Efficiency vs. Flexibility in ATM: Can Pricing Help?

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Abstract— **Driven by a number of uncertainties an appreciable share of airspace users (AU) look for "last-minute" 4D route choice gains, and thus exercise a fairly late submission of flight plans. Orders of magnitude of such gains, from AUs' perspective, are in the range of tens or hundreds of Euros per flight. However, such AU behaviour amplifies uncertainty imposed on air navigation service providers (ANSP) and network manager (NM), which is difficult to be managed cost-efficiently. Due to lower traffic load predictability, ANSPs tend to declare more conservative sector capacities, which effectively means that additional sectors need to be open sooner (at lower traffic loads) than if predictability was better.**

Against such a background, this paper revisits and extends the "Rewarding Predictability" (RP) mechanism, introduced in [1]. The original idea of the RP is to design a pricing scheme which incentivises AUs to reduce uncertainties imposed on ANSPs and NM, so that they file their flight intentions earlier and stick with them as much as possible, aiming at improved network performance. In this paper, a stochastic module is incorporated into the RP mechanism, concerning route choice process, in line with recent findings presented in [2]. This arguably more realistic representation of AUs' behaviour allows us to more credibly discuss the efficiency vs. flexibility trade-offs involved and the comparative performance of various route allocation methods in addressing those.

Keywords-ATM; network; pricing; predictability; flexibility; efficiency

I. INTRODUCTION

Driven by a number of uncertainties involved [3], a considerable share of airspace users (AU) look for "last-minute" 4D route choice gains, and thus exercise a fairly late submission (or cancellation and re-submission) of flight plans [4]. Orders of magnitude of such gains, from AUs' perspective, are typically in the range of tens or hundreds of Euros per flight, at most [5], [6]. However, such AUs' behaviour amplifies uncertainty to be managed by Air Navigation Service Providers (ANSPs) and network manager (NM). The associated effects might be higher costs imposed on some other users and likely deteriorated performance of the network as a whole. Put differently, neither the sign is clear (plus or minus, i.e. total costs vs. total benefits) of the net outcome of such a "liberal" setting, nor is the fairness of distribution of costs and benefits across the population of AUs.

There is evidence from the industry that ANSPs would strongly prefer "a more consistent delivery across the network in order to optimise available capacity and to reduce periods of over-delivery and overloads" [4]. More specifically, it is stated that "the more imprecise the projected traffic loads for airspace sectors prove to be, the bigger the safety margins will have to be which are built into their declared capacity limits" (Dr. Klaus Affholderbach, Head ATFCM Skyguide), [4]. Therefore, due to low traffic predictability ANSPs tend to declare more conservative sector capacities [7], which effectively means that additional sectors need to be open sooner (at lower traffic volume/loads) than if predictability was better. The cost of additional resources employed (staff, equipment etc.) can therefore, *ceteris paribus*, be attributed to poor traffic predictability. Hence improved predictability might yield cost savings, a part of which could be passed on to airspace users themselves. Several years ago an ANSP estimated that approximately 5-10% of its capacity is "reserved" to take care of all "non-adherence issues", arising in pre-tactical and tactical stage. That happens to correspond to the estimated "complete capacity gap" of that ANSP, i.e. the 5-10% capacity missing to reach the optimum level of delay. They consequently estimate the possible cost saving of a more predictable (compliant/reliable) system at approximately 45 million euros per annum [8].

This research is undertaken in the course of the SESAR WP-E project "Strategic Allocation of Traffic Using Redistribution in the Network" (SATURN), which explores market-based demand-management mechanisms to redistribute air traffic in the European airspace. Recognising that the recurring problem of demand-capacity balancing in ATM can be tackled in different ways, based on policy principles employed, this paper builds upon previous work developed in [9-11] and, more recently, in [1]. In [1] we put forward intertemporal pricing as an underexplored concept in ATM applications. The distinguishing underlying idea is to give AUs incentives to reduce uncertainty imposed on ANSPs/NM. Apart from employing the peak load pricing rationale, such charging system would at the same time reward earlier filing of flight intentions, since such user behaviour improves predictability for ANSPs/NM and might thus improve the performance of the network as a whole [7]. We thus labelled it as "Rewarding Predictability" (RP) mechanism. In this paper we abandon the fully deterministic approach introduced in [1] and incorporate a more realistic representation of the route choice process into the RP mechanism, in line with findings of [2].

Predictability in this context relates primarily to reduction of demand-driven uncertainty, which in turn affects the amount of resources needed by ANSPs to manage the traffic at a targeted level of service. Therefore, an increase in thus-defined predictability may be expected to have beneficial effects on other Key Performance Areas (KPAs): cost-efficiency, capacity, and environment. ICAO defines a related, but slightly different Predictability KPA, as "the ability of the airspace users and ANSPs to provide consistent and dependable levels of performance" [12].

The rest of the paper is organized as follows. Section II gives a condensed overview of most relevant past contributions. Section III, reiterating for the sake of readers' convenience much of the arguments developed in [1], discusses the rationale and assumptions of the proposed method. In section IV we describe the case study and introduce key results, which are then discussed in Section V. Section VI concludes.

II. Background

A handful of contributions in the field of economic-based demand management measures aiming to reduce airspace congestion were published in the last 15 years. For a broader review the reader is referred to [1]. We hereunder focus on a few most closely related contributions.

Reference [13] investigates the possibility of influencing airlines' route choices by differential sector pricing. The results suggest that a relatively simple differential pricing scheme might be of considerable help in reducing the en-route congestion.

In [14] the author proposes a new ANS pricing rule, wherein charges would: (1) be inversely proportional to aircraft weight, and (2) take account of the congestion cost.

An anticipatory, time-dependent ad-hoc modulation (AHM) of ANS charges is proposed in [10] and [11]. It aims to bring the traffic demand more in line with available network capacities, so that the total cost to airspace users is minimised. It puts into effect, albeit in a somewhat semi-administrative manner, another notable and desirable feature: revenue neutrality of the price modulation. The collected toll revenues are used to encourage (subsidise) the use of alternative but otherwise underutilised network segments. The results of a case study indicate that such a method may yield a fairly equitable route assignment, which seems capacity-wise more efficient compared to current flow management practices.

Reference [15] was the first to explicitly consider the possibility of applying intertemporal price discrimination in the ATM system, as an instrument to bring the demand in line with available capacity. The author discusses general prerequisites for a successful yield management implementation, namely: fixed capacity, high fixed and low variable costs, temporal variability of demand, market segmentation, etc., and concludes that certain potential exists to employ it in the ATM system. She stresses the likely issues concerned with the eventual implementation of such a system, including:

- insufficient knowledge on the airlines' elasticity with respect to route charges;
- a problem of defining a long-enough peak period (arguing that congestion would otherwise tend to move to periods before and after the peak one);
- the problem of coordination of pricing policies among the ANS providers, which seems necessary if any beneficial effect is to be achieved.

There are, broadly speaking, two principal revenue management methods employed by airlines, from which one may draw inspiration for ATM-related applications. Firstly, for low-cost carriers, an algorithm is used to compute posted fares as a function of the itinerary, departure time, date, time of purchase before departure, and seat availability on the flight [16]. Here there is a single resource controlled: one flight's seating capacity. Importantly, there is only one price available at any single moment.

For network carriers, revenue management is based on a highly complex set of procedures that allow carriers to offer multiple fares on a single flight, combining various rules and restrictions, e.g. ticket refunding, advance-purchase restrictions, valid travel days, stay restrictions, etc. [17]. Here *versioning* is employed, plus a broader perspective: connecting passengers, trip chaining, i.e. in a way connected resources, since the same seat can be sold in different combinations – as a point-to-point, or as one leg in various multiple-leg itineraries. There is thus, to some extent, an analogy with air traffic flow management, since same-sector capacity increments can be consumed by trajectories between different airport pairs.

Delgado (2015) analyses the routes submitted by airlines to be operated on a given day and compares the associated costs of operating those routes with the shortest available at the time, in terms of en-route charges and fuel consumption. Results of analysis of a sample of about 10,000 flights suggest that five out of six flights submitted the shortest route available. At the same time, some 6.4% flights (one out of 16) were found to select longer routes and save some ANS charges. This phenomenon is especially present around adjacent areas where differences in charges are significant. On the other hand, a similar proportion of flights were found to exercise seemingly irrational route choice behaviour, choosing longer and more expensive (higher ANS charges) routes [2].

III. Rationale and Assumptions

A. Rationale

We assume that the detailed airspace sectorisation (down to elementary level) is not fixed in advance. General maximum capabilities of each network segment are nevertheless known to the network manager (NM), in terms of capability to handle certain level of traffic, at certain level of utilisation of internal resources. More specifically, certain volume of airspace (e.g. a "cluster" – grouping of several sectors) can handle different levels of traffic, dependent upon the level of its fragmentation. Early filing of flight plans ("purchasing of routes" by airlines) provides a valuable indication as to which level of fragmentation of such cluster is likely to be used on the day of operation. It therefore increases predictability for ANSPs in terms of staffing (shift planning etc.) on the day, e.g. whether maximum configuration is to be applied or else. It is suggested in [18] that the planning processes are "the most significant drivers of an ATC centre's cost-efficiency". More specifically, as those processes determine staffing (the main resource of a centre) and airspace sector opening sequences, the overestimation in the planning process can result in a low cost-efficiency performance of a centre [18].

Different levels of cluster fragmentation naturally come at different level of capacity provision cost. Reference [19] suggests an average EUR 3-4 million annual Area Control Centre (ACC) cost per sector for European ANSPs (estimation domain: 10-30 sectors per ACC). The same study suggests the average annual per-sector cost of US$ 1.7 million for US ACCs (estimation domain: 25-55 sectors per ACC). Both estimates imply that being able to handle the (design) traffic with fewer sectors might translate into significant cost savings, order of magnitude of millions of euros per annum.

In line with the above, the proposed RP mechanism does not take detailed airspace sectorisation as constant; quite oppositely, active network capacities evolve over time, in line with the evolution of revealed demand (purchased routes). The very late purchase of routes is thus likely to result in very high route charges, reflecting the likely higher cost of providing the needed capacity under such circumstances.

B. Assumptions

We proceed by introducing and discussing the environment and assumptions for the proposed approach.

a) A priori known (expected) demand matrix, in terms of number of flights, including desired departure times, between any airport pair in the network. The intention of the proposed charges modulation is not to scale down the demand but to modify its spatial/temporal pattern to bring it in line with available capacities [20].

b) There are infrastructure capacity constraints which are known in advance, in terms of pre-defined maximum number of aircraft which can enter each network segment per given period of time.

c) Unit (incremental) costs of capacity provision are known in advance for each network segment. The same volume of airspace can handle different traffic volumes dependent on the level of airspace fragmentation. Those different capabilities of a given airspace volume come at different costs – the levels of which are known by NM.

d) NM is a mediator, as it is the only actor that supposedly fully comprehends the broader repercussions (network effect) of individual stakeholders' actions. Airspace users thus communicate with NM only, and NM communicates with ANSPs. NM posts prices for trajectories, based on incremental costs of capacity provision. ANSPs provide capacity, and get reimbursed the cost of capacity provided/traffic controlled.

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

f) Context: trajectory-based pricing, as perceived by users; sector-based (capacity) considerations – behind the scenes.

g) Users are offered and are free to choose their route from a menu of routes offered by the NM, that is, from a set of reasonable (e.g. typically used) trajectories per OD pair. Finite number of trajectories is a priori defined for each OD pair.

h) 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, in terms of both set of offered routes and their prices. The initial menu of routes contains the broadest set of offered routes, that is, no generation of new routes is allowed compared to initial menu, so there can only be reduced choice as the time of departure approaches.

i) 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 which are available at that moment, along with prices attached to each available route. This is similar to potential traveller looking for available flights and fares between airports A and B. Importantly, as with such traveller, time of purchase impacts both availability and prices of available options.

j) 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 utilisation (filed demand/capacity ratio) of sector-periods constituting those routes.

k) Route price dynamics (concerning time of purchase, i.e. intertemporal pricing component). For the time being, for the sake of simplicity, we consider the no-refund policy, meaning that once a user makes his choice of 4D trajectory, he can no longer change it and get any refund – that is, he made a no-refund purchase. If he decides not to use the purchased product, he goes back to the beginning of the process and purchases a new among then-available routes, at then-available prices.

The menu of available routes and their prices changes over time, reflecting the capacity constraints behind the scenes. Clearly, once the capacity of some network segment is fully consumed by previous route purchases, all routes of which that network segment forms a part are withdrawn from the menus.

C. RP Algorithm – deterministic version (RP-D)

The proposed approach works sequentially, which necessitates an assumption on the order of users' (flights') appearance in the system, i.e. of route purchase. In the example shown in this paper (Warsaw Area Control Centre, to be described in Section IV) we used randomly generated orders of flights in each mechanism run.

Figure 1 depicts the conceptual model of the proposed approach. In RP-D each flight is assumed to choose the least-cost route option offered. The cost of the route option includes the "displacement" cost (the cost of deviation from the shortest-"reference" route) plus the cost of associated route charges. Unlike with AHM model, briefly described in Section V, here there are neither current (weight- and distance-based) ANS charges nor AHM-like tolls involved. Route charge for any route option is calculated as the sum of charges attached to sector-periods that constitute that route option. Sector-period charge is calculated as a product of the base tariff (qualitatively alike unit rate in the present setting, single value for the entire national airspace assumed) and of three multipliers: M1, M2 and M3, as follows:

Sector-period charge = Base tariff x M1 x M2 x M3 (1)

M1 multiplier is the function of the number of flights which already purchased a capacity increment (through the route they purchased) in entire Warsaw ACC airspace in the considered time period, e.g. 30 minutes period. As the system successively fills up, the M1 value increases in a stepwise manner, ranging from 0.7 to 1.4 in our example. This is meant to reflect the need for further airspace fragmentation (additional sector opening) as the revealed demand increases. This further capacity provided comes at an extra cost, which we may associate with higher entry charges. And so on, until the maximum fragmentation of cluster is reached, and the final increment of capacity charged at highest rate. The employed principle has an undertone of marginal cost pricing: providing additional buckets of capacity at correspondingly higher rates.

The M1 rationale can also be seen as a penalty for late filing (or a bonus for early filing). For instance, if baseline capacity of a sector-period in a network is 18 flights, then after each 18 flights (route purchases) involving the given period in entire Warsaw ACC airspace this multiplier increases, to reflect the fact that another controller position needs to be opened to handle the traffic.

M2 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. Such a mechanism can be interpreted as a "soft" means of pre-empting excessive sector loads. At the same time, it incentivises the use of less-loaded sector-periods. M2 ranges between 0.98 and 1.52 in our example. Once the capacity of any sector-period is reached, all the routes in which that sector-period is present will no longer appear in the route menu for the subsequent users.

M3 multiplier is associated with individual sectors and reflects their expected (or historical) utilisation levels. It does not depend on the actual route purchases for the given day. It rather aims to reflect general capacity scarcity in the given sector, in terms of e.g. historical demand vs. capacity ratio for that sector. The historically more requested (utilised) sectors will therefore be more expensive than those less requested, *ceteris paribus*. In our example M3 values for individual sectors range from 0.8 to 1.2.

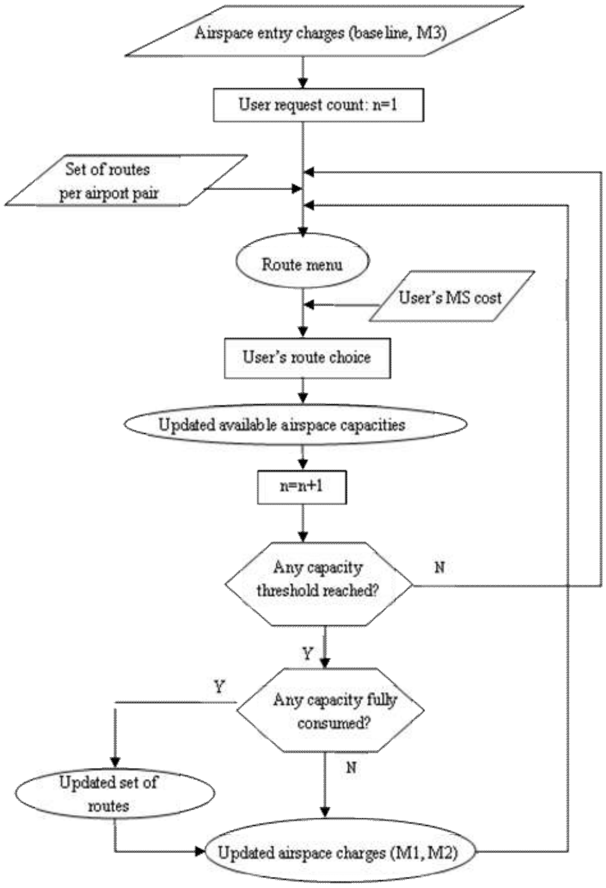

Figure 1. Flow chart of the RP-D mechanism

It should be noted that the described variant of RP-D method assumes revenue neutrality for the ANSP. To that end, M1-M3 values were designed so that, ideally, the estimated cost of ANS provision be recovered. Thus effective rebates vs. average price apply for early buyers, as well as penalties for late (and premium routes) buyers. To try to reach the revenue neutral solution (vs. the actual route charges revenues collected), we estimated costs of ANS provision to be recovered. Unit cost is estimated at 4,500 EUR per sector-hour, based on 2008 costs of ANS and ATM/CNS provision in Poland [21].

Finally, sector-period charges for adjacent airspace volumes are calculated against the base tariff for Polish sectors-periods as a reference (140 EUR), multiplied by the ratio of unit rate for the country in question and the unit rate for Poland (using June 2009 unit rates values). For example, the assumed sector-period charge of 190 EUR for Czech Republic means that the unit rate for Czech Republic was some 35% higher than unit rate for Poland in June 2009.

D. Stochastic RP mechanism (RP-S)

Informed and facilitated by the findings from ref. [2], in this version we abandon the deterministic least-cost route-choice rule applied in RP-D. Instead, we use stochastic simulation (Monte Carlo) to replicate the aggregate high-level statistics observed in [2]. As already mentioned, those suggest that, on average, five out of six flights opt for the shortest route available. Further on, one out of 16 flights were found to select longer routes and save on ANS charges. Finally, a similar proportion of flights were 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 still believe that the employed statistical approach, on aggregate, better simulates the real process than the deterministic least-cost rule.

We will use the RP-S label to denote the mechanism with such route-choice module incorporated, to distinguish it from the original, deterministic version (labelled RP-D).

IV. Case Study

To test the model a medium-scale case study using real-word data was developed. This section describes the development of this case study, and presents its key results.

The example described in this section fully replicates the example used in [1]. This is a convenient feature as it enables direct comparison of outcomes of different approaches to solving the considered demand/capacity imbalance problem.

A. Experimental Design

1) Airspace and Traffic Sample

The *Rewarding Predictability* (RP) method was tested on Warsaw ACC airspace, which suffered (as of 2009/10) from structural capacity limitations. In particular, due to characteristics of its ATM system, there was no possibility to vertically split the sectors above 9,500ft and optimise the airspace structure. As a consequence, this ACC generated 10% of total en-route ATFM delay in Europe in 2009 [22], even though it controlled only 2.3% of total flight-hours in Europe [23]. In addition, the bordering airspaces did not generate considerable ATFM delays.

A congested three-hour morning peak (4 June 2009, 09:00-12:00) was used as a traffic sample, comprising 362 flights crossing Warsaw ACC airspace (77 departures, 52 arrivals, 22 internal flights and 211 overflights). The traffic sample used contains 104 carriers. Only six carriers have more than 10 flights in the sample, amounting altogether to 142 flights (39.2% of total). Importantly, 55 carriers have only one flight in the sample each, while 80 carriers have three flights or less in the traffic sample.

Traffic data were obtained from the EUROCONTROL Demand Data Repository (DDR) application, which provides access to historical 4D trajectory SAAM/NEVAC traffic files, built on EUROCONTROL's Central Flow Management Unit data.

Warsaw ACC airspace is divided into nine sectors, with eight sectors simultaneously open in maximum configuration. The declared sector capacities were obtained from EUROCONTROL's NEVAC tool, and represent maximum allowable hourly entry counts.

The surrounding airspaces were mapped (to a lesser level of detail), to facilitate alternative routes that bypass the Warsaw airspace. Finally, we ended up with eight periods (08.30-09.00: period 0,…, 12.00-12.30: period 7) and 17 "sectors", assigning fixed capacity to each eligible sector-period.

2) Route Alternatives

The only routes initially available were the last-filed flight plans for all flights. The generation of alternative routes was performed in EUROCONTROL's SAAM platform, by seeking "shortest paths" between airports of departure and destination for each flight, under various airspace availability scenarios, while treating the last-filed take-off time as fixed in each of the scenarios.

Having that way generated certain number of route alternatives for most of the flights, we then also introduced the possibility of at-gate delay imposed on the shortest (reference) route of each flight. For the vast majority of flights (356 out of 362) an option was introduced to have them delayed at-gate by 15 minutes. For 73 flights there was a further option of longer at-gate-delay: for 61 flights the 30-minute delay was an option, while for 12 flights the 45-minute at-gate delay was an option.

As a result, we ended up with, on average, four alternatives for each flight. The number of alternatives across individual flights ranges from two to six routes. The vast majority of flights had at least three routes available, while seven flights ended up with only two routes available.

3) Route Costs

The assumed cost of flying any route consists of the "displacement" cost (the cost of deviation from the shortest-reference route), plus the cost of associated route charges. The displacement cost comprises solely the cost of deviation from the shortest ("reference") route, in both spatial and temporal dimension. The notion of "displacement cost" reflects the network manager's perspective, which was supposed to be optimising the vector of (capacity, environment) key performance indicators. Consequently, each flight had a zero-cost ("reference" route) option available. To quantify the displacement effects we used marginal strategic costs of at-gate delay and en-route extension ("base" scenario), available in [24].

4) Demand vs. Capacity Situation

Prior to focusing on results of the experiment, it may be instructive to briefly analyse the excessive demand situation in Warsaw ACC in the chosen three-hour period. Figure 2 shows sector loads that would have come up if each flight had been assigned its last-filed 4D route, against the available (declared) sector capacities. This state was clearly inadmissible, due to significant excess of demand over capacity in a number of sector-periods. On the other hand there were also a few sector-periods with capacity reserves. Hereinafter we refer to the actual CFMU resolution of this situation (i.e. the slot regulation applied) as "Scenario F".

Importantly, the Scenario F yielded major surpluses of declared core sector-period capacities, e.g. sector G handling 11 flights more than its declared capacity in period 1, etc. Therefore, to enable a more like-with-like comparison of the effects of the proposed method with that of the actually applied

ATFM slot regulation, we used actual sector-period traffic loads (Scenario F sector entry counts) as capacities in our example, wherever those exceeded the declared capacity values. We chose such an approach for the sake of comparability of effects of contrasted congestion management approaches, being fully aware, of course, that maximum bearable sector-period loads are highly context-dependent.

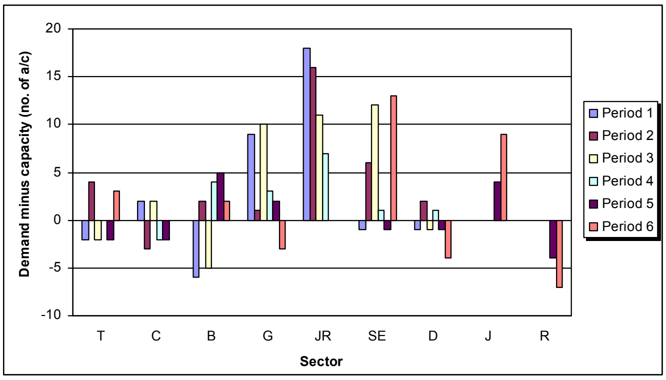

Figure 2. Planned demand vs. declared capacities, ACC Warsaw sectors

B. *Key Results*

To test the RP algorithm 1,000 runs of each its version were made with randomised order of users' show up. Table I presents some key results.

TABLE I. SUMMARY COMPARISON OF TWO RP MECHANISM VERSIONS (MEAN VALUES, UNLESS OTHERWISE STATED)

Mechanism	RP-D	RP-S
Total displacement cost (EUR) [standard deviation (EUR)]	11,547 [σ = 2,593]	17,652 [σ = 4,360]
Revenue collected from charges (EUR)	97,104	98,064
Flights allocated reference or last filed route	291.0	288.1
Flights delayed at-gate by 15 min	28.9	17.4
Flights delayed at-gate 30-45 min	2.0	3.5
Flights displaced spatially	39.6	49.4
"Unaccommodated" flights	0.4	3.5

It can be seen that the stochastic version of the mechanism (RP-S) expectedly exhibits deteriorated efficiency (increased total displacement cost), due to abandonment of the strict least-cost choice rule applied in RP-D.

On average, there are three "unaccommodated" flights more in RP-S then in RP-D version. Those are flights for which there was, according to experiment design, no available route at the moment of intended purchase. Those flights appeared as a rule towards the end of the "booking" process, i.e. typically after well more than 90% of users have already purchased their routes. The late-purchasers are therefore also exposed to greater risk of facing empty route menus, i.e. to situations with no remaining routes available, under the specific case-study assumptions. As a general way out of such a situation, such flights could be offered a route with longer delay (e.g. 60 min) or a longer rerouting (compared to the baseline route menu for the given OD pairs at the beginning of the "booking" process).

The RP-S mechanism on average yields considerably fewer short delays but slightly more longer delays compared to RP-D. This last aspect is however offset by more frequent spatial re-routings in the RP-S version.

Route charges revenues for Warsaw ACC are in both versions very stable across different runs and generally quite close to the estimated cost of ANS provision for the core period analysed, standing at 99,000 EUR.

V. DISCUSSION – PUTTING THE RP RESULTS INTO PERSPECTIVE

This session discusses the comparative performance of the newly-proposed RP-S mechanism against the two alternative ways of mitigating the demand-capacity imbalances, as well against its deterministic predecessor, the RP-D mechanism. To ease the comprehension of the forthcoming discussion we therefore first briefly reflect on the mechanics of and results obtained by applying those alternative methods on the Warsaw ACC case study.

A. *A Reflection on Scenario F and the AHM Model Results*

1) *Scenario F – actually applied slot regulation*

As Table II shows, 39 out of 362 flights were delayed due to the JR sector regulation during the chosen three-hour period, which generated a total of 683 minutes of delay [25]. Two thirds of delayed flights were imposed delays of up to 15 minutes. However, there are six flights delayed more than 30 minutes, which contribute most to the aggregate delay cost, due to nonlinearity of the delay cost function [24]. The estimated cost of delay for all 39 affected flights stands at nearly 22,000 EUR, based on assumed marginal costs of at-gate delay (full tactical cost, "Base" scenario), [24]. Nearly 60% of total delay cost is attributed to six flights only, and those may therefore be considered main losers of the ATFM slot administering process, since they were heavily penalised through no fault of their own, and, importantly, with no alternative or compensation offered.

Concerning the distributional effects, two thirds of the total delay cost burden was borne by six carriers (out of 104 carriers in the sample), which altogether perform less than a third of total flights from the sample.

2) *Ad-hoc Modulations (AHM) mechanism*

The AHM model is conceptualized as a two-level optimisation problem [11]. At the upper, system optimisation (SO) level, the route assignment is sought which minimises the deviation from an optimal vector of key performance indicators for the given network demand. Practically, such assignment yields lowest possible additional cost arising from fuel burn ("Environment" KPA) and ATFM delays ("Capacity" KPA), [26].

At the lower modelling level a continuous user-optimising (UO) problem is solved. UO stage finds a toll-and-rebate policy which replicates the SO assignment, wherein no user will have a less expensive alternative than the assigned one, in line with the definition of the *user equilibrium* notion [27].

B. *Comparative Analysis*

Table II summarises the comparison of key results of the three methods analysed.

Mean cost of displacement achieved by the deterministic RP (RP-D) mechanism (11,547 EUR) can be credibly compared with that of AHM mechanism (4,340 EUR), which is arguably the best (i.e. lowest) possible value for the given traffic, routes and airspace capacities. It can also be compared with the cost of delay due to actually applied slot regulation (F scenario), estimated at 21,842 EUR. However, most of the efficiency gains "achieved" by the RP-D mechanism vanished (unsurprisingly) in its stochastic version (RP-S), bringing the displacement cost in the latter (17,652 EUR) close to that observed in the F scenario. These differences between the AHM and other three methods could arguably be interpreted as the "price of anarchy" [28], representing in a way the quantification of the degradation of network performance due to less regulated traffic.

TABLE II. SUMMARY COMPARISON OF FOUR ROUTE ALLOCATION MECHANISMS

Method	F scenario	AHM	RP-D	RP-S
Key features	Static pricing, liberal flight plan submission; first planned-first served slot allocation (ground delays) when insufficient capacity	Centralised system-optimum assignment, followed by modulation of charges to balance distributional effects	Triple price discrimination: time of use, location of use, and time of purchase; deterministic route choice	Triple price discrimination: time of use, location of use, and time of purchase; stochastic route choice
Total displacement cost (EUR) [standard deviation (EUR)]	21,842	4,340	11,547 [σ = 2,593]	17,652 [σ = 4,360]
Flights allocated reference or last filed route	323	327	291	288
Flights delayed <16min	26	10	29	17.4
Flights delayed 16-45 min	10	0	2	3.5
Flights delayed >45 min	3	0	0	0
Flights displaced spatially	0	25	39.6	49.4
"Unaccommodated" flights	0	0	0.4	3.5
Displacement cost (in EUR) borne by 5 most affected carriers [cumulative number of those carriers' flights]	12,625 [112]	2,413[a] [123]	4,319 [128]	6,509 [120]

a. Does not include the effects of tolls and rebates imposed in the UO stage.

Overall, Table II results imply that the AHM mechanism yields (by definition) lowest total displacement cost compared to both RP mechanism versions and, particularly, to the F scenario. However, those gains in efficiency come at a price, primarily in terms of reduced route choice flexibility.

Further discussing the results shown in Table II, we note that in the AHM mechanism 90% of flights are assigned their reference routes, while the remaining 10% are displaced from their reference route in space (more often) or/and time. This compares to 20% "displaced" flights in the RP method, wherein both spatial and temporal spreading of demand is extensively at place.

The bottom row of Table II provides an indication of the distributional effects of different mechanisms employed. It shows the displacement cost burden borne by five most affected carriers in each mechanism. It suggests that both RP and AHM mechanism seem to perform considerably better than the F scenario in this respect.

Due to the specificity of the case-study (severe excess of demand over maximum employable capacity in Warsaw ACC), possible gains in terms of financial cost efficiency (reduced cost of capacity provision and consequently reduced unit rate) have not been demonstrated.

VI. SUMMARY AND CONCLUSIONS

This paper revisits the role of pricing in addressing the problem of demand-capacity imbalances in an airspace network, in the European context. The stochastic *Rewarding Predictability* (RP-S) pricing mechanism is introduced. Compared to its deterministic predecessor (RP-D), introduced in [1], RP-S mechanism is, at a given level of data availability, on aggregate believed to be a better replica of airspace users' route-choice behaviour.

The results of application of the RP-S mechanism on a medium-scale case study are contrasted against the outcomes of several alternative methods. We quantify the degradations of airspace network performance as a function of the degree of traffic regulation, that is, of various mechanisms/policy principles employed.

The RP method, employing three-dimensional price differentiation (time of use, location of use, and time of purchase) and *first-come, first-choice* discipline, can itself be seen as a "middle path" between the other two methods analysed. On one side there is a costly and arguably (occasionally) inequitable current "*laissez faire*" flight intentions submission regime, helped by first-planned first-served slot allocation (F scenario). On the other side is the super-efficient but rather restrictive AHM method, which could also be perceived as lexicographic efficiency-equity optimization. The results suggest that the AHM method expectedly yields superior network efficiency, compared to both RP mechanism and, especially to present practices. However, those gains in efficiency come at a price, primarily in terms of sacrificed route choice flexibility. Or, from an opposite angle, the *laissez faire* regime – ample route-choice liberty (including the time of flight plan filing) has its efficiency and equity price, representing the cost of the lack of coordination. Finally, we also show that efficiency of air traffic assignment (management) can be improved without necessarily deteriorating the equity dimension.

The proposed concept gives rise to a number of practical questions, concerning first of all the dynamics of the proposed process. The probably most obvious question might be: what if the contracted ("purchased") trajectory turns out impossible to deliver on the day of operation, due to e.g. weather conditions? This is a clearly valid point at present, which could initiate an exploration of some remedying compensation mechanisms, which falls beyond the scope of this paper. However, its importance is expected to be diminishing in the future, due to expected far greater predictive capability brought about by collaborative decision making, further strengthened through the introduction of improved weather forecasting [29].

This work should primarily be seen as an incremental contribution to an ongoing debate on improved ways of mitigating demand-capacity imbalances. The policy decision as to which method will be employed strongly depends on the extent of airspace users' acceptance. To that end, some encouraging feedback has been obtained at second SATURN project's stakeholder workshop (London, 21 April 2015). Specifically, there were airspace users' views that if the supply-side predictability (including weather) could be substantially improved, then they might in principle see themselves involved in a kind of route charging mechanism that rewards the demand-side predictability. With this in mind, further testing of RP mechanism on larger-scale instances is expected to provide a fuller insight into its likely effects.

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REFERENCES

[1] R. Jovanović, O. Babić, V. Tošić, "Pricing to reconcile predictability, efficiency and equity in ATM". 11th USA/Europe ATM R&D Seminar, 2015, Lisbon, Portugal.

[2] L. Delgado, "European route choice determinants". 11th USA/Europe ATM R&D Seminar, 2015, Lisbon, Portugal.

[3] J. Pepper, K. Mills, and L. Wojcik, "Predictability and uncertainty in air traffic flow management". 5th USA/Europe ATM R&D Seminar, 2003, Budapest, Hungary.

[4] EUROCONTROL SKYbrary, "Sector Over-deliveries and Overloads", [Online], Available: http://www.skybrary.aero/index.php/Sector_Over-deliveries_and_Overloads#Further_Reading [Accessed July 2014].

[5] S. Altus, "Effective flight plans can help airlines economize". Boeing AERO Magazine, Issue 35, Quarter 03, 2009, pp. 27-30.

[6] A. Cook, and G. Tanner, "A quantitative exploration of flight prioritisation principles, using new delay costs". Journal of Aerospace Operations 1(3), 2012, pp. 195-211.

[7] G. Tobaruela, P. Fransen, W. Schuster, W. Ochieng, and A. Majumdar, "Air traffic predictability framework – Development, performance evaluation and application". J AIR TRANSP MANAG 39, 2014, 48-58.

[8] EUROCONTROL SKYbrary, "Sector Over-Deliveries Due to Non-Adherence/Response", [Online], Available: http://www.skybrary.aero/index.php/Sector_Over-Deliveries_Due_to_Non-Adherence/Response [Accessed July 2014].

[9] R. Jovanović, "Economic measures for air traffic demand management". PhD thesis. University of Belgrade-FTTE. 2011.

[10] R. Jovanović, V. Tošić, M. Stanojević, and M. Čangalović, "Self-financing modulation of air navigation charges to incentivise a more efficient use of airspace capacity", 5th International Conference on Research in Air Transportation ICRAT 2012, Berkeley, USA.

[11] R. Jovanović, V. Tošić, M. Čangalović, and M. Stanojević, "Anticipatory modulation of air navigation charges to balance the use of airspace network capacities", TRANSPORT RES A-POL, 61, 2014, pp. 84-99.

[12] ICAO, "Manual on global performance of the air navigation system." Doc. 9883, 1st ed., 2009.

[13] K. Deschinkel, J-L. Farges and D. Delahaye, "Optimizing and assigning price levels for air traffic management". TRANSPORT RES E-LOG vol. 38, 2002, pp. 221-237.

[14] M. Raffarin, "Congestion in European airspace. A pricing solution?" J TRANSP ECON POLICY vol. 38, Part 1, 2004, pp. 109-126.

[15] P. Leal de Matos, "Yield management for privatized air traffic control?", J OPER RES SOC vol. 52, 2001, pp. 888-895.

[16] E. Bachis and C. Piga, "Pricing strategies by European traditional and low cost airlines: or, when is it the best time to book on line?" Mimeo. 2006.

[17] M. Alderighi, "Fare dispersions in airline markets: A quantitative assessment of theoretical explanations". J AIR TRANSP MANAG 16, 2010, pp. 144-150.

[18] G. Tobaruela, A. Majumdar, W. Ochieng, W. Schuster, and P. Hendrickx, "Enhancing cost-efficiency and reducing capacity shortages: strategic planning and dynamic shift management". 10th USA/Europe ATM R&D Seminar, 2013. Chicago, Illinois, USA.

[19] Helios for EUROCONTROL Performance Review Commission, "The impact of fragmentation in European ATM/CNS". 2006.

[20] V. Tošić, O. Babić, M. Čangalović, Dj. Hohlačov, "A model to solve en route air traffic flow management problem: a temporal and spatial case", 1st USA-Europe ATM R&D Seminar, 1997, Saclay, France.

[21] EUROCONTROL Performance Review Commission, "ATM Cost-effectiveness (ACE) benchmarking report 2008". June 2010.

[22] EUROCONTROL Performance Review Commission. "Performance Review Report: An assessment of air traffic management in Europe during the calendar year 2009 (PRR 2009)." May 2010.

[23] EUROCONTROL Performance Review Commission, "ATM Cost-effectiveness (ACE) benchmarking report 2009". June 2011.

[24] A. Cook and G. Tanner, "European airline delay cost reference values". Final report. Univ. of Westminster for EUROCONT. PRU. March 2011.

[25] EUROCONTROL Demand Data Repository. www.eurocontrol.int/ddr

[26] European Commission, "Commission Implementing Regulation (EU) No 390/2013, Laying down a performance scheme for air navigation services and network functions.", 2013.

[27] S. Dafermos, "Toll patterns for multiclass-user transportation networks". TRANSPORT SCI vol. 7, 1973. pp. 211-223.

[28] T. Roughgarden and E. Tardos, "How bad is selfish routing?", J ACM 49(2), 2002, pp. 236-259.

[29] SESAR Consortium, "The ATM target concept." SESAR Definition Phase – Deliverable 3, 2007.