Coordinated Capacity and Demand Management in the European Core Area

Results of a large-scale COCTA case study

Radosav Jovanović,
Nikola Ivanov,
Goran Pavlović, Obrad Babić
University of Belgrade – Faculty of Transport and Traffic Engineering,
Belgrade, Serbia
[r.jovanovic; n.ivanov;g.pavlovic; o.babic]@sf.bg.ac.rs

Frank Fichert
Department of Tourism and Transportation,
Worms University of Applied Sciences,
Worms, Germany
fichert@hs-worms.de

Arne Strauss
Warwick Business School,
University of Warwick,
Coventry, UK
arne.strauss@wbs.ac.uk

Stefano Starita
Sirindhorn International Institute of Technology,
Thammasat University,
Thailand
stefano@siit.tu.ac.th

***Abstract*—The coordinated capacity and demand management (COCTA) concept assumes a new role for the Network Manager (NM), having contractual relations with Air Navigation Service Providers (ANSPs) and Aircraft Operators (AOs). The NM orders en-route airspace capacity from ANSPs at strategic level and defines/adjusts sector opening schemes at pre-tactical level (capacity management). On the demand side, the NM offers trajectory products to AOs, which are defined based on both AOs' business/operational needs and network performance goals (demand management). In this context, a mathematical model was developed which exemplifies this joint capacity and demand management process. The model aims at minimizing the sum of cost of capacity provision and cost of delays and re-routings, by managing airspace sector configuration over time and trajectory assignments. In this paper we particularly present how the NM defines trajectory products to incentivise AOs' trajectory choices and to achieve the target network performance. We use a large-scale case study covering eight ANSPs in Western and Central Europe to evaluate the benefits of joint capacity and demand management decisions and to illustrate trade-offs between different performance indicators. We compare the network performance achieved by COCTA under nominal conditions against the results of a Baseline scenario.**

Keywords- network performance, network manager, demand management, standard trajectory, discounted trajectory.

Foreword- This work is envisaged as a part of the SESAR 2020 Exploratory Research project "Coordinated capacity ordering and trajectory pricing for better-performing ATM" (COCTA). Opinions expressed in this work reflect the authors' views only.

I. INTRODUCTION

In the COCTA concept the future Network Manager (NM) asks for (orders) en-route airspace capacity from Air Navigation Service Providers (ANSPs). This capacity management process spans over the long term (five years), the strategic (up to one year) and the pre-tactical (up to one day before the day of operations) stage, involving different capacity orders at different stages. On the demand side, the NM defines and offers to Aircraft Operators (AOs) a range of trajectory products, which are defined based on both AOs' business/operational needs and the network performance goals. These two processes – capacity and demand management – referred to as the COCTA mechanism, are performed by the NM in a coordinated approach in order to optimize a vector of network performance indicators.

To support the concept, we have described a redesigned ATM value-chain, as well as roles and the institutional relations between the NM, ANSPs, and AOs [1]. Following the general COCTA mathematical model [2], we further developed a model to support the initial capacity management decisions taken by the NM at strategic level. A two-step decision-making method, consisting of Scenario Identification and Scenario Testing, was proposed and tested using a small-scale case study [3]. It demonstrated the fundamental trade-offs between the scope of capacity orders and demand management measures necessary to establish a demand-capacity balance.

In this paper we use a large-scale case study to further evaluate the benefits of joint capacity and demand management decisions, as well as trade-offs between different performance indicators. First, building upon research presented in [3], we briefly explain how the NM makes capacity management decisions at strategic stage, i.e. defining the specific sector-opening scheme (SOSc), taking into account traffic variability in the network. After a SOSc has been chosen for a representative day based on the NM's system-optimum objective, we present how the NM defines trajectory products to incentivise AOs' trajectory choices and achieve the target network performance. We compare the network performance achieved by COCTA under nominal conditions against the results of a Baseline scenario, which models a Non-COCTA framework and resembles the current system to the extent possible.

The remainder of the paper is structured as follows: Section II briefly describes the COCTA concept. Section III outlines the new features of the mathematical model to support the pre-tactical decision-making process. The results of the large-scale case study are presented in Section IV. Conclusions and an outlook are given in Section V.

II. COCTA CONCEPT AND MECHANISM OVERIVEW

Within the COCTA concept, the NM is mandated a new role: it has suitable instruments for steering capacity and demand in a coordinated manner and is responsible for the network performance (as defined by policy makers). Implementing the COCTA concept would require a political agreement on the European level and alignments in the EU's legal framework.

One of the key proposed changes concerns the way airspace capacity is allocated in the European network and ordered from ANSPs by the NM. In the proposed setting the NM asks for airspace capacities in line with expected demand, employing a network-centred, demand-driven approach, as opposed to the current piecemeal supply driven practice, which is often tailored towards local/ANSP traffic peaks. COCTA capacity management and planning is a continuous process and is subject to negotiations, and eventually contracts, between the NM and ANSPs. Depending on the assumed flexibility of the provision of air navigation services (ANS), capacity orders can be adjusted as one-off decisions or dynamically in time. As a consequence, better utilization of en-route capacity is expected, with associated beneficial cost implications.

In the redesigned ATM value-chain, we propose a novel approach to demand management as well. The first element is the new en-route ANS charging principle, which is based on airport-pairs. The base charge for a flight between any two airports, i.e. the charge without applying additional demand management incentives, only depends on the MTOW of an aircraft. These charges are calculated for a schedule season (or one year), based on envisaged traffic flows, strategic capacity order and associated costs which have to be recovered (assuming cost recovery). This principle takes away incentives from AOs to fly longer routes in order to save on en-route ANS charges, which should reduce CO_2 emissions and make AOs' route choice more predictable (absent wind).

Second, the NM defines and offers differentiated trajectory products to AOs (trajectory management), mindful of AOs' business needs and preferences, as well as of overarching network performance targets. Building on top of airport-pair base charges, the NM applies a specific type of trajectory pricing (incentives), aiming to guide AO's trajectory choices to establish a demand-capacity balance, measured over multiple performance indicators: cost-efficiency, delays, environmental impact and equity (without negatively affecting safety). These trajectory products are named Standard Trajectory (ST) and Discounted Trajectory (DT)[1].

Both ST and DT are structurally the same: an AO that purchases either of them will acquire the right to fly a specific origin-destination combination for a specified charge, but the NM retains the right to decide shortly prior to the departure day which trajectory will be available (within agreed margins). The only difference between ST and DT is that the margins (spatial or temporal) for DT are significantly wider than for ST, and hence DT would be offered to AOs at a discount.

The NM aims to improve network performance by optimizing the use of the airspace capacity which has been ordered from ANSPs. The demand management starts once the initial capacity order is made, i.e. up to one year before the day of operation. At that moment, the NM has a fairly good estimate of 1) the cost of capacity provision to be recovered via airspace charges, as well as 2) a scope of anticipated costs associated with delays or re-routings, which are related to the 'pricing' of the DT product to manage demand.

The current COCTA mechanism is primarily designed for the strategic and the pre-tactical stage, while both the long-term and the tactical stage (day of operations) are considered to a certain extent only. In this paper, we demonstrate how the new concept of demand management works under nominal conditions which are linked with the pre-tactical stage. This assumes capacity being delivered and flights executed as planned, i.e. without disruptions occurring on the tactical level.

III. COCTA MODEL: COORDINATED CAPACITY AND DEMAND MANAGEMENT

A. *Strategic capacity ordering*

The NM's decisions with respect to capacity and demand management in the strategic and pre-tactical phases of the COCTA mechanism are exemplified by the COCTA mathematical model which reflects the related timeframe.

At strategic level the NM decides on initial capacity ordering from ANSPs; in this case, the NM asks for sector-opening scheme (SOSc) for each Areas Control Center (ACC). In the decision-making process, the NM accounts for traffic variability, in terms of overall traffic levels and traffic patterns, stemming mainly from the non-scheduled portion of demand. The mathematical model for the capacity ordering is described with (1)-(6). Note that there are two types of decisions to be made: assignments of trajectories r to flights f via y_r^f, and SOSc decisions z_{acu} over time. The NM aims to minimize the sum of capacity cost, which is determined with SOSc, and displacement cost, which represents the additional cost for AOs arising from delayed or re-routed flights (1). Each flight needs to be assigned to exactly one route (2) and an active sector configuration has to be defined for each airspace (3). Sector capacity constraints are defined with (4), while (5) and (6) are binary constraints for variables. This formulation had been proposed in our earlier work [3].

In this paper, we focus on the resulting capacity ordering decision, i.e. SOSc for each airspace considered. We use this as an input to the model at the pre-tactical stage, i.e. for demand management (which is the main focus of this paper).

1 Please note that in some of our previous works you may find different names of these products. Namely, Purchased Specific Trajectory (PST) corresponds to Standard Trajectory (ST), while Flexibly Assigned Trajectory (FAT) has been changed to Discounted Trajectory (DT).

Sets:

O	Set of origin-destination pairs
F	The set of all flights
R_f	The set of routes available to f
U	Time horizon
A	Set of airspaces
C^a	Set of configurations for airspace a
P^c	Partition of elementary sectors corresponding to a configuration

Indices:

f	Flights
od	Origin and destination airports
u	Time index
r	Route
a	Airspace
c, c'	Airspace's configuration
p	Airspace sector (collapsed or elementary)

Parameters:

γ_a	Variable cost of providing one sector-time unit for airspace a
K_p	Maximum capacity of volume of airspace p
$\bar{h}_{ac}$	Number of sector-time units consumed by airspace a operating in configuration c
d_r^f	Displacement cost of route r for flight f
b_{frpu}	Is equal to 1 if route r uses sector p at time u, 0 otherwise

Variables:

$$z_{acu} = \begin{cases} 1, & \text{if airspace } a \text{ configuration is } c \text{ at time } u \\ 0, & \text{otherwise} \end{cases}$$

$$y_r^f = \begin{cases} 1, & \text{if flight } f \text{ is assigned to route } r \\ 0, & \text{otherwise} \end{cases}$$

$$\min_{\substack{z,y \\ y}} \sum_{a\in A} \gamma_a \sum_{u\in U} \sum_{c\in C^a} \bar{h}_{ac} z_{acu} + \sum_{f\in F} \sum_{r\in R_{od_f}} d_r^f y_r^f \tag{1}$$

$$\text{s.t.} \sum_{r\in R_{od_f}} y_r^f = 1 \qquad \forall f \in F \tag{2}$$

$$\sum_{c\in C^a} z_{acu} = 1 \qquad \forall a \in A,\ u \in U \tag{3}$$

$$\sum_{f\in F} \sum_{r\in R_f} b_{frpu}\, y_r^f \leq K_p z_{acu} + |F| \sum_{c'\neq c} z_{ac'u} \qquad \forall a \in A,\ c \in C^a,\ p \in P^c,\ u \in U \tag{4}$$

$$z_{acu} \in \{0,1\} \qquad \forall a \in A,\ c \in C^a,\ u \in U \tag{5}$$

$$y_r^f \in \{0,1\} \qquad \forall f \in F,\ r \in R_{od_f} \tag{6}$$

B. *Demand management*

In the period between the initial capacity order and the pre-tactical phase, which we refer to as booking horizon, the NM needs to make decisions on trajectory products: prices, margins for delays/re-routings and supply. The NM can define prices as one-off decision or adjust prices dynamically, depending on the assumed regulatory and business environment. Also, the NM decides on trajectory product offers, that is, to which airport-pair markets DTs are offered in addition to STs. Finally, the NM needs to assign flights to trajectories within the limits of their purchased product. Potentially, the NM decides on how much capacity needs to be re-ordered at a certain point in time in the booking horizon (again, depending on the assumed flexibility of capacity provision).

In this paper, we consider the ST product prices to be fixed, DT prices (discounts) to be decided at the latest at pre-tactical level and without an option to adjust capacity once the initial order has been made.

1) *Trajectory products, prices and supply*

ST prices are calculated and pre-determined in the strategic phase, based on the estimated cost of capacity provision over a given period (e.g. a year). On the other hand, the DT pricing poses a major challenge, since the uncertainty associated with non-scheduled demand levels and AOs' choice behaviour makes it significantly more difficult to find an optimal solution.

The main objective is to minimize overall system costs by incentivizing a set of flights/traffic flows to select DT, so that the NM can assign final trajectories in a more flexible way. However, if an AO chooses DT, less payment is received to cover the overall capacity provision cost. Therefore, we face a trade-off between obtaining more flexibility that may (!) lead to cost savings and receiving ideally just as much income as needed to cover the cost of capacity provision.

The (modelled) decision of which flights/traffic flows are the ones that should be encouraged to select a DT are established by running multiple simulations with known scheduled and assumed non-scheduled flights. Namely, we solve the problem of assigning flights to trajectories for many different potential materialisations of non-scheduled flights (at strategic level). Then, we identify flights/flows which were displaced from their preferred trajectories (to minimise overall cost (1)) and record frequency and scope of delays or re-routings, as well as costs thereof (which we refer to as "displacement costs"). Based on a delay and re-routing analysis, we define margins for ST and DT. Margins for ST are such that fine-tuning the final trajectory within them implies only very minor operational cost imposed on AO concerned. Then, we focus on the flights/flows that were actually assigned to a trajectory outside the ST margins (be it in time or space).

The rationale behind this approach is that we aim to incentivize only certain flights to accept more flexibility in return for a discounted charge, choosing those flights that might be subject to demand management measures of a certain scope. These flights/traffic flows within a certain region will be the best candidates to be offered a choice between ST and DT, since having a flexibility to displace those flights leads to improved network performance.

The approach described above has been developed to be able to run a case study based on actual flight data. Since currently AOs don't have a choice between ST and DT, there is no empirical information on the 'demand function' for DTs available. In case of an implementation of COCTA, after few periods the NM would have sufficient empirical information to decide on the offer and pricing of DTs.

2) Trajectory products choice

We assume that AOs decide between ST and DT products following a binary logit choice model. In the absence of relevant (purchase/transaction) data to analyse and calibrate the model, we consulted AO representatives regarding flight planning matters [4]. In the end, we decided for a simple and effective solution, since binary logit functions are commonly used to represent such choices, for instance in the context of customized B2B pricing [5]. They have an advantage over linear functions in that the probability of choosing DT increases at a non-uniform rate around a certain infliction point (where the curvature of a given line changes). In other words, small changes of the DT price around this infliction point will result in big changes of the choice probability, whereas price changes further away will hardly have any impact on the choice probability. This is in contrast to linear curves, where the change in probability is the same at any price point.

For a given flight, an AO chooses between ST (priced at p_{ST}) and DT (priced at p_{DT}), and this choice depends on the ratio of these two prices. We assume that all AOs can be clustered into certain market segments in a way such that each member of a given segment has the same probability distribution of buying DT versus ST. To illustrate, we depicted such curves in Figure 1. Each market segment is associated with a specific threshold value t, which represents the infliction point of the price ratio where the probability of buying DT just equals 50%. For example, t=0.9 represents a segment where members are choosing DT with 50% probability when the DT price is 90% of the ST price. We rely on STATFOR definition of market segments [6] and define four market segments to represent potential different AOs' behaviour. For instance, Low cost carriers are associated with parameter t value of 0.9 indicating that they are more sensitive to discounts than Business aviation flights (t=0.75). In between are Charter and Cargo (t=0.85) and Traditional carriers (t=0.8).

We emphasise that these functions and parameters have been chosen arbitrarily since we do not have any data that could be used to estimate this function. Actual choice behaviour might look rather different; however, it is also true that the binary logit is highly flexible and, given choice data, can easily be estimated using maximum likelihood techniques. It has to be stressed, that DTs will be offered to all AOs on a non-discriminatory basis. However, we expect different demand functions, since - as an example – the costs of delays are usually higher for a traditional carrier flying into its hub are than for a LCC without transfer passengers.

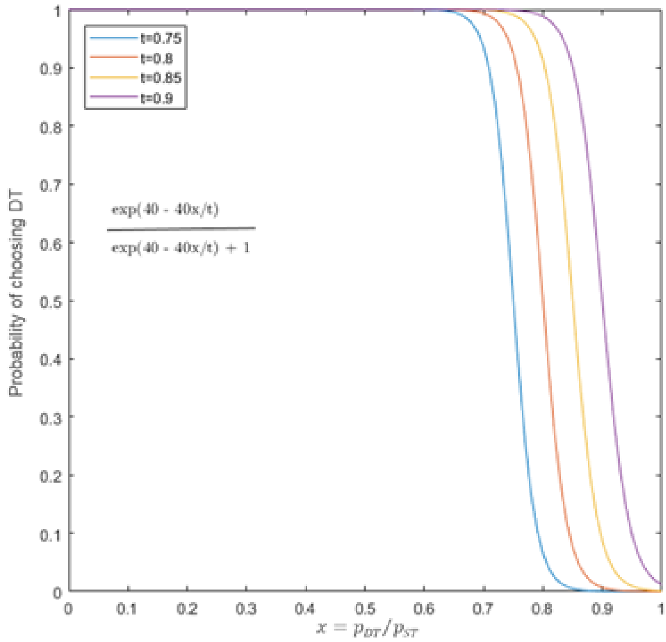

Figure 1. Illustrative product choice model

When AO choose trajectory products, final trajectories are assigned to flights based on the model (1)-(6) with the addition of constraint (7):

$$\sum_{u\in U}\sum_{c\in C} \bar{h}_{ac} z_{acu} \le h_a \qquad \forall a \in A \qquad (7)$$

This constraint expresses that the total sum of sector hours used in the proposed sector opening scheme of an airspace a must not exceed the total sector hours h_a for that airspace. With this addition, we can use the model for the given traffic materialisation to determine flight assignments. DT and ST products are characterised by defining different sets R_f^{DT} and R_f^{ST} that are associated with any given flight f: R_f^{DT} will contain a superset of trajectories in R_f^{ST}.

IV. Numerical Results

A. Case Study

The large-scale case study uses real capacity and demand data, obtained from EUROCONTROL Demand Data Repository (DDR2) service through the EUROCONTROL Network Strategic Tool (NEST).

The network considered consists of eight ANSPs and 15 ACCs/sector groups[2] in Central and Western Europe. The COCTA concept at its current state is only developed for the en-route airspace and therefore, most of the selected ACCs provide ANS services primarily in the upper airspaces (13 ACCs/sector

[2] Sector groups are basically operational units of an ACC and reflect the division of the ACC's airspace. For instance, ACC Karlsruhe Upper Area Control Centre is "divided" into four clusters: Central, East, South and West. Each of these clusters has its own sectorisation and sector opening schemes.

groups), with two ACCs which cover both upper and lower airspaces. Lower airspaces are in Hungary and Slovakia, which are less complex in nature compared to, for instance, lower airspaces in Switzerland or Germany, making them suitable for testing the COCTA concept. A graphical illustration of the case study airspace and its position in Europe is given in Figure 2.

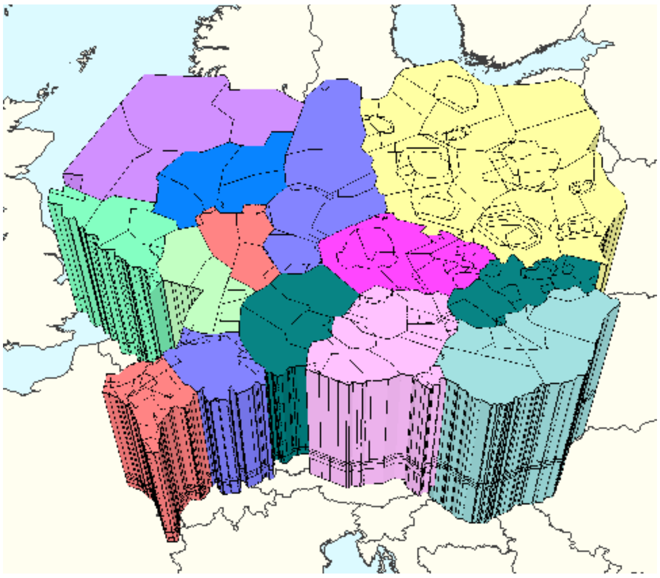

Figure 2. Large-scale case study network

We analyzed airspace configuration usage during the year 2016 to identify the set and the frequency of configurations used by the ACCs. We finally selected a total of 173 different configurations for the 15 ACCs/clusters in the case study, with between six and 26 possible configurations per individual ACC involved.

For model testing, we estimate the ANSP cost data based on cost and capacity information provided in the ATM Cost-effectiveness Benchmarking report. Since some of the ANSPs in our case study have changed their airspace sectorisation over the last years, which influences costs per sector-hour, we only use the most recent data available from 2015 [7].

For every ANSP in the case study, we calculated the average ATCO costs per sector-hour based on the average number of ACC ATCOs on duty per sector-hour and the average employment costs per ATCO hour (in the case of Germany we used operational data for ACC Karlsruhe only). We treat these average ATCO costs per sector hour as variable costs in our model. Moreover, we calculated the average total cost per day to determine cost recovering charges.

To obtain a set of flights, we chose the busiest day on record in 2016: 9th September 2016, with a total of 34,594 flights in the European airspace. Since the ANS charging scheme favours shortest routes in the COCTA context, we first generated shortest routes for the traffic sample (many flights have already filed shortest plannable routes in their last filed flight plans). Using NEST, we generated alternative trajectory options, both in horizontal and vertical plane, crossing different elementary sectors (Figure 3).

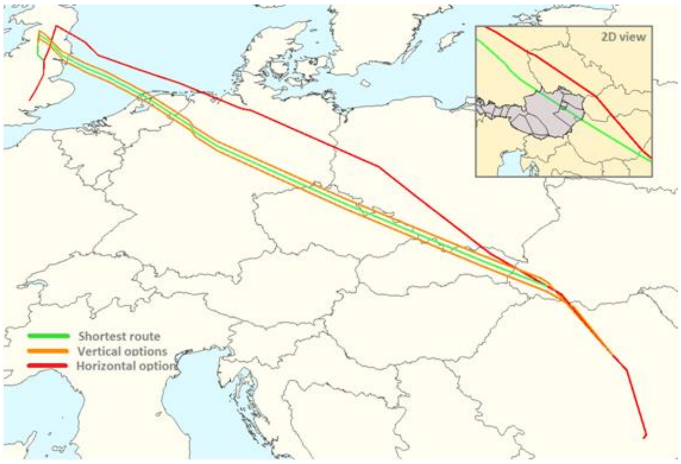

Figure 3. An example of a trajectory and its alternative options

Finally, the traffic sample consists of 11,211 individual flights, with almost 50,000 additional trajectory options (crossing different elementary sectors). We also consider several levels of delays (e.g. 5, 10, 15, etc. minutes) for flights, thus further increasing the number of different 4D options. We consider delays only for shortest routes, i.e. we apply only one demand management measure per flight (delay or re-routing or flight-level change).

To estimate delay and re-routing costs per aircraft type we make use of findings presented in [8] and [9]. Scheduled flights make around 85% of total demand in the case study traffic sample, while the remaining 15% are non-scheduled, in line with the annual averages [10].

B. *Model testing*

To keep the paper more streamlined, in this section we focus on pre-tactical modelling considerations. For further details of relevant long-term and strategic methodological considerations, we refer to [11].

At pre-tactical level, having already decided on the capacity orders (SOSc) for the day of operation, the NM has to define trajectory product margins and prices and offer them to AOs, aiming at a recovery of capacity costs. Like in the current practice, in the COCTA concept cost recovery should be ensured on an annual level. However, since it is very challenging to demonstrate the cost recovery within that timeframe, we demonstrate it on daily basis (which ensures recovery over a longer time horizon as well).

To account for uncertainty associated with a number of flights expected to materialise on the day of operation (colloquially termed “D day”), as seen from the strategic and pre-tactical planning (i.e. days and weeks ahead of D day), we use three different demand profiles. Those concern the numbers of non-scheduled flights showing up on D day. The first demand profile assumes that approximately 50% of all non-scheduled flights anticipated in the strategic phase would appear on the day of operation. The second one assumes a 75% show-up rate, and the last profile assumes 95% of all non-scheduled flights showing up on D day. These percentages translate into total demand comprising respectively:

- 10,850 flights (Moderate demand);
- 11,000 flights (High demand);
- 11,150 flights (Very-high demand).

At pre-tactical level, we compare two different scenarios: COCTA and Baseline.

COCTA scenario: With the SOSc fixed, the only instrument left at the NM's disposal to improve network performance at this stage is trajectory product differentiation and trajectory charging. As mentioned above, the NM uses DT products to be able to spread the demand in space and time in the network, but at a lower charge in return. Also, based on simulations in the strategic phase, the NM has some expectations in which portions of the network DT products might be needed so that the demand gets accommodated by available capacities. The idea is to test how the NM can manage the demand, once the decision on SOSc had been made and what network performance would materialize under different traffic levels expected for that day of operations.

BASELINE scenario: The Baseline scenario mimics the current system, to the extent possible. We assume that the majority of flights will choose the shortest route (~80%), while other flights might take some longer routes, as already observed in practice [12]. Basically, there is 80% chance that a flight will take the shortest route and 20% that it will choose a longer route in the Baseline scenario. In this case, the NM reacts only if there is no sufficient capacity in a portion of airspace and applies a regulation with the aim to minimise ATFM delay minutes, instead of delay cost. Re-routings are applied only if it is not possible to obtain a feasible solution by delaying flights only (maximum delay being 90 minutes).

Practically, we use the same inputs (SOSc on the capacity side and scheduled and non-scheduled traffic samples on the demand side), but different demand management instruments:

- to incentivise trajectory choices, with assumed binary logit choice model, and minimise total cost (COCTA).
- to regulate demand with administrative demand management measures and minimise delay minutes (Baseline).

In summary, the NM makes the following decisions regarding trajectory products: ST and DT spatio-temporal margins, ST and DT prices, which flights/flows will be offered DT along ST (supply) and decision on final trajectory. We describe this decision-making process in the following pseudo-code:

A. Trajectory margins and supply decision

1) SOSc and scheduled flights for a representative day (fixed)
2) For i=1 to number_of_iterations_A:
  - Chose a random traffic sample representing materialisation of non-scheduled flights (for each of the three traffic scenarios)
  - Run COCTA model described in [4] to find an optimal trajectory assignment for a given SOSc
  - Record network performance indicators for each iteration
3) Analyse results (number delayed or re-routed flights, scope of delays and re-routings, distribution of associated displacement cost)
4) *Identify a set of candidate flights to be offered DT for step B*
5) *Define ST and DT margins for step B*

B. Trajectory prices and assignments

1) Calculate ST prices based on SOSc for anticipated traffic level, as elaborated in [5]
2) For i=1 to number_of_iterations_B:
  - Simulate non-scheduled traffic materialisation (scheduled flights are known and fixed)
    Select discounts for DT prices to:
      i) maximise the probability of "candidate" flights/flows choosing DT product (based on assumed choice model and parameters)
      ii) the total DT discount for all trajectories is within ±*d%* (starting with d=5%) of average displacement cost calculated in step A3
  - Simulate AO choices based on choice model and offered prices
  - Run COCTA model described in [4] now with set of trajectories available for each flight based on chosen trajectory product
  - Record network performance indicators for each iteration;
3) If network performance (primarily total cost-efficiency) averaged over all iterations is not within +10% from stage A (*condition*) then:
  - increase *d* in steps of 5 (until 20) and repeat B2
Else:
  - adjust ST and DT margins (Step A5) and repeat B
4) Repeat B3 until *condition* is met
5) *Decide on trajectory prices*
6) *Decide on trajectory assignments*

C. Results

The results of the model testing using the same case study, at the strategic level, for a representative day in a season, can be found in [11]. They are summarized in Figure 4: There is an (expected) trade-off between capacity cost and displacement cost, with an optimum solution below the maximum capacity provision.

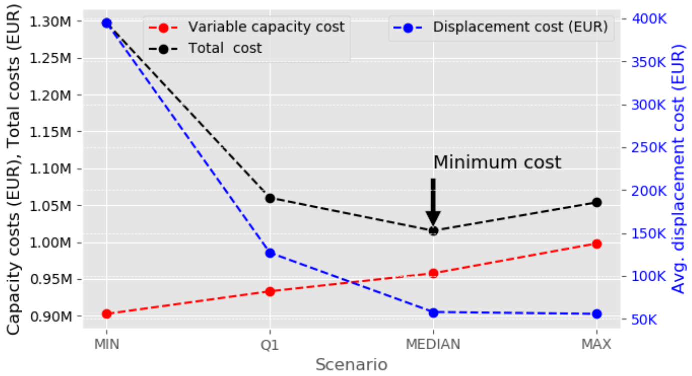

Figure 4. Capacity and displacement cost trade-off between different capacity ordering scenarios

Assuming that the NM has already decided on SOSc per ANSP/ACC according to these results, in this section we show the results of pre-tactical testing of the previously chosen COCTA SOSc (MEDIAN) [11] and compare them to the results of testing the modelled (non-COCTA) Baseline scenario using the same SOSc and traffic samples (both scheduled and non-scheduled). Based on many trials and experiments (several hundreds), we define margins for trajectory products as:

- ST: re-routing up to 2NM or delay up to 5min
- DT: re-routing up to 45NM or delay up to 30min

The results of the pre-tactical model testing for the COCTA and the Baseline scenarios are given in Table I.

Table I shows the performance of the COCTA mechanism under the chosen SOSc (MEDIAN) for each of the three demand profiles. Obviously, even more challenging demand profiles deteriorate the network performance only to a small degree when the COCTA mechanism is in force. The performance deterioration with increasing demand is very small with respect to delay, with 300 additional flights (i.e. 10,850 -> 11,150) being accommodated by the unchanged SOSc at a penalty of only 530 additional delay minutes, the vast majority of which stems from delays of 5 to 15 minutes. A greater portion of additional demand is being accommodated by means of spatial displacement (facilitated by offering DT discount for longer trajectories assigned). As a result of more frequent re-routings environmental performance is expectedly somewhat negatively affected on average, with 16.4t more extra-CO_2 emitted in the Very-high than with the Moderate demand profile, corresponding to 5.2t extra fuel burned in total, or merely 0.39 kg extra fuel burned per flight, on average.

Importantly, the aggregate DT discount needed to drive user trajectory choices into the desired direction (closer to network optimum) seems very reasonable (55-60 thousand EUR in total). Furthermore, the aggregate DT discount increases with rising demand at lower pace than the corresponding displacement costs, which are estimated to range between 49,000 and 62,000 EUR.

TABLE I. PRE-TACTICAL TESTING, COCTA MEDIAN SOSC VS. MODELLED NO-COCTA BASELINE

Performance indicators	COCTA MEDIAN SOSc			Baseline MEDIAN SOSc[3]		
	Moderate	High	Very-High	Moderate	High	Very-High
Number of flights in the scenario	10,850	11,000	11,150	10,850	11,000	11,150
Feasibility (%)	100	100	100	93	93	72
Total number of sector half-hours	3,063	3,063	3,063	3,063	3,063	3,063
Total DT discount (EUR)	55,529	57,743	59,791	n/a	n/a	n/a
Number of re-routed flights	733	781	836	199	322	322
Number of delayed flights	204	235	286	1,211	1,716	1,638
Total delay (min)	1,143	1,357	1,675	22,210	50,806	44,259
Average delay per flight (min)	0.105	0.123	0.150	2.0	4.6	4.0
Avg. delay per delayed flight (min)	5.60	5.77	5.85	18.3	28.6	25.9
Avg. num of flights delayed 5 min	192	218	264	537	386	449
Avg. num of flights delayed 15 min	11	15	21	396	434	448
Avg. num of flights delayed 30 min	0.50	1.20	1.30	90	354	285
Avg. num of flights delayed 4 5min	0	0	0	106	290	244
Avg. num of flights delayed 60 min	0	0	0	45	132	110
Avg. num of flights delayed $\geq$ 90 min	0	0	0	38	120	102
Avg. extra CO_2 (kg) emitted per flight	8.86	9.56	10.10	3.05	9.69	8.83

Table I also suggests a notably better performance of COCTA compared to the modelled Baseline, which applies the same SOSc, but minimizes delay minutes, rather than displacement cost, as already elaborated. For any given demand profile COCTA yields an order-of-magnitude lower total delay minutes than the Baseline, accompanied by much narrower distribution of flight delays, with hardly any delay longer than 15 minutes (all differences are statistically significant at 5% level).

[3] Values shown are averages across feasible iterations only.

This comparison should nevertheless be taken with caution, given the time horizon to which it relates. More specifically, it is unlikely that an anticipation of such poor performance in the Baseline scenario, obtained in the strategic/pre-tactical stage, would realistically remain unaddressed until the day of operation by the NM and/or ANSPs involved. Some of the capacity and demand management measures would likely be triggered, which would alleviate what seems to be a dramatic demand/capacity imbalance in the example we study. Indeed, in practice, ANSPs sometimes decide to apply (pre-tactically) mandatory re-routing scenarios to alleviate congestion in certain sectors [13], since re-routings are not considered in the capacity planning phase [14]. Also, AOs do not always support the application of mandatory re-routings [15], not just because of the additional cost, but because there is no assessment of benefits for the network as a whole [16]. Moreover, AOs raised a concern that ANSPs might sometimes use mandatory re-routing scenarios to reduce ATFM delays to comply with their local delay targets [15]. In the COCTA system, with airport pair charging and trajectory pricing incentives, re-routing becomes a network-centric instrument to effectively establish a demand-capacity balance, with clear benefits for AOs overall.

In any case, there seem to be obvious and tangible benefits of coordinated capacity ordering and management across the network, including still very basic product (trajectory) differentiation with associated price differentiation.

Concerning the performance of the Baseline scenario itself, it should be noted that the Moderate demand (10,850 flights) can on average be accommodated with arguably bearable average delay of 2.0 minutes per flight. However, additional increase in demand, while keeping the SOSc unchanged, severely affects the network performance. This is particularly the case concerning the incidence of delays ≥ 30 minutes, but also in terms of CO_2 emissions, as re-routings become inevitable at some point. It should finally be noted that in more than 25% of cases there was no feasible solution in the Baseline scenario when the demand profile was Very-High, and that even Moderate or High demand profiles could not have been accommodated each time (feasibility rate of 93% for each of them). This practically means that, in such cases, delays longer than 90 minutes or/and mandatory re-routings would have to be applied to fit the traffic into available capacities.

V. CONCLUSIONS AND OUTLOOK

In this paper we summarize the proposed changes in the ATM value-chain and briefly explain the COCTA capacity and demand management process developed so far. We introduce the new features to the previously developed COCTA mathematical model to support the decision-making process at the pre-tactical level.

For the pre-tactical model testing, we use the SOSc chosen at the strategic level as an input parameter and introduce different trajectory products: Standard Trajectory (ST) and Discounted Trajectory (DT). Based on assumed parameters of the choice model, airlines decide which product they opt for, depending on the discount the NM could offer (probabilistic model). In this case study and the pre-tactical timeframe that we have analysed, it was assumed that the NM cannot re-order (ask for and negotiate) more capacity; it has to recover the capacity costs and defines sector-opening schemes for each ACC.

The results of pre-tactical stage testing suggest that coordinated capacity ordering, as such, yields a reduced need for capacity provision. This can be inferred from the experiment where identical SOSc have been used for both the COCTA and the Baseline scenario, which shows clear performance advantages (especially concerning total delay minutes and the distribution thereof) brought about by COCTA. To reach the level of network performance achieved within the COCTA framework, the Baseline setting necessitates tangibly higher capacities in some parts of the network. In other words, COCTA consumes considerably fewer capacities to achieve the performance comparable to the non-COCTA setting. Finally, improvements in delay and/or cost-efficiency domains expectedly come at an environmental penalty, which is however fairly small, not exceeding, on average, 1.8kg extra fuel per flight compared to the non-COCTA Baseline.

Product and price differentiation (standard – ST vs. discounted trajectories – DT), according to preliminary tests conducted in quite a limited context, seem to be capable of driving the individual airspace users' trajectory choices towards network-optimum traffic allocation, yielding as a result a satisfactory vector of network performance indicators.

We currently work on testing further product differentiation, wherein a ‘premium trajectory’ would also be offered to AOs, allowing for short-notice trajectory choice, in return for a premium charge. This comes in response to stakeholder feedback received in the course of the project, stressing the specific requirements of certain market segments [4].

Empirical data is missing for the choice model calibration, which limits our ability to make credible policy recommendations. Based on stakeholder feedback, including some relevant AO feedback too, the proposed concept nevertheless seems a promising way forward in improving the network performance.

In future work one could use surveys and/or conjoint analysis to elicit AOs’ sensitivity to pricing and their valuation of these products in a simulated environment. This way, one could obtain more realistic models of customer choice, although they may still suffer from the usual shortcomings of such methods (such as the fact that the purchase scenarios are just simulated).

Further research would be necessary for definitive conclusions on the prospects of the proposed concept. To that end, one of obvious next steps seems to be adjusting and testing the concept under non-nominal conditions. This first of all relates to uncertainties concerning capacity delivery on the day of operations, but also delays caused by e.g. weather and/or airport related issues matter. Broadening the research scope to include the tactical phase, as well as terminal airspace and airports, is also one of the planned extensions of the COCTA project. Finally, an investigation into relevant legal and regulatory aspects would also be desirable, including e.g. details of relationships NM-ANSPs and NM-AOs, or necessary changes to the SES performance scheme, as suggested by stakeholders at the COCTA final dissemination event (Brussels, 14 September 2018).

ACKNOWLEDGEMENT

This project has received funding from the SESAR Joint Undertaking under grant agreement No 699326 under European Union's Horizon 2020 research and innovation programme.

R. Jovanovic thankfully acknowledges the support of the Ministry of Education and Science of the Republic of Serbia, TR36033.

REFERENCES

[1] COCTA consortium, "ATM value-chain redesign," 2017. https://cocta.hs-worms.de/fileadmin/media/SESAR/699326-COCTA-D3.1-ATM_value-chain_redesign-01_00_00.pdf

[2] S. Starita, A. Strauss, R. Jovanovic, N. Ivanov, and F. Fichert, "Maximizing ATM Cost-efficiency by Flexible Provision of Airspace Capacity," in *SESAR Innovation Days (SIDs 2016)*, 2016.

[3] S. Starita *et al.*, "Coordinated capacity and demand management in a redesigned ATM value chain: Strategic network capacity planning under demand uncertainty," in *7th SESAR Innovation Days*, 2017.

[4] COCTA consortium, "Final mechanism design," 2017. https://cocta.hs-worms.de/fileadmin/media/SESAR/699326-COCTA-D4.2-Final_mechanism_design-02_00_00_FINAL.pdf

[5] R. L. Phillips, *Pricing and revenue optimization*. Stanford University Press, 2005.

[6] EUROCONTROL STATFOR, "Market Segment Rules." [Online]. Available: https://www.eurocontrol.int/sites/default/files/content/documents/official-documents/facts-and-figures/statfor/statfor-market-segments-rules.pdf. [Accessed: 16-Mar-2018].

[7] EUROCONTROL, "ATM Cost-Effectiveness (ACE) 2015 Benchmarking Report with 2016-2020 outlook," 2017.

[8] A. Cook and G. Tanner, "European airline delay cost reference values. Final Report. University of Westminster for EUROCONTROL Performance Review Unit," 2015.

[9] EUROCONTROL, "Standard Inputs for EUROCONTROL Cost-Benefit Analyses, Ed. 8.0," 2018.

[10] EUROCONTROL PRC, "Performance Review Report: An Assessment of Air Trafc Management in Europe during the Calendar Year 2016," 2017.

[11] COCTA consortium, "Choice-based joint capacity ordering and pricing model," 2018. https://cocta.hs-worms.de/fileadmin/media/SESAR/699326-COCTA-D5.3-Choice-based_joint_capacity_ordering_and_pricing_model_01_00_00.pdf

[12] L. Delgado, "European route choice determinants," in *11th USA/Europe ATM R&D Seminar Seminar*, 2015.

[13] EUROCONTROL, "ATFCM Operations Manual: Network Operations Handbook. Ed 21.0," 2017.

[14] EUROCONTROL, "Capacity assessment and planning guidance document, Ed. 2.8," 2013.

[15] EUROCONTROL, "Annual Network Operations Report 2014, Annex I - Airspace Users View," 2015.

[16] C. Woodland, "Understanding Dynamic Airspace," in *The Network Manager User Forum 2018*, 2018.