl}^{(h)} \qquad \forall a \in A, h \in H \tag{24}$$

$$\sum_{\substack{r\in R_f,\\ m\in M_f}} x_{f,r}^{(m)} = 1 \qquad \forall f \in F \tag{25}$$

$$x_{f,r}^{(m)} \in \{0; 1\} \qquad \forall f \in F, r \in R_f, \mathrm{m} \in M_f \tag{26}$$

$$P_s^{(h)} \geq 0 \qquad \forall s \in S, h \in H \tag{27}$$

In order to solve the problem (eq. 18-27) and compute the Stackelberg equilibrium point, some reformulations are necessary (see for instance Labbé et al., 1998). First, the bilevel problem must be transformed into a single level problem, i.e., with a unique objective function and a set of linear constraints. This is achieved by reformulating the second level objective (eq. 20) into a set of equivalent constraints. In fact, since no flight can bear a negative cost, the function is separable with respect to flights. The meaning of this objective is that for each flight the chosen route and departure time (i.e., $x^{(m)}_{f,r}$ s.t. $x^{(m)}_{f,r} = 1$) must be the least costly one among all alternatives available for that flight. This can be equivalently expressed through a set of constraints, noting that the route uniqueness constraints (eq. 25) impose that for each flight, only one $x^{(m)}_{f,r}$ will be equal to one.

Therefore, the followers' objective is equivalent to:

$$\sum_{\substack{o\in R_f,\\ i\in M_f'}} C^{b_f}_{o,gs^{(\boldsymbol{i})}_{\boldsymbol{f,o}}} \cdot x^{(i)}_{f,o} \le C^{b_f}_{r,gs^{(\boldsymbol{m})}_{\boldsymbol{f,r}}} \cdot x^{(m)}_{f,r} \qquad \forall f \in F, r \in R_f, m \in M_f \qquad (28)$$

By replacing the AUs objective function (eq. 20) with equation 28, an equivalent single level formulation of the model is obtained. This formulation however is still non-linear because of the terms containing the product of two variables (i.e., $cr_{r,b_f} \cdot x^{(m)}_{f,r}$. Since $x^{(m)}_{f,r}$variables are binary, it is possible to linearise these terms through variable substitution.

Let us introduce a new set of variables $y^{(m)}_{f,r}$defined as follows:

$$y^{(m)}_{f,r} = \begin{cases} cr_{r,b_f} & if \quad x^{(m)}_{f,r} = 1 \\ 0 & if \quad x^{(m)}_{f,r} = 0 \end{cases} \qquad \forall f \in F, r \in R_f, m \in M_f \qquad (29)$$

The $y^{(m)}_{f,r}$ variables are equal to the route charges component for the chosen route assignment and zero for all non-chosen alternatives. This is enforced by adding the following constraints to the model:

$$y^{(m)}_{f,r} - cr_{r,b_f} \le 0 \qquad \forall f \in F, r \in R_f, m \in M_f \qquad (30)$$

$$cr_{r,b_f} - y^{(m)}_{f,r} - N^{(m)}_{f,r} \cdot (1 - x^{(m)}_{f,r}) \le 0 \qquad \forall f \in F, r \in R_f, m \in M_f \qquad (31)$$

$$y^{(m)}_{f,r} - N^{(m)}_{f,r} \cdot x^{(m)}_{f,r} \le 0 \qquad \forall f \in F, r \in R_f, m \in M_f \qquad (32)$$

Eq. 30 imposes equality between $y^{(m)}_{f,r}$ and cr_{r,b_f} when $y^{(m)}_{f,r}$ is not zero; Eq. 31 binds cr_{r,b_f} and $y^{(m)}_{f,r}$ to be equal when $x^{(m)}_{f,r}$ is 1; the third constraint (eq. 32) forces $y^{(m)}_{f,r}$ to be zero when $x^{(m)}_{f,r}$ is zero. $N^{(m)}_{f,r}$ terms are *Big-M* (i.e., arbitrarily high) values.

The resulting single level linear CPLP formulation is then:

$$min \sum_{\boldsymbol{f\in F, r\in R_f, m\in M_f}} GS^{(m)}_{f,r} \cdot x^{(m)}_{f,r} \qquad (33)$$

$$s.t. \sum_{\substack{\boldsymbol{f\in F, m\in M_f},\\ \boldsymbol{r\in R_f} | \exists s\in(S_n \land S_r)}} y^{(m)}_{f,r} \ge \sum_{\substack{\boldsymbol{f\in F, r\in R_f, m\in M_f}\\ s\in(S_n \land S_r}} Ur_n \cdot D_{s,r} \cdot Wb_f \cdot x^{(m)}_{f,r} \qquad \forall n \in N \qquad (34)$$

$$\sum_{\substack{o\in R_f,\\ i\in M_f{}'}} (cg_{b_f}\cdot\, i +\, ca_{b_f}\cdot\, e_{des,o}\ )\cdot x_{f,o}^{(i)} +\, y_{f,o}^{(i)} \le C^{b_f}_{r,gs_{f,r}^{(m)}}\cdot x_{f,r}^{(m)} \qquad \forall f\in F, r\in R_f, \in M_f \qquad (35)$$

$$\sum_{\substack{f\in F, r\in R_f, h\in H,\\ m\in M_f|(m+e_{s,r})\in T_h}} x_{f,r}^{(m)} \le Q_s^{(h)} \qquad \forall s\in S, h\in H \qquad (36)$$

$$\sum_{\substack{f\in F|\ dep_f=a,\\ r\in R_f, h\in H,\\ m\in M_f|m\in T_h}} x_{f,r}^{(m)} \le Q_{a,dep}^{(h)} \qquad \forall a\in A, h\in H \qquad (37)$$

$$\sum_{\substack{f\in F|\ des_f=a,\\ r\in R_f, h\in H,\\ m\in M_f|(m+e_{a,r})\in T_h}} x_{f,r}^{(m)} \le Q_{a,arr}^{(h)} \qquad \forall a\in A, h\in H \qquad (38)$$

$$\sum_{\substack{f\in F|\ (dep_f=a)\vee(des_f=a),\\ r\in R_f, h\in H,\\ m\in M_f|(m+e_{a,r})\in T_h}} x_{f,r}^{(m)} \le Q_{a,gl}^{(h)} \qquad \forall a\in A, h\in H \qquad (39)$$

$$\sum_{\substack{r\in R_f,\\ m\in M_f}} x_{f,r}^{(m)} = 1 \qquad \forall f\in F \qquad (40)$$

$$y_{f,r}^{(m)} - cr_{r,b_f} \le 0 \qquad \forall f\in F, r\in R_f \in M_f \qquad (41)$$

$$cr_{r,b_f} - y_{f,r}^{(m)} - N_{f,r}^{(m)}\cdot(1 - x_{f,r}^{(m)}) \le 0 \qquad \forall f\in F, r\in R_f \in M_f \qquad (42)$$

$$y_{f,r}^{(m)} - N_{f,r}^{(m)}\cdot x_{f,r}^{(m)} \le 0 \qquad \forall f\in F, r\in R_f, \in M_f \qquad (43)$$

$$x_{f,r}^{(m)} \in \{0;1\} \qquad \forall f\in F, r\in R_f, \in M_f \qquad (44)$$

$$P_s^{(h)} \ge 0 \qquad \forall s\in S, h\in H \qquad (45)$$

This results in a mixed-integer linear programming problem.

4. Computational example

The CPLP model, as illustrated in the previous section, is tested on a regional-scale instance of real air traffic data: all traffic departing between 6:00 and 10:00[6] on 12th September 2014 that crosses, departs from, or arrives to French airspace (2376 flights in total). This traffic sample includes a time period of high traffic (7:00-10:00), and one of medium and low traffic (6:00-7:00) density, and includes regional, continental and inter-continental flights. The airspace sectorisation and related nominal sector capacities used in this example correspond to the configurations in use during 12th September 2014, as we assume that it is representative of configurations on Fridays. The configurations in use at each hour comprise of 85 to 100 active airspace sectors including terminal approach areas at major airports (see Figure 1). A sector is considered active if it is a part of a specific configuration (i.e. in use) at the specific time.

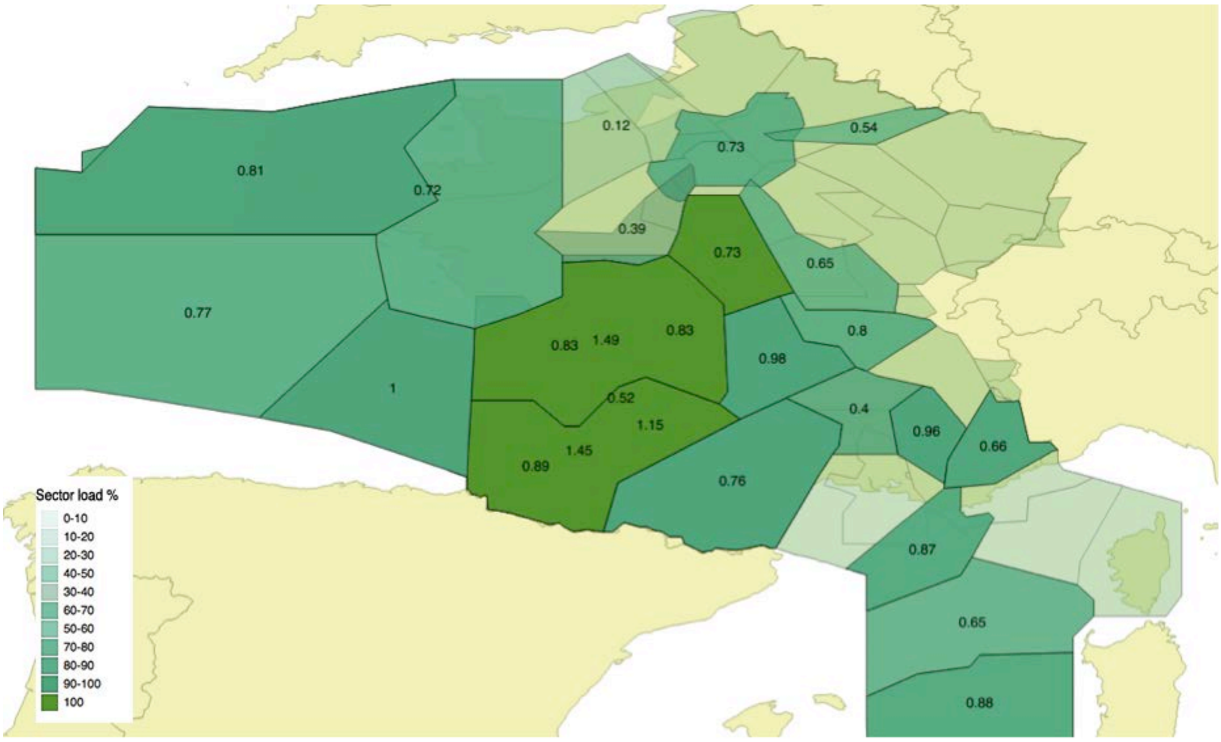

Figure 1. Load on capacitated active sectors at 10:00 on 12th September 2014 (historical data). Sectors with a darker colour have a higher load.

The traffic distribution, according to historical data on actually flown routes for this traffic sample, presents the highest traffic peaks between 9:00 and 10:00. A sector is considered to be in a peak hour if its load factor during that hour is greater than a fixed threshold of 0.5. Nominal hourly capacity is a finite value, available for 36 to 40 of the sectors declared as active (which we refer to as *capacitated active sectors*), depending on the hour. For all remaining sectors, the capacity value is equal to infinity, i.e., capacity is not a constraint. Figure 1 illustrates the load on French upper airspace at 10:00.

Preliminary tests proved the provided nominal capacity values ($Q_s^{(h)}, Q_{a,dep}^{(h)}, Q_{a,arr}^{(h)}, Q_{a,gl}^{(h)}$ terms in eq. 21-24) to be too restrictive for obtaining a feasible assignment of flights. It was therefore necessary to adapt the model allowing capacity constraints to be violated, with a penalisation in the objective function for exceeding the capacity. Within reasonable limits of 10-15% violation,

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[6] All times are given in UTC – Coordinated Universal Time

this relaxation is coherent with actual practice in air traffic control (which is also evident in historical data on last filed flight plans, hence referred to as *Lffp*, see Table 2).

Prior to running the CPLP model on this data sample, it is necessary to determine routing options for flights, given as a combination of route and departure time. The pool of available routes per O/D pair-aircraft type triple was determined through a clustering process on historical flight data from the two weeks preceding 12th September. This process was necessary to ensure that only routes that differ significantly from one another in terms of geographical distance were taken into account. Specifically, as a width of an airway is 19 km, we consider the same all the routes for which the distance between the points where the distance between the two routes is maximal, measured in 3-dimensional space is less than 20 km. The clustering process reduces the number of viable routes per O/D pair-aircraft type triple from the tens available in the data to an average of 3.7 routes per O/D pair.

Concerning departure time options, in the current example, each flight has a possible departure time shift of up to 30 minutes before and 30 minutes after the requested departure time for that specific flight by the AU. The shift is divided in 5-minute long slots, meaning that a flight with requested departure time at 5:00 will be assigned one of the following possible departure times by the model: [4:30; 4:35; 4:40; 4:45; 4:50; 4:55; 5:00; 5:05; 5:10; 5:15; 5:20; 5:25; 5:30]. We assume that a 5-minute granularity is precise enough to describe a process that is to be applied in the strategic phase. Departure times in the last-filed flight plans available through the EUROCONTROL DDR2 data sets are used as proxies for the requested departure times.

The 2014 unit rates for ANSP air navigation charges are taken from EUROCONTROL (2014a). Costs for ground and airborne aircraft operations, i.e., maintenance[7], fleet utilisation[8], and crew costs, as well as the average fuel burn values, are taken from European airline delay cost reference value report (Cook and Tanner, 2011) where relevant cost coefficients (per minute) for twelve reference aircraft types are identified and calculated. These are estimated to cover 90% of European air traffic. Aircraft different from these twelve are assigned the cost coefficients of the closest of the twelve, using the square root of the maximum take-off weight of the aircraft as a proxy. AUs are subdivided into four types: full-service, low-cost, charter, and regional. Based on this subdivision, flights are grouped into three different flight operational cost profiles, as shown in Table 1.

Table 1. Cost scenarios assigned to flights

Cost scenario	Flight categorisation
Low	All low-cost carrier flights
High	Full-service flights into hub airports, regional flights into hub airports
Base	All other flights

5. Results

This test was carried out on an i7 processor laptop where the CPLP model (equations 33 – 45) was implemented in the Mosel language and solved through the built-in branch and bound algorithm of Xpress optimiser version 7.7. The model has approximately 128000 constraints and 40000 binary variables, for this example. Due to the mathematical complexity of the model, it was not

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[7] Maintenance costs of delay incurred by aircraft relate to factors such as the mechanical attrition of aircraft waiting at gates (strategically or tactically) or aircraft accepting longer re-routes in order to obtain a better departure slot (tactically). Maintenance costs are based on the block-hour maintenance costs, and are allocated across the taxi and airborne phases of the flight, out of which the cost per minute of ground or airborne maintenance coefficients are calculated.

[8] Fleet costs refer to the full cost of fleet financing, such as depreciation, rentals and leases of flight equipment.

possible to solve it exactly: the final solution has a 5% optimality gap, which was reached after approximately sixteen hours of computational time.

The obtained modulated rates for France are 62.64€ for the off-peak and 71.12€ for the peak, as opposed to a historical unit rate of 65.92€. Objective function values obtained are 1594 minutes of global shift with 11 violated capacities.

As for the route and departure time assignment to flights, the solution obtained is evaluated according to the performance indicators described in the following text. When applicable, values are given also from the route assignment obtained from historical data on *Lffp*.

- *En-route charges*: sum of the route charges imposed on the flights, used to cover the costs of ANS provision; calculated according to eq. 12, measured in € per flight;
- *Operational costs:* sum of the costs for operating the aircraft for the assigned route duration plus the ground shift component; calculated according to eq. 15, measured in € per flight;
- *Departure shift:* absolute difference between the requested and assigned departure time. Measured in minutes per flight;
- *Arrival shift:* absolute difference between the arrival time obtained by departing at requested arrival time using the shortest route and the assigned arrival time. Measured in minutes per flight;
- *Horizontal flight efficiency:* difference between the origin-destination en-route distance of assigned routes, and the great circle distance between the origin and destination, expressed as a percentage of the great circle distance;
- *Temporal flight efficiency:* difference between the duration of the shortest route and the duration of the assigned route; measured in minutes per flight;

Indicator values are summarised in Table 2.

Table 2. Performance indicator values for the obtained route and departure time assignments with (CPLP) and without (Lffp) unit rate modulation

Indicator (Avg. per flight)	***Lffp***	**CPLP**
En-route charges (€)	1572.89	1412.43
Operational costs (€)	6934.17	6941.35
Departure shift (minutes)	0.00	0.35
Arrival shift (minutes)	1.67	0.58
Horizontal flight efficiency	0.12	0.11
Temporal flight efficiency	4.00	0.39

Results show that the proposed modulation of en-route charges does not impact flight costs in a significant way. Route charges for the chosen routes with CPLP, are on average 10% lower than with *Lffp* chosen routes. Traffic distribution with CPLP, additionally, proves to be much more efficient from the temporal point of view.

Table 3 illustrates the obtained distribution of traffic over airspace sectors. The average sector load per hour is lower in CPLP with respect to *Lffp*. Since the nominal capacity value is usually not the same across different capacitated sectors, moving flights from sectors with high to the ones with low utilisation, reduces the average load over the whole network. This result is confirmed by the distribution of traffic load over the number of capacitated active sectors, as shown again in Table 3. Figure 2 further illustrates the geographical distribution of traffic over French upper airspace.

A mild price modulation (off-peak rate is 4.5% lower and peak rate is 7.9% higher than the historical unit rate) proves to be effective in improving traffic load over airspace sectors.

Obtained sector load figures in the CPLP route assignment are systematically lower than historical data. The number of violated capacities (number of sectors with >100% load) also decreases from a total of 31 in the *Lffp* to 11 with CPLP as the traffic moves across underutilised sectors (the number of sectors with load < 30% goes from 11 to 40).

Table 3. Sector loads with (CPLP) and without (*Lffp*) unit rate modulation at different hours

	6:00		**7:00**		**8:00**		**9:00**		**10:00**	
	Lffp	**CPLP**	***Lffp***	**CPLP**	***Lffp***	**CPLP**	***Lffp***	**CPLP**	***Lffp***	**CPLP**
Avg. sector load	0.79	0.23	0.75	0.58	0.71	0.64	0.85	0.76	0.78	0.53
N. of sectors with 0-10% load	0	6	0	0	0	0	0	0	0	1
10-20% load	2	12	1	2	0	0	0	0	1	1
20-30% load	0	7	1	0	1	2	3	2	2	7
30-40% load	4	8	1	7	1	2	2	2	2	5
40-50% load	3	2	4	6	7	6	2	3	1	5
50-60% load	4	1	4	6	7	6	2	2	3	4
60-70% load	4	0	10	10	6	10	3	5	5	7
70-80% load	6	0	4	1	7	5	5	5	6	3
80-90% load	2	0	3	2	4	4	8	9	10	3
90-100% load	3	0	4	3	1	2	7	5	4	1
>100% load	8	0	6	1	5	2	7	6	5	2
N. of capacity-constrained sectors	36		38		39		39		39	
N. of active sectors	90		95		100		99		100	

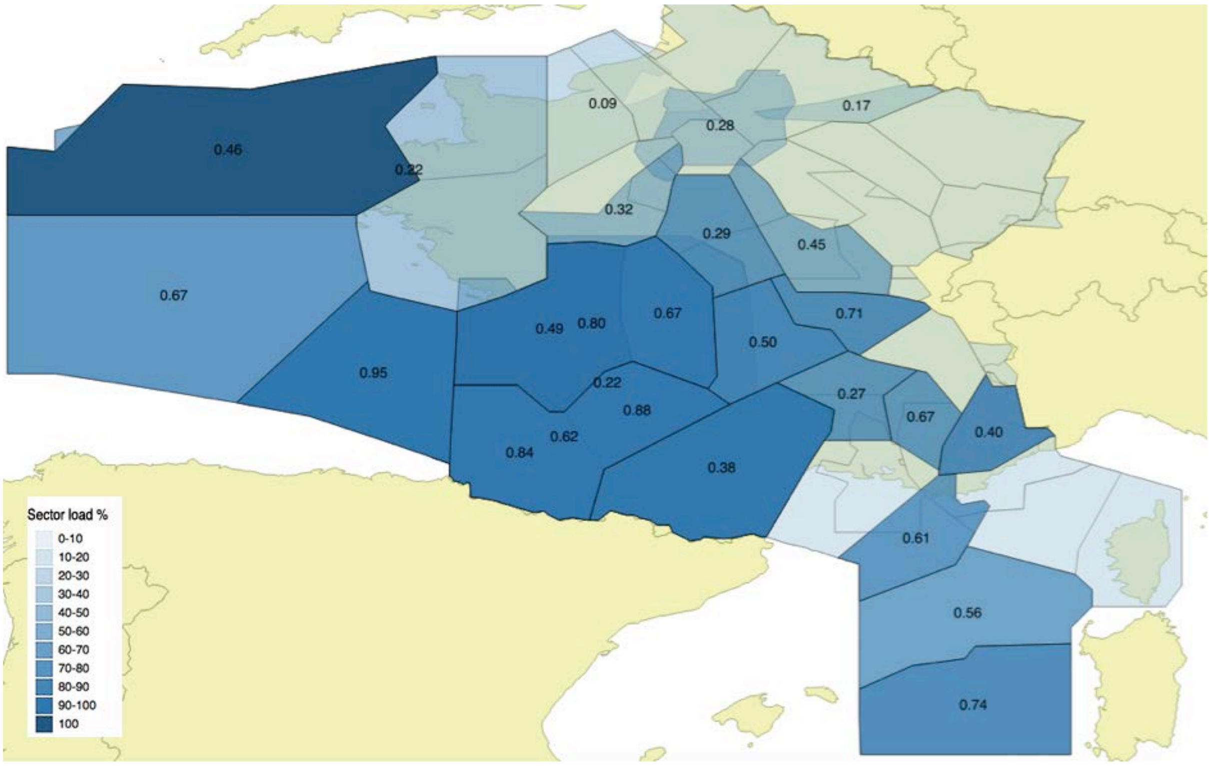

Figure 2. Load on capacitated active sectors at 10:00 on 12th September 2014 (with CPLP). Sectors with a darker colour have a higher load.

6. Conclusions and further development

This paper discusses the introduction and possible use of a centralised peak-load pricing (CPLP) mechanism to redistribute air traffic in the European airspace in order to resolve capacity-demand imbalances strategically. Relying on a bilevel mixed-integer linear programming formulation, CPLP captures the relationships between the central planner, in charge of setting the rates to minimise the overall difference between assigned and requested departure times, and the airspace users seeking the cheapest routes for their flights. The proposed mathematical formulation solves CPLP at 5% optimality gap for a regional-scale sample and obtained results are encouraging under several performance metrics, suggesting that en-route charges modulation could, indeed, represent a viable measure to address the issue of growing airspace capacity-demand imbalances in Europe. Even though CPLP has not been solved exactly, the chosen modelling approach is a good contribution to the bilevel problems, as to the best of our knowledge, the largest data instances on which bilevel linear formulations are tested commonly include no more than a hundred commodities (i.e., users) on networks with a few hundred arcs (see for example Violin, 2014, Sec. 5.8.3). Nevertheless, the significant weakness of requiring rapidly increasing calculation time as the system studied grows in size and complexity, means that in order to apply CPLP on the European network for an entire day, a heuristic approach that sacrifices as little accuracy as possible in exchange of much faster computation times is mandatory. This is currently under study. Different CP objective functions, such as the minimisation of flight inefficiency (i.e., the horizontal additional flight length with respect to the shortest route connecting an O/D pair), will also be evaluated as a part of future work.

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